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Will M33 become an elliptical galaxy after the M31-Milky Way Merger?

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ABSTRACT

As M31 and the Milky Way approach and merge, M33 will experience increasingly strong tidal forces, changing its kinematic stellar structure. M33's proximity to Earth makes it one of the most well-studied galaxies in the universe, allowing its initial conditions to be understood with high precision and thus making it a prime laboratory for the study of the evolution of satellite galaxies as their host galaxies merge. The canonical theory of elliptical galaxy formation holds that they form from spiral galaxies repeatedly undergoing galaxy interactions, thus M33 is anticipated to become more elliptical as M31 and the Milky Way merge. If M33 is indeed becoming more elliptical as M31 and the Milky Way merge, then the canonical theory of elliptical galaxy formation is proven by the best laboratory available to us. We find that M33's stars become increasingly isotropically distributed and M33 as a whole becomes more dispersion supported with time, thus M33 is becoming elliptical. This finding lends credence to the canonical theory of elliptical galaxy formation.

Keywords: Local Group, Satellite Galaxy, Galaxy Interaction, Spiral Galaxy, Elliptical Galaxy, Rotational Velocity Supported, Dispersion Supported,

1. INTRODUCTION

As M31 and the Milky Way (MW) approach and merge, the movement of stars and dark matter will redistribute mass throughout the entire Local Group, a gravitationally bound group of galaxies composed of M31, MW, and their satellites. This movement will change the gravitational tides that M33, M31's largest satellite galaxy (a smaller galaxy that orbits another, larger, galaxy known as its "host"), experiences, changing the structure of its gravitational potential and thus internal stellar structure. This may result in M33 changing from a disk-shaped (in baryonic matter) spiral galaxy into an ellipsoid-shaped elliptical galaxy.

A galaxy is "a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity" (Willman & Strader 2012). This departure from adherence to Newtonian gravity when only considering baryons is explained by the presence of dark matter in a spherical halo that composes the vast majority of matter in a typical galaxy, a non-baryonic substance that is only known to interact with baryonic matter via gravity. Galaxies are not static objects, changing, or "evolving," with time, giving rise to the study of galaxy evolution. It is believed that the shape of a galaxy changes over the course of galaxy interaction, the process in which two galaxies get sufficiently close that their mutual gravitational pulls exert significant enough force to change each individual galaxy's evolution from what it would have been if it were isolated.

Galaxies can in most cases broadly be divided into disk-shaped spiral galaxies and ellipsoid-shaped elliptical galaxies, with M33 falling into the spiral category. Spiral galaxies are rotational velocity-supported, meaning that they are prevented from collapse by the tangential velocity possessed by stars associated with rotation in the xy plane (here and henceforth, z is the axis in which a galaxy's angular momentum vector is directed and x and y form perpendicular right-handed coordinates with respect to z). Elliptical galaxies are dispersion supported, meaning that they are prevented from collapse by the tangential component of the dispersion velocity possessed by stars caused by isotropically distributed random motions. M33 is $\sim 4*10^{10}M_{\odot}$, placing it firmly above the dwarf galaxy mass cutoff of $\sim 5*10^{9}M_{\odot}$ but below the $\sim 10^{12}M_{\odot}$ masses of M31 and MW. This means that the evolution of M33 can be informed by and give clues to the evolution of both dwarf galaxies and their larger cousins. Elliptical dwarf galaxies are generally believed to result from spiral dwarf galaxies whose stars have gained enough dispersion velocity to be dispersion supported (Geha et al. 2003). Elliptical galaxies are generally believed to have arisen from repeated galaxy mergers, with many spiral galaxies combining their masses to form a larger elliptical galaxy (Lazar et al. 2023). Taken together, these facts imply that ellipsoidality is a consequence of tidal interactions. Simulations, such as the one shown in Figure 1, back up this theory by showing that initially spiral dwarf galaxies become more elliptical as they continue to interact with their host galaxy (Łokas et al. 2015). Simulations of M33 in particular indicate that its current morphology has been heavily influenced by a past closer encounter with M31, indicating that M33 is likely to continue to be shaped by its larger neighbors (Semczuk et al. 2018).

The tidal evolution of M33 has been overlooked in the literature, with few attempts being made to simulate its evolution and those that have focusing on evolving it to its current state rather than predicting its future (Semczuk et al. 2018). These past-focused simulations aim to reproduce the present-day morphologies, positions, and velocities of M31 and M33 (Semczuk et al. 2018). Of particular interest are the reproduction of M33's two-arm structure and a burst of star formation in M33 at outer radii ∼2 Gyr ago, both believed to be the result of gas compression from tides during a close encounter with M31 (Semczuk et al. 2018). Although these features have been qualitatively reproduced, simulations from different authors are not quantitatively consistent, with gaps as large as a Gyr between model estimated times of M31-M33 closest approach (Semczuk et al. 2018). Dwarf elliptical galaxies are generally associated with dense local environments, yet three mysteriously orbit M31, implying that there might be something special about M31 that makes its satellites particularly ellipsoidal. Recent studies have called the applicability of galaxy formation theories of elliptical galaxies to M33-sized galaxies into question, with only 3% of young elliptical galaxies showing signs of recent tidal interactions, half the rate of the general galaxy population (Lazar et al. 2023). Whether M33, whose proximity allows it to be more closely studied than any other potential future small elliptical galaxy in the universe, turns into an elliptical galaxy following interactions with the M31-MW system provides a unique ability to defend or disprove the canonical theory of elliptical galaxy formation in the low-mass regime or gain insight into a peculiarity of the M31 system.

2. THIS PROJECT

This paper analyzes the relative dominance of dispersion and rotational velocity in supporting M33 with time. This is achieved by measuring the level of symmetry in the kinetic energy of M33's stars and the ratio of the average circular velocity of stars to the average dispersion velocity of stars. If M33 is becoming more dispersion-dominated with time, it is morphing from a spiral into an elliptical galaxy.

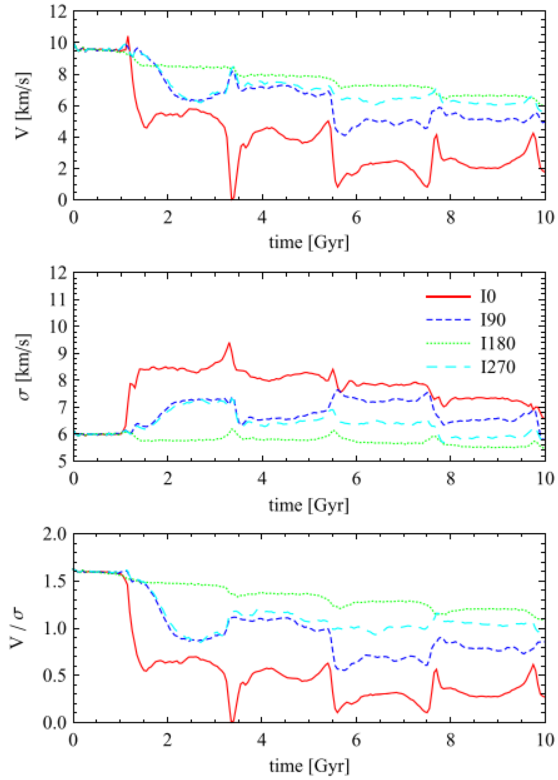

Figure 1. The simulated time evolution of the average rotational velocity, V and velocity dispersion, σ, of a satellite galaxy interacting with a MW-like galaxy, from Łokas et al. (2015). The "Ix" lines represent simulations where the satellite disk has an x-degree inclination with respect to the host galaxy disk. Note that as time increases and the satellite galaxy increasingly interacts with its host, the satellite galaxy becomes more dispersion-supported.

This analysis addresses the question of whether M33 is becoming more ellipsoidal with time.

If M33 is becoming more ellipsoidal with time, it lends credence to the traditional picture of elliptical galaxy formation in which galaxies become elliptical through tidal interactions with other galaxies, although this result could alternatively be taken as evidence for the special tendency of M31 satellites towards ellipsoidal shapes. If M33 does not become elliptical, even though its proximity to a large galaxy merger makes it a prime candidate for tidal force-induced morphology changes, the traditional theory is shown to not be universally applicable, motivating the investigation of under what scenarios, if any, it applies to M33-like galaxies.

3. METHODOLOGY

This paper analyzes the results of the N-body simulation of the future of the M31-MW-M33 system described in Van der Marel et al. (2012). An N-body simulation numerically calculates the evolution of some system of N interacting particles. The simulation goes through some number of timesteps, at each timestep calculating the forces acting on a particle due to its neighbors and changing the position and velocity of the particle at the next timestep accordingly. In this simulation, each galaxy's stellar disk, stellar bulge (if applicable), and dark matter halo were broken into between 50,000 and 1,020,000 representative particles (see Van der Marel et al. (2012) Table 1 for the exact number of particles of each galaxy component) that interacted through gravity only.

Radial velocities are confined to the xy plane while dispersion velocities are isotropic, so the more overall kinetic energy of the system is directed into the z direction as opposed to the x and y directions, the more dispersion supported and thus ellipsoidal the galaxy is becoming. The redistribution of kinetic energy into the z direction can be spotted in two ways: the ratio of kinetic energy in the z direction to kinetic energies in the x and y directions approaching unity, as on the left of fig 2, and stellar velocities becoming primarily dispersion-supported rather than rotational velocity-supported, as on the right of fig 2.

The total kinetic energy in the ith coordinate, KE_i, is trivially calculated via a sum of the individual kinetic energies of stars:

$$KE_i = \sum_{n=0}^{N} \frac{1}{2}(v_{i,n})^2, \tag{1}$$

where $v_{i,n}$ is the velocity of the nth star in the ith direction. The rotational velocity expected for strictly gravitationally-driven circular orbits is obtained by setting the outward centripetal force experienced by an orbiting star equal to the inward gravitational pull experienced by the star, yielding

$$V = \sqrt{\frac{GM}{r}}, \tag{2}$$

where G is the gravitational constant, M is the total mass of the galaxy interior to the orbit, and V is the circular orbital velocity at r, the distance of the orbit to the center of the galaxy. The dispersion velocity of that same star i is merely the portion of its velocity along the direction of rotation that is not due to rotational velocity:

$$\sigma = V_x - V, \tag{3}$$

where V_x is the total velocity of a star in the x direction and σ is the dispersion velocity of a star in the x direction.

One plot will have time on the x-axis and $\frac{KE_x}{KE_z}$ and $\frac{KE_y}{KE_z}$ on the y-axis. If the two lines approach unity as time increases, then the kinetic energy of the system is equipartitioned between all three coordinates and thus M33 is dispersion supported. If the two lines remain above unity as time increases, then M33 is retaining a preference towards rotational velocity and thus remains a spiral galaxy. The two lines should not go significantly below unity. The other plot will have time on the x-axis and $\frac{V}{\sigma}$ on the y axis. The smaller this value, the more dispersion-supported and thus elliptical M33 is.

Due to the current wide acceptance of the canonical theory of elliptical galaxy formation, we anticipate that our results will support it. Thus, we anticipate our plots will show $\frac{KE_x}{KE_z}$ and $\frac{KE_y}{KE_z}$ approaching one and $\frac{V}{\sigma}$ decreasing.

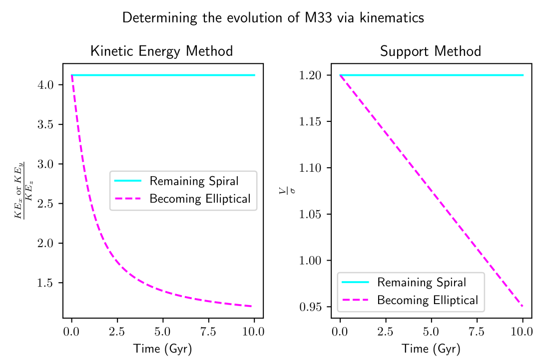

Figure 2. How the increasing ellipticality of M33 could theoretically be spotted using the "Kinetic Energy Method" of measuring the ratios of kinetic energies in various dimensions to detect increasing isotropy and the "Support Method" of measuring the ratio of rotational velocity to dispersion velocity to detect increasing dispersion support. On the left, the ratio approaching unity indicates increasing ellipticality, on the right, the ratio decreasing indicates increasing ellipticality.

4. RESULTS

Application of the kinetic energy method yields Figure 3. As time increases and M33 draws closer to M31 and MW, the kinetic energy in M33's x and y directions relative to the kinetic energy in M33's z direction decreases, as predicted in Figure 2 would occur when M33 is becoming kinetically more isotropic and thus elliptical. This indicates that M33 is becoming more elliptical with time as it increasingly tidally interacts with M31 and MW.

Application of the support method yields Figure 4. As time increases and M33 draws closer to M31 and MW, M33's disk stars have more randomly dispersed velocities, that is, M33 becomes increasingly supported by dispersion rather than rotational velocity, as predicted in Figure 2 would occur when M33 became increasingly elliptical. This, like the kinetic energy method, indicates that M33 is becoming more elliptical as it increasingly tidally interacts with M31 and MW.

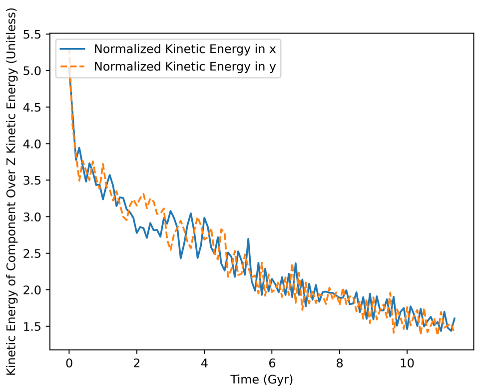

Figure 3. The Kinetic Energy Method of determining if M33 is becoming elliptical. The x-axis represents the elapsed simulation time and the y-axis represents the ratio of each kinetic energy component in the direction of disk rotation to the direction outside of disk rotation. The kinetic energy is becoming increasingly evenly spread in all directions, indicating that M33 is becoming increasingly elliptical.

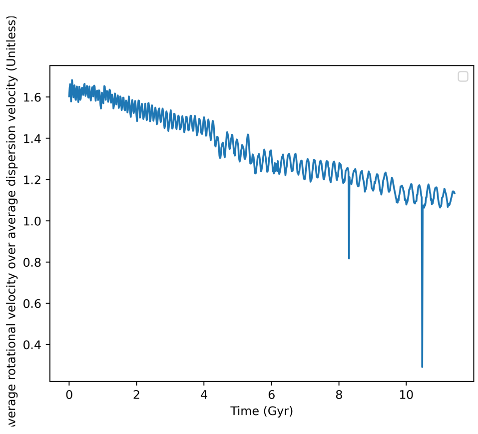

Figure 4. The support method of determining if M33 is becoming more elliptical. The x-axis represents the elapsed simulation time and the y-axis represents the ratio of the average stellar rotational velocity to the average stellar dispersion velocity. The general downward trend of the ratio indicates that M33 is becoming increasingly dispersion-dominated and thus elliptical. The two dips at timesteps 616 and 732 are believed to be errors in the data and are ignored in our analysis.

5. DISCUSSION

We found that M33 is becoming increasingly elliptical, with its kinetic energy becoming more isotropically distributed and its disk stars increasingly dispersion supported. This agrees with our hypothesis that M33 will evolve following the canonical theory of elliptical galaxy formation via galaxy interaction. This finding of increasing dispersion support agrees with the findings of the simulations performed by Łokas et al. (2015) shown in Figure 1. This indicates that spiral galaxies tend to become elliptical galaxies due to tidal interactions with other galaxies, supporting the canonical theory of elliptical galaxy formation.

One timestep in our simulation, timestep 742 (0-indexed), was removed as visual inspection found that modal velocity of stars in that timestep was several kilometers per second off from 0, indicating an issue in the simulation. Timesteps 616 and 732 should have similarly been removed in Figure 4 and were removed in our analysis. Removing these data points is the only realistic recourse when the authors do not have access to computing power to reproduce the simulation, however, this does bias our data towards our hypothesis to the manual intervention of authors to preserve cleanliness. We also used a cutoff of 10 kpc to separate the inner and thus considered part of M33's disk from the outer, tidally stripped part of M33's disk on the grounds that 10 kpc reasonably represents the radius within which almost all of M33's original mass was located. The authors investigated an alternative 8 kpc cutoff and found it made no difference in the qualitative nature of Figures 3 and 4, however other cutoffs within a few kpc of 10 kpc are all reasonable and could produce different results. Finally, our results are unable to differentiate between proving the canonical theory of elliptical galaxy formation and proving that the M31 system is uniquely likely to produce elliptical galaxies; due to the preponderance of evidence, the authors lean towards the first interpretation, however our quantitative results do not alone rule out the latter interpretation.

6. CONCLUSION

As M31 and the Milky Way approach and merge, M33 will experience increasingly strong tidal forces, changing its kinematic stellar structure. M33's proximity to Earth makes it one of the most well-studied galaxies in the universe, allowing its initial conditions to be understood with high precision and thus making it a prime laboratory for the study of the evolution of satellite galaxies as their host galaxies merge. The canonical theory of elliptical galaxy formation holds that they form from spiral galaxies repeatedly undergoing galaxy interactions, thus

M33 is anticipated to become more elliptical as M31 and the Milky Way merge. If M33 is indeed becoming more elliptical as M31 and the Milky Way merge, then the canonical theory of elliptical galaxy formation is proven by the best laboratory available to us.

We find that M33's stars become increasingly isotropically distributed and M33 as a whole becomes more dispersion supported with time, thus M33 is becoming elliptical, agreeing with our hypothesis that the canonical theory of elliptical galaxy formation would hold.

As is always the case with N-body simulations, a rerun with a higher resolution (each particle representing less mass) would lend further confidence to our results by making the simulation closer to reality. As the focus of this paper was the M33 system whereas Van der Marel et al. (2012) was focused on the entire M31-MW-M33 group, a higher resolution in M33 could be achieved without increasing computation time simply by lowering the resolutions of M31 and MW. The simulation of Van der Marel et al. (2012), which is now over a decade old, could also be re-run with more modern observational estimates for parameters. Although likely insignificant and not worth the immense increase in computational complexity, the inclusion of radiative processes would also lead the simulation closer to reality. A parameter exploration of cutoff values of r beyond which stars are considered tidally removed from M33 would also be useful in assuring that the results of this paper are independent of a parameter that is free within some bounds.

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Software: A stropy Collaboration et al. 2013; Price-Whelan et al. 2018 doi: 10.3847/1538-3881/aabc4f), matplotlib Hunter (2007), DOI: 10.1109/MCSE.2007.55, and numpy van der Walt et al. (2011), DOI : 10.1109/MCSE.2011.37

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