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Research Assignment 4

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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 potential 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. 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. By size, 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 (Semczuk et al. 2018). These past-focused simulations aim to reproduce the present-day morphologies, positions, velocities, and rotation curves 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.

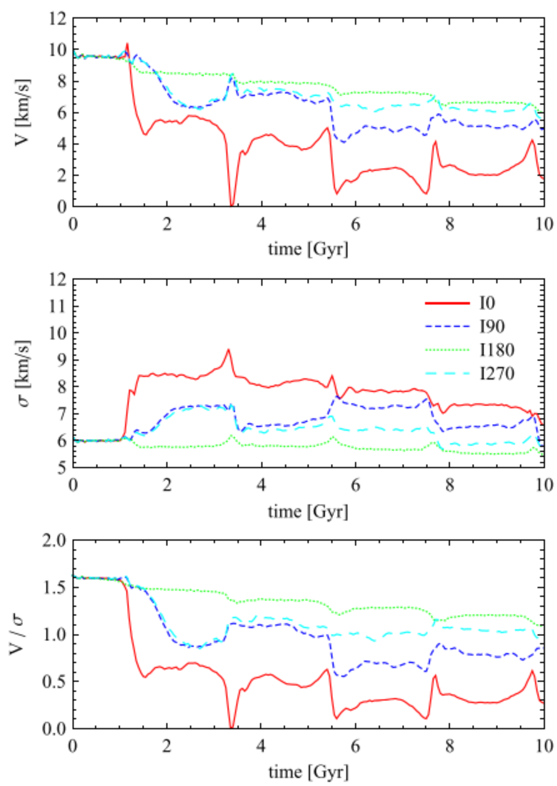

Figure 1. The simulated time evolution of the average rotational velocity, V and velocity dispersion, σ, of a satellite galaxy interacting with a MW-like galaxy, from Lokas et al. (2015). The "Ix" lines represent simulations where the satellite disk has an x-degree inclination with respect to the host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

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 spread of velocities from those predicted solely by rotation. If M33 is becoming more dispersion-dominated with time, it is morphing from a spiral into an elliptical galaxy.

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-M31 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 stars deviating more extremely from the rotation curve, the perpendicular velocity v vs. xy plane-projected distance from the center of the galaxy r relation obeyed by stars traveling in strictly gravitationally-driven circular orbits, 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 rotation curve 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

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

where G is the gravitational constant, M is the total mass of the galaxy interior to the orbit, and V_c is the circular orbital velocity at r, the distance of the orbit to the center of the galaxy.

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 the distance from the center of the galaxy when projected to the xy plane on the x-axis and the perpendicular velocity on the y-axis. A line will be plotted of the expected rotation curve and all of the stars will be plotted as points. The closer stars are to the expected rotation curve line, the more rotationally supported and thus spiral the galaxy. There will be multiple instances of this plot at different times to track the time evolution of the relative rotational support of M33.

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 the spread of stars around their rotation curve increasing with time.

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 decrease, 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.

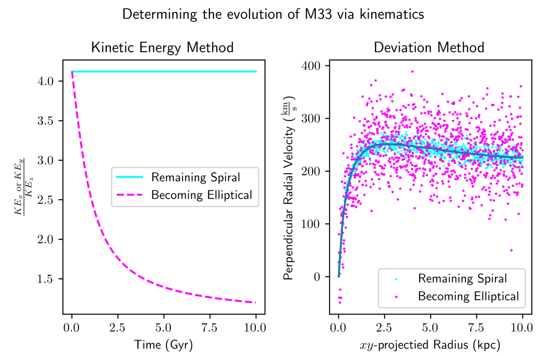

Figure 2. How the increasing ellipticality of M33 could theoretically be spotted using the "Kinetic Energy Method" of measuring the ratios of kinetic energies in various dimensions and the "Deviation Method" of measuring the increased deviation of stars from following their expected gravitational velocity curve. On the left, the ratio approaching unity indicates increasing ellipticality, on the right, the increased scatter of stars from the value predicted solely by rotational velocity (blue line) indicates increasing ellipticality.

Application of the deviation 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.

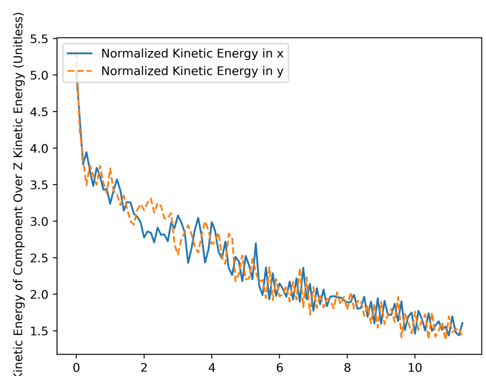

Figure 3. The Kinetic Energy Method of determining if M33 is becoming elliptical. The x-axis represents the elapsed simulation time and the y-axis represents the ratio of each kinetic energy component in the direction of disk rotation to the direction outside of disk rotation. The kinetic energy is becoming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

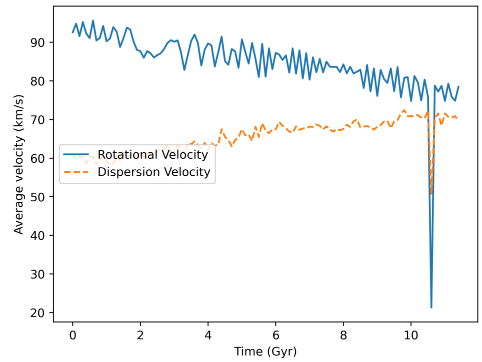

Figure 4. The deviation method of determining if M33 is becoming more elliptical. The x-axis represents the elapsed simulation time and the y-axis represents the average velocity of a disk star at that time that is contained within circular rotation velocity as opposed to dispersion velocity. The general downward trend of circular rotation velocity and upward trend of dispersion velocity indicates that M33 is becoming increasingly dispersion-dominated and thus elliptical.

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. This result agrees with the findings of the simulations performed by Łokas et al. (2015) shown in Figure1. 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.

The sudden average velocity dip just after 10 Gyr in Figure 4 is concerning as it could indicate a numerical issue that impacts our figures and thus findings. We used a cutoff of 8 kpc to separate the inner and thus considered part of M33's disk from the outer, tidally stripped part of M33's disk, however, this cutoff was somewhat arbitrary. This cutoff could be introducing specific bias that would need to be accounted for via the investigation of other cutoff choices.

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