Draft version May 1, 2020
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The Future Morphological Evolution of M33

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(Dated: May 1, 2020)

Keywords: Local Group, Stellar Disk, Spiral Galaxy, Satellite Galaxy, Galaxy Interaction

1. INTRODUCTION

As of 2012, at least 27 satellite galaxies are known to be associated with the Milky Way and 32 with Andromeda, the two dominant galaxies of the Local Group (McConnachie 2012). These satellite galaxies, as demonstrated in N-body simulations in Mayer et al. (2001), have likely been significantly altered by tidal interactions with their host galaxy. In a process commonly referred to as tidal stirring, the visual appearance of the stellar structure in these galaxies can change dramatically. Astronomers typically refer to the change in appearance of a galaxy as morphological evolution.

We define galaxies (massive or dwarf) as a collection of gas, dust, and stars within a dark matter halo. Galaxies can evolve in several ways, one of which is a changing stellar population as a result of star formation or aging. The composition of a galaxy, referring to the ratio of stars to gas and to dust, can also change by many different mechanisms. Lastly, the internal structure and shape of a galaxy can change, reflecting different internal dynamics. Morphological evolution falls into this third category. Galaxy morphology has been of interest to extra-galactic astronomers for a very long time, partly because it is the most apparent quality of a galaxy. However, galaxy morphology can be quite nuanced and reveal much information about the internal dynamics of the galaxy in question. Understanding what processes in what galaxies lead to certain morphologies is of peak interest to astronomers.

The Triangulum galaxy, hereby referred to as M33, is the third most massive galaxy of the Local Group and a satellite to the Andromeda galaxy (M31). M33 is a flocculent spiral galaxy, meaning that it is a spiral disk galaxy without well defined spiral arms. M33 is the only spiral disk galaxy in the Local Group that is a satellite to a more massive galaxy. Nearly all satellites to the Milky Way or M31 are dSphs. Hydrodynamical simulations conducted in Semczuk et al. (2018) show that the faint two spiral arm signal and distorted (rotated) gas disk observed in M33 today can be explained by a recent close encounter with M31 (see Figure 1).

It is not obvious how the morphology of M33 will change in the future due to tidal interactions. Mayer et al. (2001) proposes that disky satellite galaxies eventually form dSphs after sufficient tidal stirring, but it is unclear whether this process is occurring in M33. Alternatively, Semczuk et al. (2018) suggests that a recent tidal interaction induced a stronger spiral arm pattern as well as a burst of star formation in M33. It is possible that another similar encounter may further strengthen a distinct spiral arm pattern.

2. THIS PROJECT

In this paper, we will investigate how M33s morphology will change in the future, after the Milky Way-M31 major merger. We will focus on the evolution of M33s disk shape and spiral pattern.

3. METHODOLOGY

The simulation data that we will be using comes from the collisionless N-body simulation conducted in van der Marel et al. (2012). An N-body simulation refers to any numerical integration of a gravitational system of 3 or more massive bodies. In these simulations, the massive bodies are many particles that represent either the stellar or dark matter that make up the three most massive Local Group galaxies. The collisionless aspect of these simulations simply means that the only way that these particles interact is through gravity—no other physics required.

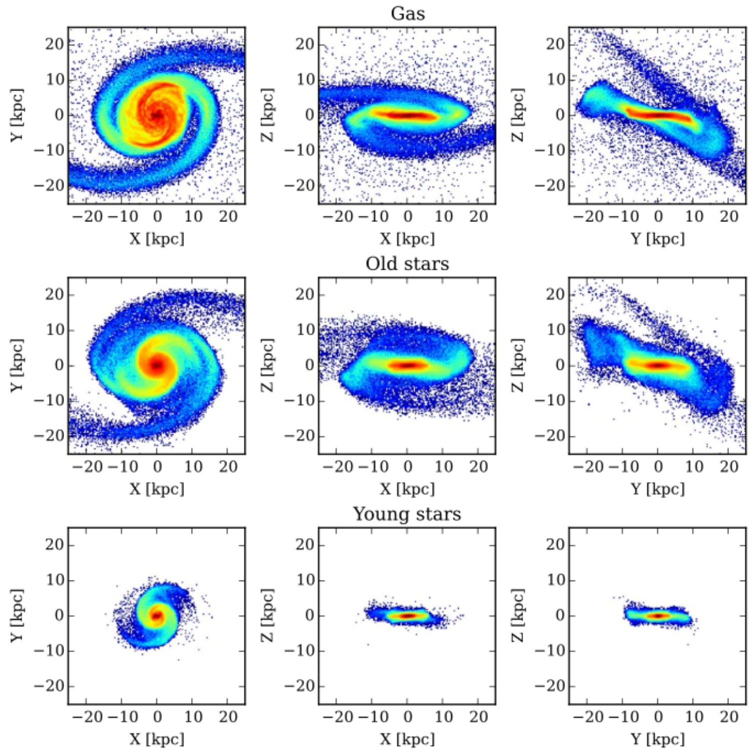

Figure 1. Figure 6 from Semczuk et al. (2018). Surface density distributions of the gas, young stars, and old stars in the simulated M33 after its interaction with M31. Demonstrates the introduction of novel morphology (spiral arms, warped disk at large radii) as a result of tidal interaction.

Our approach to studying the evolving morphology of M33 is to use the method which has always defined galactic morphology: visual inspection. Using simulation data, however, gives us much flexibility in how we approach this. For example, we can rotate our virtual representation of the galaxy and view it from multiple perspectives. We will do this in much the same way as demonstrated in Figure 1. We will also overlay constant density contours to aid our visual inspection. To measure how elliptical or spheroidal-like M33 will become, we will measure its axial ratio. Both of these methods are depicted in Figure 2.

The first step in our analysis is to define a coordinate system centered at M33s center of mass in the time-step of interest, with the z axis normal to the disk (or parallel to the minor elliptical axis). We will first calculate the center of mass using the usual formula $\vec{R} = (1/M)\sum_i m_i\vec{r}_i$, where M is the total mass of all the particles and m_i and $\vec{r}_i$ are the mass and position of an individual particle. In this calculation we will only use stellar particles and exclude all dark matter particles. This calculation will cease to be accurate later in the simulation when M33 has lost a significant portion of its mass. The particles that are no longer bound to M33 will continue to influence the calculation of its center of mass. To compensate for this, we will use an iterative process to locate the center of mass. With every iteration, particles outside a shrinking distance from the previous center of mass will be discounted and a new center of mass will be calculated. The process will continue until the location converges. Once we center our coordinate system on the center of mass, we will calculate the direction of M33s overall angular momentum $\vec{L} = \sum_i \vec{r}_i \times \vec{p}_i$ and rotate the galaxy so that it is now parallel to the z-axis.

Once we are in the correct coordinate system, we can create our density plots. Since all stellar particles of M33 in this simulation are of the same mass, we do not need to calculate any densities. A 2D histogram that counts the number of particles in each bin, normalized, will give us what we need. In this coordinate system, an x vs. y plot will give us a face-on perspective and allow us to visually inspect for any spiral structure. Contours of constant density could help us identify spiral arm signals that may not otherwise be distinct. Our next step would be to measure M33s axial ratio, and we will attempt to do this using two methods. The first involve manually fitting an ellipse to the edge-on 2D density plot (x vs. z or y vs. z), as demonstrated in Figure **??**. The axial ratio would then be calculated from the major and minor axes of this best fit ellipse. The second method will be to obtain the major and minor axes

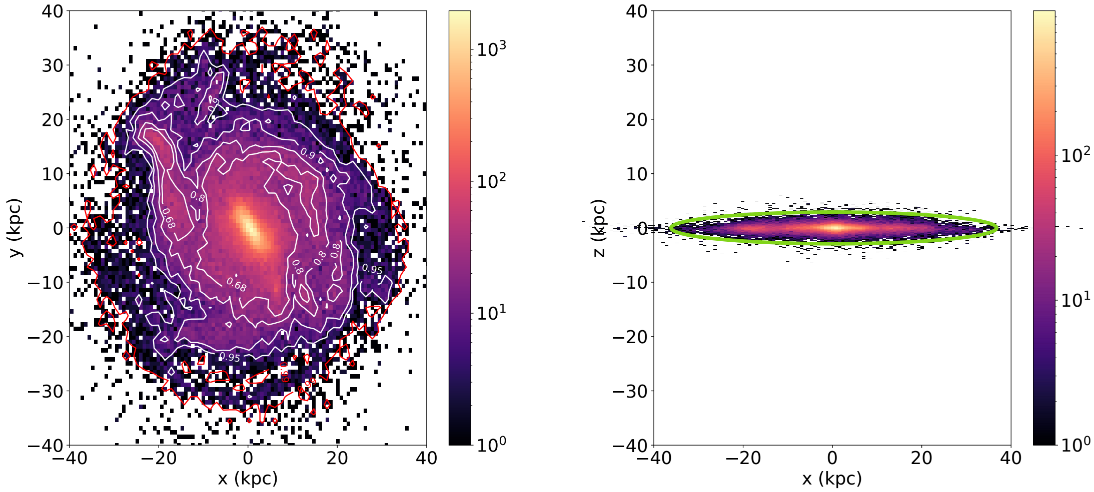

Figure 2. Examples of 2D density plots. Simulated M31 is shown face-on (left) and edge-on (right) relative to its disk. Face-on perspective features overlaid contours of constant density, which help distinguish low contast disk structure. Edge-on perspective is fit with an ellipse. Measuring the ratio of minor to major axes of the ellipse is equivalent to measuring the axial ratio of the M31 disk.

by measuring the spread of the 1D density profiles along these two axes. The latter method is more quantitative, but mass loss may introduce error. We are considering using the inter-quartile range (the distance between the 25th and 75th percentiles) as our axes lengths, as this measure of spread is robust to outliers and therefore compensates for particles no longer gravitationally bound to M33.

We predict that M33 will evolve into an elliptical or spheroidal galaxy. M33 is the only spiral galaxy in the Local Group that is a satellite to a larger galaxy. While this could mean that M33 is wholly unique, it more likely means that tidal interactions quickly evolve spiral galaxies into other morphologies. As mentioned in section 1, the vast majority of satellites to Andromeda and the Milky Way are dSphs (McConnachie 2012). If we see this change in M33, it suggests that many of these galaxies could have been similar to M33 in the past.

4. RESULTS

5. DISCUSSION

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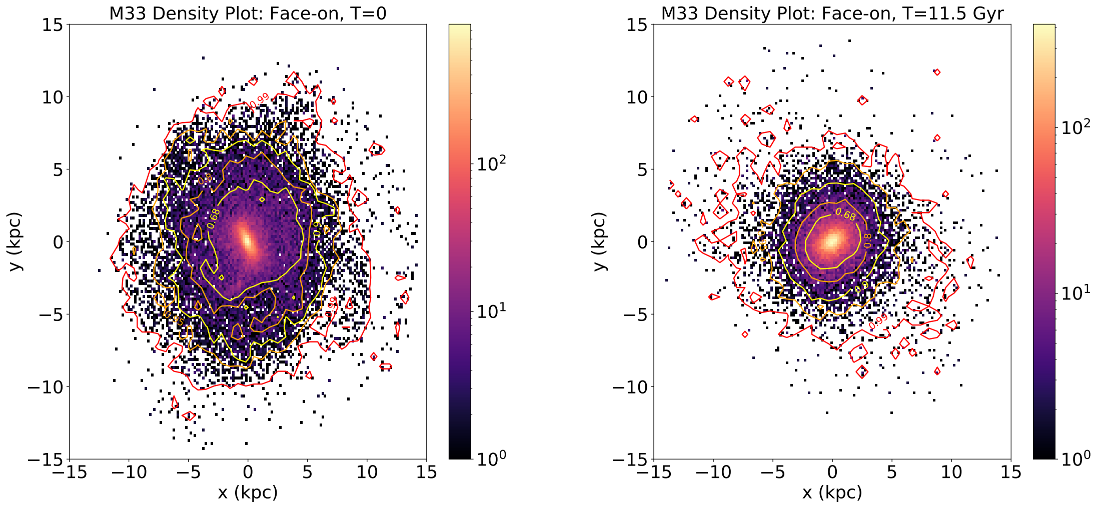

Figure 3. 2D Density plots of our simulated M33 at current day (left) and 11.5 Gyr from now (right). Position within the plane of the disk is shown by the X and Y axes, while the color depicts stellar density in logarithmic scale. No spiral arm pattern can be observed here, but M33 is shown to become much more compact.

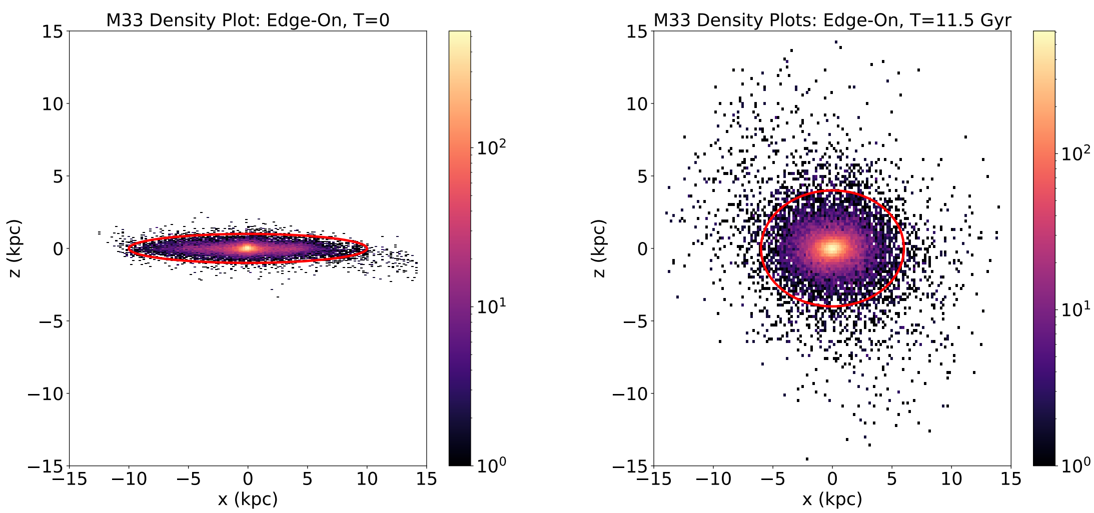

Figure 4. 2D Density plots of our simulated M33 at current day (left) and 11.5 Gyr from now (right). Position is shown by location along the X and Z axes, where the Z-axis is perpendicular to M33s "disk." As in Figure 3, color shows density in logarithmic scale. Ellipses shown are fitted to the disk profile to demonstrate axial ratios. Future simulated M33 shows very little trace of a disk at all, and appears to have become very spheroidal.

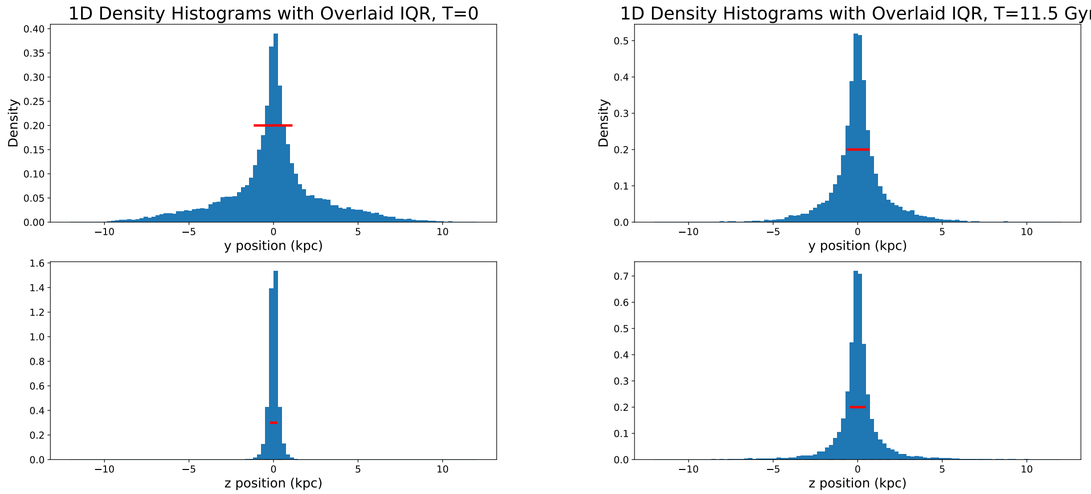

Figure 5. 1D normalized density histograms of simulated M33 at current day (left) and 11.5 Gyr in the future (right). Top row shows density projected into the y-axis (parallel to disk), while bottom shows density on the z-axis (perpendicular to disk). Red line segments show the extent of the IQR for each 1D density profile. Throughout the simulation, the y-axis/disk distribution becomes more compact, while the z-axis/bulge distribution spreads out. X-axis distributions are not displayed, but show no significant difference to those of the y-axis.