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Dark Matter Halo Remnant Shape After Major Merger

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1. INTRODUCTION

Every galaxy is theorized to be surrounded by a **dark matter halo** – a cluster of invisible matter that exerts gravity and extends far beyond the visible boundaries of a galaxy. These dark matter clusters accrete in uneven ”filaments” or ”sheets” in space, leading them to be clumpy and asymmetric (K. T. E. Chua et al. 2019). Thus, each dark matter halo has unique properties that can be quantified and studied (N. E. Drakos et al. 2019). When galaxies merge, their dark matter halos also merge with each other, changing their properties. Quantifying how a merger affects the structure of a dark matter halo is one of the ways we can draw conclusions about how galaxies change over time.

A **galaxy**, as defined by B. Willman & J. Strader (2012), is ”a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton’s laws of gravity.” In this definition, dark matter is necessary to explain the formation of galaxies; dark matter clusters exert the gravitational force needed to condense gas and dust into galaxies. Since the shape of each dark matter halo is unique to a galaxy, it is closely entwined with the galaxy’s growth and merger history (N. E. Drakos et al. 2019). Dark matter clusters are, theoretically, the only site of galaxy formation; therefore, understanding how a halo can be changed has implications for **galaxy evolution** overall. Galaxy evolution studies how galaxies in the early universe were assembled, and how they have been formed into the diverse structures we see today. Since dark matter halos are exclusive to the galaxy they surround, discovering patterns in dark matter halo properties could shed light on greater trends in galaxy evolution.

Galaxy mergers and dark matter halos are modeled using N-body simulations. An N-body simulation models interactions between particles in a system under the effects of some force; in the case of galaxy mergers, an N-body simulation models collisions between two or more galaxies under the influence of each other’s gravity. The baryon components of a galaxy such as gas, stars, and dust are difficult to simulate, so many of these simulations are done with only dark matter particles, in what is referred to as a DMO simulation (K. T. E. Chua et al. 2019). While these simulations are good approximations for dark matter-dominant regions of a galaxy, they are not accurate for the bright, baryon-dominant components of a galaxy such as the galactic center, which can alter the shape of nearby dark matter distribution (see Figure 1) (M. G. Abadi et al. 2010). Dark matter halo studies are primarily interested in studying the shape, spin, concentration, and mass profile of these structures.

There are many uncertainties when using N-body simulations to examine dark matter halos. How a halo is reshaped as a result of merger is, as previously mentioned, one of the primary focuses of dark matter halo studies. One of the biggest questions in regard to halo shape is the effect baryons have, especially on the ”inner” halo where the galaxy is located (K. T. E. Chua et al. 2019). Papers such as M. G. Abadi et al. (2010) outline one way to tackle the inclusion of baryons in a simulation of this nature. Active galactic nuclei can also pose issues in determining the properties of dark matter halos, since they eject baryons and dark matter from the galactic center (K. T. E. Chua et al. 2019). In many simulations, such as N. E. Drakos et al. (2019), two equal-size galaxies are used to examine how a **major merger** influences the dark matter halo. Mergers between galaxies of comparable size are considered major mergers, while collisions between a larger galaxy and a smaller galaxy are considered minor mergers. In actuality, major mergers are rare; it is much more common for galaxies of different sizes to merge.

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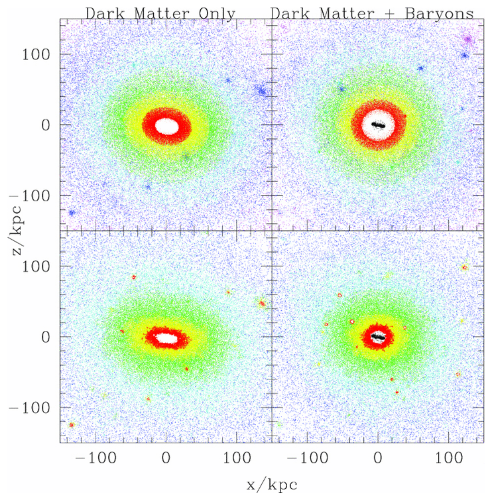

Figure 1. Figure 4 from M. G. Abadi et al. (2010). In this paper, the effects the baryon component of a galaxy has on dark matter halo shape was examined. These graphs represent the distribution of particles included in an N-body simulation, plotted so that the galaxy is viewed face-on – position in the x direction versus the position in the z direction. The top panels represent simulations where particles were binned according to their gravitational potential, while in the bottom panels, they are binned by their density. On the left, only the particles that make up the dark matter halo were used, while on the right, the baryon components that make up the bright parts of the galaxy were included. In the right-hand panes, the shape and position of the central galaxy is depicted in black. In the dark matter + baryons simulation, the halo becomes more spherical due to the presence of the central galaxy.

2. THIS PROJECT

In this paper, I will examine and quantify the shape of the dark matter halo remnant resulting from a major merger between two galaxies in the **Local Group**: our Milky Way Galaxy and the Andromeda Galaxy. The Local Group describes the collection of galaxies near and including the Milky Way; of major interest is the study of the eventual merger of the Milky Way and the Andromeda Galaxy (M31), which are expected to collide in 4-5 billion years.

This paper is designed to address how the Milky Way-M31 merger will influence the shape of the remnant halo. From previous work such as N. E. Drakos et al. (2019), it appears that halo remnants are stretched along the axis where they collide. I will examine if predictions such as these are true for the halo remnant of this specific major merger.

Dark matter halos are unique to each galaxy; therefore, studying their evolution can lend some insight into the history of the galaxy itself. Since a majority of galaxies are thought to have gone through a merger, studying the dark matter halo can reveal trends in galaxy evolution that apply to many galaxies.

3. METHODOLOGY

In order to examine this merger, I will use a modified version of the N-body simulation described in R. P. van der Marel et al. (2012). This simulation does not include collisions between individual particles. Gas makes up only a small portion of the total galaxy mass, so it was excluded from the simulation as well. The galaxies in the simulation have dark matter halos represented by a **Hernquist Profile**. The Hernquist Profile, as defined in L. Hernquist (1990), is the distribution of mass within a given radius in a spherical object. Each galaxy has 500,000 dark matter particles that make up its halo. Each galaxy's disk mass was chosen to best suit its observed rotation curve and is represented by an exponential profile. Each galaxy's bulge mass was determined from literature values, and set up with an $R^{1/4}$ profile. Initially, the Milky Way is at rest, and set at the origin of the Galactocentric frame.

I will modify the simulation to only include the dark matter halo particles. Although the smaller Triangulum Galaxy (M33) is involved in this event and included in the simulation, only the Milky Way and M31 merge, so only their particles will be considered in this simulation. I will examine the combined halo remnant after the merger has occurred, and the dark matter halo has settled – about 9 billion years in the future, or around snap number 630 in the files for both galaxies. In order to examine the combined dark matter halo, I will concatenate the arrays for the positions and masses of each dark matter particle in each galaxy for the snapnumber 630 file. I will be using the high-res version of the file, since I am only examining one snapnumber instead of a sequence of files. Once I have the concatenated array of the combined halo particles, I will fit the Hernquist Profile to the data. I will then use the Python package *photutils* to plot elliptical **isodensity contours** on 2-D histograms of the spatial projections. An isodensity contour represents points on the graph that have the same density (see Figure 2). Photutils will return the ellipticity of a given isodensity contour; in this project, I will use the ellipticity of the isodensity contour closest to the scale radius determined by fitting the Hernquist Profile to obtain the axial ratios. Once the axial ratios are obtained, they can be compared to determine the overall shape of the halo.

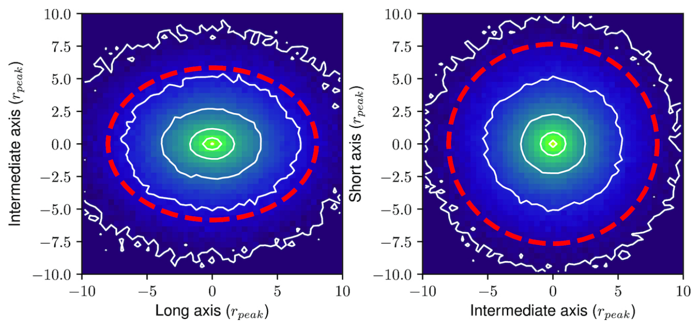

Figure 2. Figure 6 from N. E. Drakos et al. (2019). The results of a simulation of a major merger between two equal-sized galaxies. Plotted on top of a diagram of the halo particle distribution are iso-density contours (white) and the shape ratio (red). The shape ratio generally agrees with the iso-density contours. This diagram is very similar to what I intend to produce with my project.

The Hernquist mass profile is defined as:

$$M(r) = M_{halo} r^2/(a+r)^2 \tag{1}$$

Where M_{halo} is the mass of the dark matter halo, r is the distance to the Galactic center, and a is the scale radius. The scale radius of the Hernquist Profile represents the radius that encloses the majority of the mass in a galaxy. The scale radius for the merger remnant will be determined by trying multiple values until the profile closely resembles the halo mass distribution. After the projections of the galaxy in x, y, and z are plotted and the isodensity contours are fitted using photutils, the shape of the halo can be determined. Halos are approximated by ellipsoids, which are triaxial; their shapes are described by the axial ratios q and s. These ratios are written as

$$q = b/a \tag{2}$$

$$s = c/a \tag{3}$$

where a is the length of the major axis, b is the length of the intermediate axis, and c is the length of the minor axis. The axial ratios are related to the ellipticity by the generalized equation

$$e = 1 - m/w \tag{4}$$

Where e is the ellipticity, m is the length of the major axis of the ellipse, and w is the length of the minor axis of the ellipse. K. T. E. Chua et al. (2019) defines the "Triaxiality Parameter" as

$$T = (1-q^2)/(1-s^2) \tag{5}$$

where T is the triaxiality of the distribution, and q and s are the axial ratios described above. The value of T determines the shape of the halo; if T > 0.67, the halo is considered prolate, but if T < 0.33, the halo is considered oblate (K. T. E. Chua et al. 2019). If 0.33 < T < 0.67, the halo is considered triaxial (K. T. E. Chua et al. 2019).

I will produce three plots in total. I will first plot and fit the Hernquist mass profile to determine the scale radius. After the scale radius has been determined, I can create two plots of the particle position projections. I will plot the projection in x versus the projection in y, and then plot the projection in z versus the projection in y. Using photutils, I will overplot isodensity contours on these graphs. Photutils will return the ellipticity of a given isodensity contour, which can be used to determine the axial ratio. I will compare the axial ratios taken from the elliptical contours closest to the scale radius; the scale radius encloses most of the mass of the remnant, making it an appropriate choice to use to determine the triaxiality.

Following from the results of N. E. Drakos et al. (2019) and M. G. Abadi et al. (2010), I expect to find that the combined dark matter halo of the merged galaxies will become more axisymmetric. Galaxies on radial orbits will generally form prolate halo remnants, while galaxies on tangential orbits will form oblate remnants (N. E. Drakos et al. 2019). M31 is on a mostly radial orbit with respect to the Milky Way, so I expect the halo remnant will most likely be prolate.

4. RESULTS

Figure 3 shows the fitting of the Hernquist Profile for the dark matter halo remnant. The remnant halo mass profile was created by computing the mass enclosed at about every 6 kpc, starting at 5 kpc from the center out to a radius of 200 kpc. The Hernquist Profile was computed via equation (1), using the same radius bins that were used to create the remnant mass profile. The best fit for the Hernquist Profile is achieved with a scale radius of 96 kpc; with this scale radius, the fractional difference between profiles is within 7% at all radii.

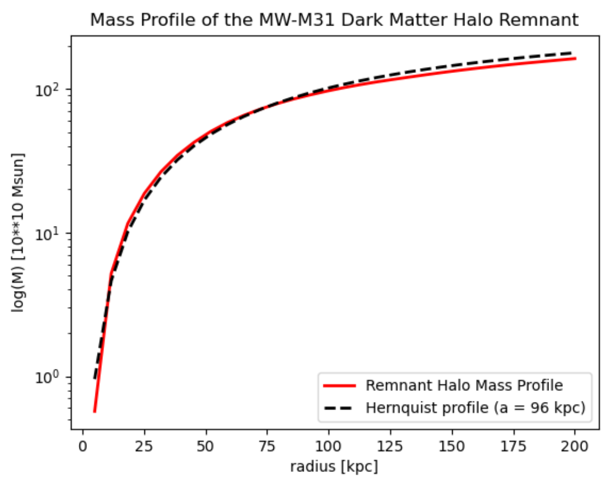

Figure 3. The fitting of the Hernquist Profile for the halo remnant. The distance from the center of the halo remnant is plotted on the x axis, while the log of the mass in $10^{10} M_{sun}$ is plotted on the y axis. The red line represents the mass of the combined dark matter halo at every radius, starting from 5 kiloparsecs from the center of the merged galaxy, up to 200 kiloparsecs. The dashed line represents the Hernquist Profile. The best fit for the Hernquist Profile is obtained using a scale radius of 96 kpc.

Figure 4 represents the particle projections in the x and y directions. The projection in x is plotted on the x axis and the projection in y is plotted on the y axis; in order to use photutils, the axes in kpc must be converted to pixels. The colormap represents the density of the particles; yellow areas are more densely packed, while dark purple areas are less dense. Elliptical isodensity contours were overplotted on the distribution using photutils. For determining the axial ratio q, I have chosen to define x as the intermediate axis b, and y as the major axis a. The ellipticity of the 96 kpc isodensity contour determined from this graph is 0.155. Using this result in equation 4, the axial ratio q is 0.845.

Figure 5 represents the particle projections in the z and y directions, with z plotted on the x axis and y plotted on the corresponding y axis. Like in Figure 4, the axes were converted from kpc to pixels in order to use photutils; also like Figure 4, the colormap represents densely populated areas in yellow, and sparsely populated areas in purple. To determine the axial ratio s, I have chosen to define z as the minor axis c, while the y axis, as in Figure 4, represents the major axis a. The ellipticity of the 96 kpc isodensity contour determined from this graph is 0.2. Using this result in equation 4, the axial ratio s is 0.802.

5. DISCUSSION

With the axial ratios q and s determined from Figures 4 and 5 respectively, the Triaxiality Parameter (equation 5) was found to be 0.8. Following the definition in K. T. E. Chua et al. (2019), this result suggests that the remnant is prolate in shape. This measurement agrees with my hypothesis for the final shape.

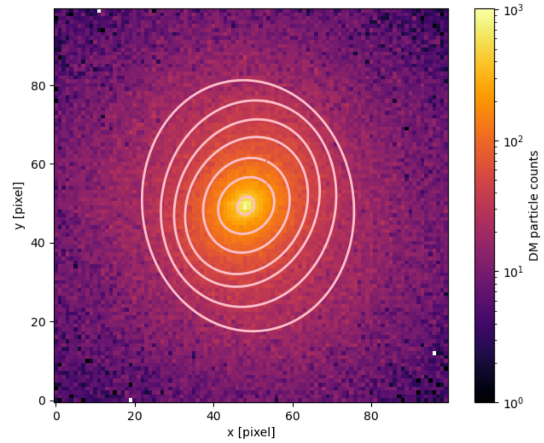

Figure 4. The dark matter particle projections in the x and y directions of the halo remnant. A colormap was used to represent the particle count density. Axes are plotted in pixel widths. Elliptical isodensity countours are plotted overtop in pink. In the inner halo, the distribution is more circular, while at larger radii, it becomes more elliptical.

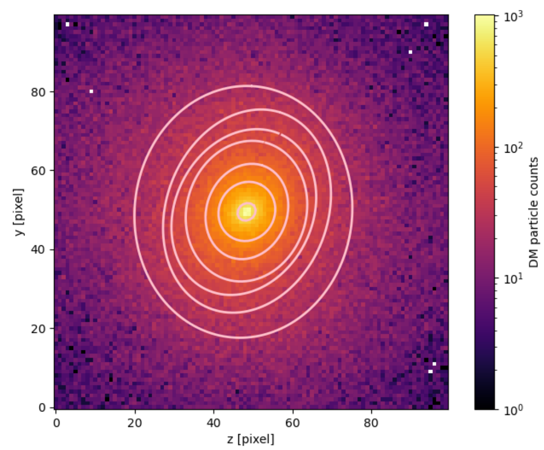

Figure 5. The dark matter particle projections in the z and y directions of the halo remnant. A colormap was used to represent the particle count density. Axes are plotted in pixel widths. Elliptical isodensity countours are plotted overtop in pink. As observed in the XY projection histogram, the ellipticity of the halo appears to increase based on distance from the center.

The remnant's prolateness agrees with the predictions for halo shape based in papers such as N. E. Drakos et al. (2019) and M. G. Abadi et al. (2010); galaxies on radial orbits with respect to each other, such as the Milky Way and M31, will produce prolate halo remnants. This result's consistency with the literature suggests that dark matter halos undergo quantifiable and predictable changes based on the properties of the merger. These results can be applied to study the halos of galaxies to determine what kind of merger it may have undergone.

The triaxiality of the halo is dependent on the radius at which the axial ratios are measured. The choice of the scale radius of the Hernquist Profile is appropriate, but since it is only one measurement, it neglects how the triaxiality changes with radius. To address this, mulitple radii could have been chosen to compare axial ratios, thus determining how the Triaxial Parameter changes with radius for this distribution. This measurement also excludes how the interal energy available to the remnant alters its shape; N. E. Drakos et al. (2019) determined that the axial ratio s scaled roughly linearly with energy. If energy had been considered, the measured axial ratio s may have been different.

REFERENCES

Abadi, M. G., Navarro, J. F., Fardal, M., Babul, A., & Steinmetz, M. 2010, Monthly Notices of the Royal Astronomical Society, 407, 435, doi: 10.1111/j.1365-2966.2010.16912.x

Chua, K. T. E., Pillepich, A., Vogelsberger, M., & Hernquist, L. 2019, Monthly Notices of the Royal Astronomical Society, 484, 476, doi: 10.1093/mnras/sty3531

Drakos, N. E., Taylor, J. E., Berrouet, A., Robotham, A. S. G., & Power, C. 2019, Monthly Notices of the Royal Astronomical Society, 487, 993, doi: 10.1093/mnras/stz1306

Hernquist, L. 1990, ApJ, 356, 359, doi: 10.1086/168845

van der Marel, R. P., Besla, G., Cox, T. J., Sohn, S. T., & Anderson, J. 2012, The Astrophysical Journal, 753, 9, doi: 10.1088/0004-637X/753/1/9

Willman, B., & Strader, J. 2012, The Astronomical Journal, 144, 76, doi: 10.1088/0004-6256/144/3/76