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The Future of M33's Stellar Disk Structure as a Result of Tidal Interactions

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ABSTRACT

The strong tidal influence exerted on satellite galaxies by a massive host is thought to significantly alter their internal dynamics and structure in a process referred to as tidal stirring. Tidal stirring seems to dominate the evolution of dozens of dwarf satellite galaxies orbiting the Milky Way and Andromeda galaxies, preferentially changing disk-dominated galaxies into elliptical and spheroidal ones. In this paper, we explore the effects of a further 10 billion years of tidal stirring on M33, the most massive satellite galaxy in the Local Group. This will illuminate whether the effects of tidal stirring are consistent over a wider range of satellite galaxy masses. Using N-body simulations of the Local Group over the next 10 billion years, we find that M33's stellar disk structure will likely become more centrally concentrated, truncated, and much thicker, with a final axial ratio above 0.6. This supports the conclusion that tidal stirring will convert disk-dominated satellite galaxies into elliptical or spheroidal ones, even outside the dwarf galaxy mass regime.

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 the Andromeda galaxy (McConnachie 2012). These two massive galaxies, their satellites, and a number of more distant galaxies that orbit their center of mass, make up a gravitationally bound association of galaxies referred to as the Local Group. The satellite galaxies within the extended dark matter halos of the Milky Way and Andromeda, as demonstrated in N-body simulations in Mayer et al. (2001), have likely been significantly altered by tidal interactions with their host galaxies. Strong tidal fields acting on a galaxy can induce mass loss as well as many different instabilities in the motion of its stars, also referred to as the internal dynamics. The many ways that tidal forces can restructure galaxies are collectively referred to as tidal stirring. Over the course of billions of years, tidal stirring can dramatically alter the internal dynamics of a galaxy in ways that are reflected in its observed structure. Astronomers classify galaxies by visual appearance into groups referred to as morphologies, and overall changes in appearance over time is called morphological evolution.

We define a galaxy as a collection of gas, dust, and stars within a massive dark matter halo. The observed properties of Galaxies can change in many distinct ways, for example: the stellar population changes due to aging or new star formation, the distribution of gas and dust changes, or changing internal dynamics results in an altered overall structure. Tidal interactions have an important role to play in all of these evolutionary mechanisms, especially for satellite galaxies which live within the dark matter halo of their host (Mayer et al. 2001).

The Triangulum galaxy (also known as M33) is the third most massive galaxy of the Local Group and a satellite to the Andromeda galaxy (M31). Almost all satellite galaxies of the Milky Way or M31 are dwarf spheroidal types (dSph), with an occasional dwarf elliptical (dE) or dwarf irregular (dIrr). M33 is the only disk satellite galaxy to either of these massive host galaxies (McConnachie 2012). M33 is an Sc type galaxy, which means that it is a spiral galaxy with tightly wound spiral arms and no central bar. The spiral arms of M33 are quite faint and indistinct, which leads to some disagreement among astronomers as to just how many spiral arms there are (see Dobbs et al. (2018) and Semczuk et al. (2018)). However, there is consensus that there are two relatively prominent arms. It is thought that M33 had a close encounter with M31 around 2 billion years ago due to a burst of star formation in this period. This

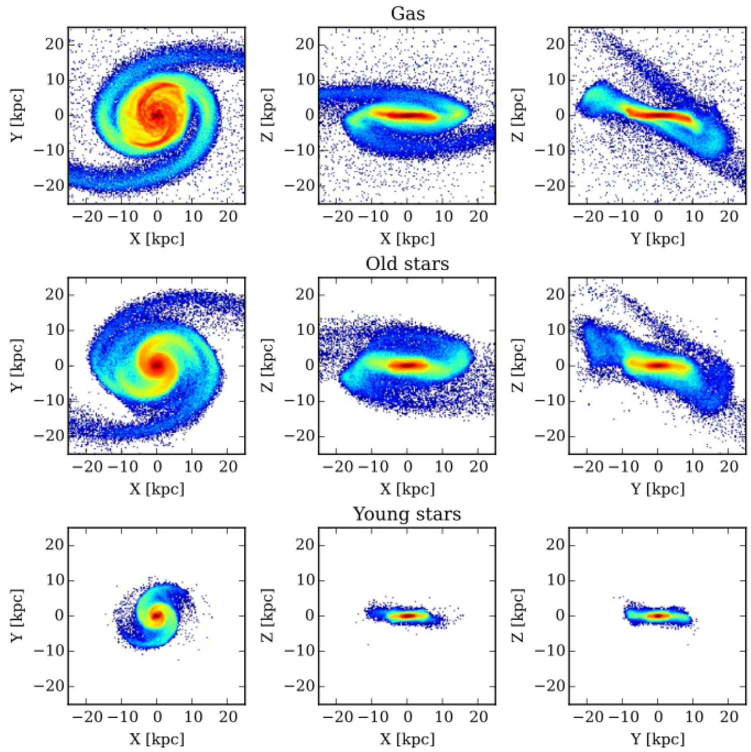

Figure 1. Figure 6 from Semczuk et al. (2018). Surface density distributions of the gas, young stars, and old stars in the simulated M33 after its interaction with M31 2 billion years ago. Demonstrates the introduction of novel features (spiral arms, warped gaseous disk at large radii) as a result of tidal interaction.

close encounter was modeled in Semczuk et al. (2018) with N-body/hydrodynamical simulations, and the resulting tidal interaction was found to induce the dominant two spiral arm pattern we see today, as well as M33's peculiar gaseous disk that is warped away from the stellar disk at large radii (Figure 1).

It is relatively well understood that the tidal forces can change initially disky satellite galaxies into thicker dEs and dSphs (Mayer et al. 2001), but it is not obvious how this process extends to higher mass satellite galaxies. The warped gaseous disk shown to be the result of a tidal interaction (Semczuk et al. 2018) seems to suggest that M33's disk is currently thickening. However, this phenomenon is exclusive to larger radii, and the inner disk does not seem significantly changed. However, we should be careful in making conclusions from one example of a close encounter, as there is evidence that tidal stirring is sensitive to the orientation of the satellite galaxy during its close approach (Łokas et al. 2015). The results of many close encounters over a long period of time may not be predicted well by the effects of a single close tidal interaction.

2. THIS PROJECT

In this paper, we will investigate how M33's disk structure will change in the future after many close encounters with its host galaxy. Using an N-body simulation of the Local Group we will investigate M33's disk for features such as spiral arms or a central bar, as well as measure the thickness of the disk 11.5 billion years in the future. It is predicted that over this period of time, the Milky Way and M31 will collide and merge, and M33 will have many close encounters with both M31 and the merger remnant.

We believe that this study should provide a strong prediction of what M33's stellar disk will look like after billions more years of tidal interactions with its host galaxy. With our N-body simulation we should be able to accurately predict the general structure of M33's disk, especially in regards to the thickness of the disk. We must take some care in making predictions on the formation of spiral arms, as the formation of spiral arms in pure N-body simulations is not completely understood, and relevant physics may be missing without simulated gas. However, a general assessment of M33's morphology should be feasible.

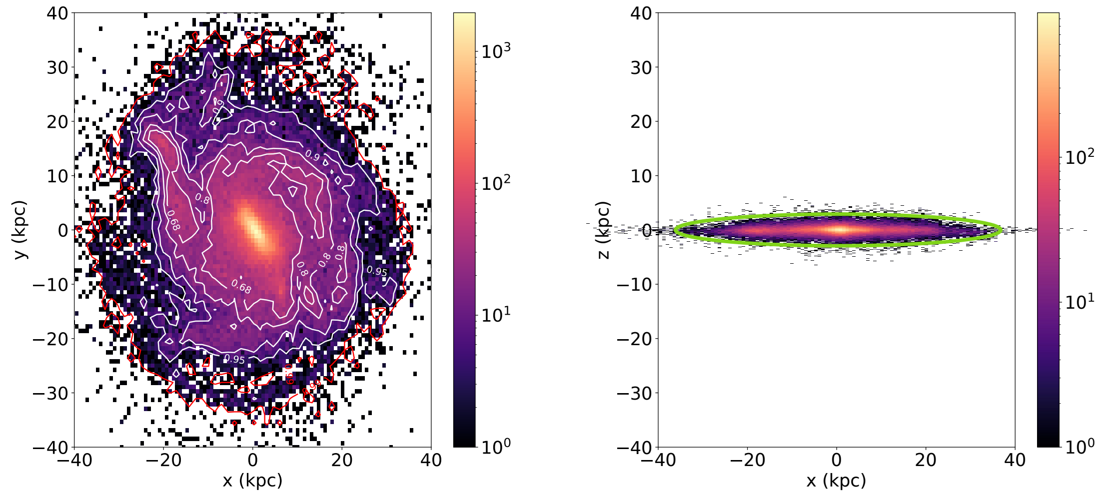

Figure 2. Examples of 2D density plots. Simulated M31 is shown face-on (left) and edge-on (right) relative to its disk. Face-on perspective features overlaid contours of constant density, which help distinguish low contrast disk structures. Edge-on perspective is fit with an ellipse. Measuring the ratio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

Answering the question of M33's future evolution is valuable not only in understanding M33, but also all the other satellite galaxies of the local group and tidal interactions in general. It is important to determine whether or not M33 is heading down the same evolutionary path as the other dwarf satellites of the Local Group. Knowing what M33 will become over the course of billions of years may shed light on the origins of other satellite galaxies and whether they may have been more like current day M33 in the past.

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 galaxies. The collisionless aspect of these simulations simply means that the only way that these particles interact is through gravity—no other physics required. The three most massive Local Group galaxies (MW, M31, M33) are simulated over a period of approximately 11.5 billion years, during which the Milky Way and M31 are projected to collide and merge.

Our approach to studying the evolving stellar disk 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 visual aids onto our representations of M33 to assist in this analysis. Density contours will help us identify disk features such as spiral arms, a central bar, and the characteristic disk thickness (example shown in Figure 2). For a more quantitative measurement of disk height, we will compare the characteristic width of M33's density profile projected onto different axes.

The data set at our disposal consists of the masses, positions, and velocities of many particles that make up M33 at different times during the simulation. The first step in our analysis is to define a coordinate system for plotting that is centered at M33's center of mass, with the z axis normal to the disk (or parallel to the minor elliptical axis). We will first calculate the center of mass of the stellar particles 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. 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, no matter how far away they are. 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

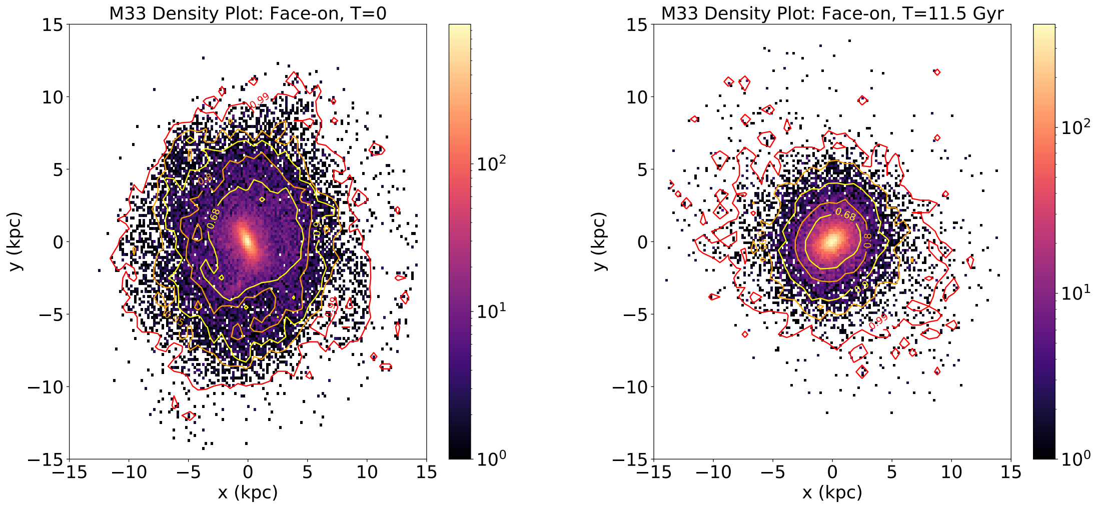

Figure 3. 2D Surface density plots of our simulated M33 at current day (left) and 11.5 Gyr from now (right). Position within the plane of the disk is shown by the X and Y axes, while the color depicts stellar density in logarithmic scale. No spiral arm pattern can be observed here, but M33 is shown to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

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 M33's 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. Again, this calculation will only use particles within a reasonable distance of the center of mass.

Once we are in the correct coordinate system, we can create visual representations of M33 in the form of 2D density plots. The axes of these plots are defined by a 2D plane in space, and colored bins on this plot represent the local surface density of the galaxy. 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 an accurate density plot. 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. Surface density contours will be plotted us identify spiral arm signals that may not otherwise be distinct. Our next step would be to measure M33's disk height, and we will do this by determining the disk axial ratio. This would involve fitting an ellipse to the stellar disk from an edge-on perspective (X or Y vs. Z), as demonstrated in Figure 2. The axial ratio would then be calculated from the ratio of major and minor axes of this best fit ellipse. Due the subjectivity of the manual best fit, we will attempt a more quantitative approach as well. This approach will involve calculating the characteristic width of M33's 1D density profile projected onto each of our spatial axes. The inter-quartile range (IQR) is our ideal measure of spread, as this parameter is robust to outliers and therefore unaffected by significant mass loss. This simply involve calculating the range between the 25th and 75th percentiles in position along the axis.

We predict that M33's stellar disk will become thicker, and its morphology will appear to be more elliptical or spheroidal galaxy. We believe that many tidal interactions over a long period of time will have a more chaotic effect compared to the single close encounter discussed in Semczuk et al. (2018). As mentioned in section 1, tidal interactions are likely responsible for turning disky dwarf satellites into dSphs and dEs. It is likely that the same process is occurring in M33, except over a longer time due to its more massive halo. If this is determined to be the case, this could shed light on the history of disk galaxies, and provide evidence that disk galaxies can only survive in the absence of significant tidal interactions.

4. RESULTS

Figures 3 and 4 display our calculated 2D surface density plots discussed in section 3. Figure 3 compares current day and future M33's stellar disk from a face-on perspective. Our future model of M33 features a quite truncated disk and a denser galactic center. Density contours suggest a smooth radial decrease in density in the inner disk, without

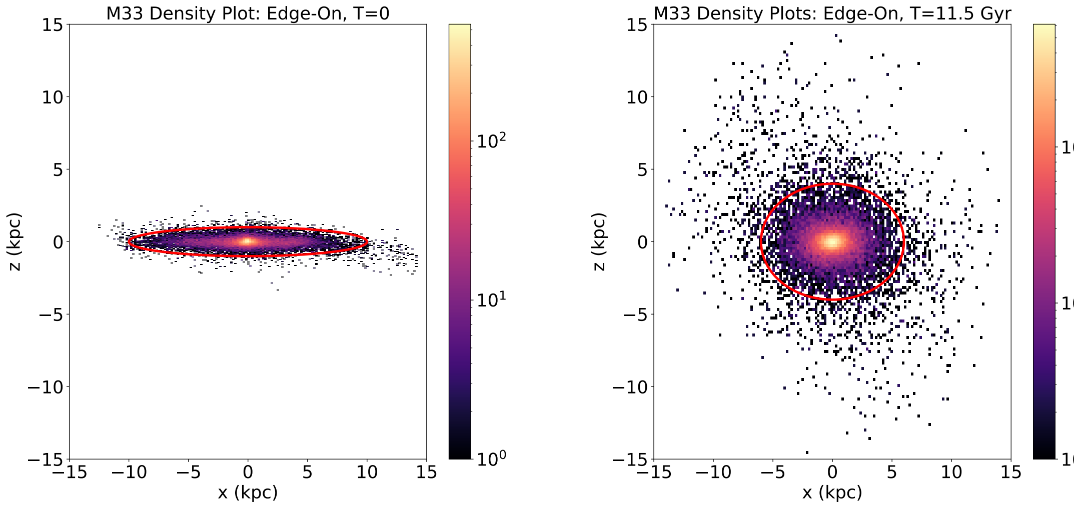

Figure 4. 2D Surface density plots of our simulated M33 at current day (left) and 11.5 Gyr from now (right). Position is shown by location along the X and Z axes, where the Z-axis is normal to M33's "disk." Color depicts density in logarithmic scale. Ellipses shown are fitted to the disk profile to demonstrate approximate axial ratios. M33's disk is shown to have been significantly truncated and thickened, with a structure more described as elliptical or even spheroidal.

any spiral density patterns. At larger radii, particles appear more scattered and chaotic, likely as a result of continuing mass loss.

Figure 4 shows 2D density plots of current and future M33 from an edge-on perspective relative to the stellar disk/major elliptical axis. Our initial model is characterized by a neat flat disk, about 1-2 kpc thick at the center, with no central bulge. Our future model of M33 appears to have a disk between 6 and 8 kpc thick, a distance much more significant to the radial size of the disk. Due to a more centrally concentrated density profile with a long positive tail in every direction, the border between the disk and scattered unbound particles is unclear. This makes precise visual judgement difficult, but the overall structure of M33 has clearly evolved away from being disk-like. Ellipses (red) were visually fitted to the disk profile to provide estimates of the axial ratio. Estimate for initial model was a ratio of 0.1; for the final model 0.65.

Figure 5 graphically displays our attempt to quantitatively measure the change in M33's axial ratio. We chose 2 axes, one parallel to the plane of the disk and one normal to it, and projected 1D density profiles onto these axes. We then measured the IQR of these distributions (shown by red line segment), and took the ratio to obtain an approximate axial ratio. While we note that the IQR does not characterize the density profile far beyond the inner peak, our hope is that taking the ratio of these spreads will provide a more accurate result than wider but noisier statistical parameters. Our measured axial ratios were .144 for the initial density profile and .615 for the final. This is consistent with our visual analysis, and further supports the evolved M33's classification as an elliptical galaxy.

5. DISCUSSION

Our results outlined in Section 4 support the conclusion that M33 will cease to be a disk galaxy over the next 10 billion years. Specifically, our model predicts a truncated, very thick disk. With an axial ratio of above 0.6, this galaxy is squarely in the elliptical regime: approximately E4, following the Hubble system. While our initial model of M33 lacked the subtler spiral arm patterns of the real M33, it is unlikely that would have a significant effect on our results, given the absence of a flat disk altogether. This result agrees with the tidal stirring processes studied in Mayer et al. (2001), and extends the analysis to even higher mass satellites.

6. CONCLUSIONS

In this study we analyzed the effects of tidal stirring on the most massive satellite galaxy in the Local Group, M33. The goal was to illuminate whether the effects of tidal stirring on dwarf satellite galaxies are analogous to those of

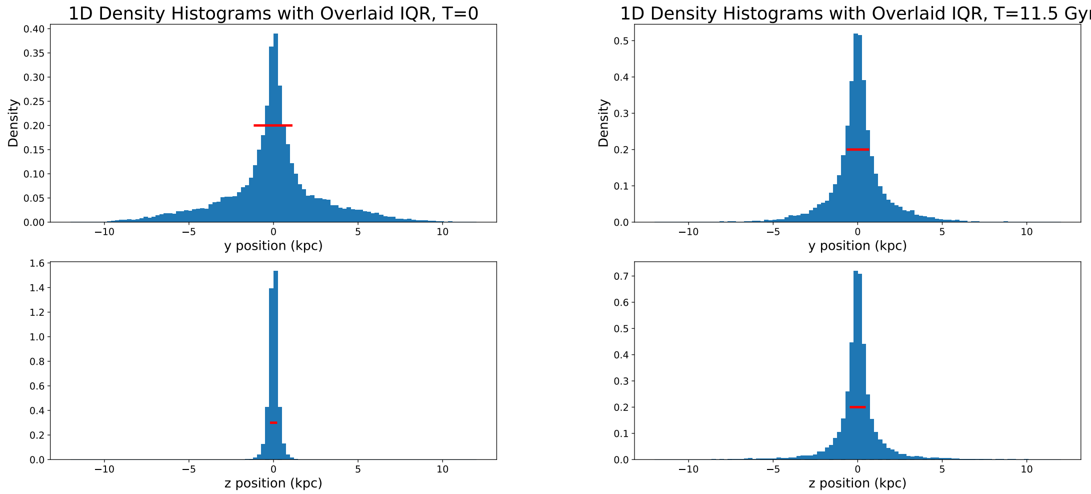

Figure 5. 1D normalized density histograms of simulated M33 at current day (left) and 11.5 Gyr in the future (right). Top row shows density projected into the y-axis (parallel to disk), while bottom shows density on the z-axis (perpendicular to disk). Red line segments show the extent of the IQR for 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.

more massive satellites. We observed the future evolution of M33's stellar disk structure in a gravitational N-body simulation of the three most massive galaxies in the Local Group over 10 billion years.

We did find that our projected model of M33 becomes more elliptical-like. This was observed as a truncated and thickened disk structure, resulting in an axial ratio of over 0.6, typical of mid-range elliptical galaxies. This result appears to be analogous of the typical effects of tidal stirring on dwarf satellite galaxies. This did line up with our initial predictions, however, more information is needed to clearly categorize this M33 model in a morphology classification. More information about the internal motions of stars may be useful in this regard.

While we hesitate to make generalized conclusions from this case study, this result seems to suggest that tidal stirring is not a mass-sensitive process. This may have implications for the evolution and interactions of all galaxy types, not just satellites. It would be interesting to see future studies explore the effects of tidal fields on massive galaxies in a more comprehensive manner. This would allow us to compare and contrast various scenarios such as a satellite galaxy in a more massive host halo versus massive galaxies in a dense galaxy cluster.

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- numpy (van der Walt et al. 2011, DOI : 10.1109/MCSE.2011.37)
- scipy (Jones et al. 2001-,Open source scientific tools for Python. http://www.scipy.org/)
- Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018 doi: 10.3847/1538-3881/aabc4f)
- Jupyter Notebooks (The Jupyter Team et al. 2016; doi:10.3233/978-1-61499-649-1-87)

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