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Tidal Transformation of M33's Stellar Disk in the Future MW–M31–M33 Interaction

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ABSTRACT

In this paper, we investigate the morphological and dynamical evolution of M33's stellar disk under repeated tidal interactions with the Milky Way galaxy (MW) and the Andromeda galaxy (M31) over the next 12 gigayears. We analyze snapshots of simulations from an integrated system of the three galaxies. We attempt to quantify M33's mass loss, disk density profile changes, and warp growth. Our analysis points toward significant tidal stripping and a flared or warped outer disk, as well as structural transformations consistent with prograde tidal stirring scenarios.

Keywords: Local Group — Jacobi Radius — Spiral Galaxy — Tidal Stripping — Disk Warping

1. INTRODUCTION

Paragraph 1: Topic Introduction.
In the **Local Group**, dwarf spiral galaxies are often subjected to strong tidal forces from massive neighbors—in this case, the Milky Way or Andromeda. Compared to these two, the Triangulum Galaxy, M33, is a lower-mass spiral galaxy which is thought to experience repeated interactions with the larger galaxies in the coming gigayears. These encounters are believed to produce **Tidal Tails**, **Tidal Bridges**, and even warp the disk itself. We study these morphological signatures as a crucial method for understanding and tracing the underlying **Dark Matter Halo** structure and the orbital history of satellites in the Local Group context, examples of which we see in the 2001 paper by Mayer and D'Onghia in 2010 (e.g., Mayer et al. 2001; D'Onghia et al. 2010).

Paragraph 2: Why the Topic Matters.
By definition, a **galaxy** is a gravitationally bound collection of stars, gas, dark matter, etc., distinguished from star clusters by virtue of its dark matter-dominated potential. When we use the term **galaxy evolution**, we are specifically referring to the processes—both internal (for example, star formation) and external (for example, accretion and mergers)—that drive changes in a galaxy's structure, kinematics, and stellar populations over cosmic time. M33 is an excellent example and case study for how satellite galaxies in dense environments can be changed and transformed under tidal stirring. We see phenomena such as shedding mass and potentially quenching star formation due to repeated orbital passages.

Paragraph 3: Current Understanding.
As of right now, we have done numerical simulations and observational studies to demonstrate, for example, that if the orbit is strongly prograde and has multiple close pericenters, we believe that these galaxies may develop bars or experience thickening via **Tidal Stripping** (Lokas et al. 2015; Pardy et al. 2016). Furthermore, in addition to this, we have also been able to see the importance of the **Jacobi Radius** in delimiting which stellar particles remain bound to the satellite's halo. In Figure 1, we are able to see the illustration of one such result from our code. This figure is a depiction of M33's bound stellar mass fraction versus time, where we see a loss of mass over the next 12 gigayears. As we can see from this graph, the takeaway is that repeated encounters can slowly begin to peel away a considerable fraction of the stellar disk over just a few gigayears, which we see happening after the 4 Gyr mark.

Paragraph 4: Open Questions.
Even after all the progress and research that we have done, we still have a few key questions remaining. One

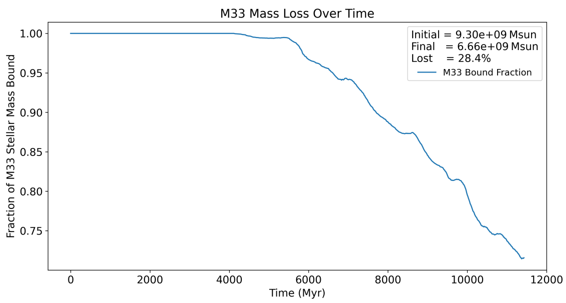

Figure 1. Stellar mass fraction of M33 bound inside its Jacobi radius as a function of time, generated by our simulation code. The x-axis is time in Myr, and the y-axis is the fraction of M33's initial stellar mass still bound. Tidal encounters cause substantial mass loss, especially after close pericenter passages.

of these questions is: how quickly does the M33 disk thicken, and does it adopt a spheroidal morphology, or does it remain in the form of a disk-like structure even after the change in bound mass? Do we find that the outer gas disk undergoes significant **Disk Warping**, or does it become completely tidally truncated? It also raises the question: to what extent do **minor mergers** or the presence of hot halo gas accelerate mass loss and morphological changes? To better understand these issues and try to find an answer, our current efforts are focused on high-resolution N-body hydrodynamical simulations and new observational constraints on M31's orbital parameters (van der Marel et al. 2012). One of the key questions we address here is how the M33 disk reacts dynamically to multiple orbits over the next few gigayears.

2. THIS PROJECT

Paragraph 1: Specific Project Focus.
In this project, we investigate the detailed structural and kinematic evolution of M33's stellar disc during multiple future close passages with both M31 and the MW. More specifically, we are going to measure the disc's radial truncation and thickness changes, allowing us to identify any tidally driven bar or spiral instabilities, which will then allow us to determine how much stellar mass is stripped from the outer regions over the next several gigayears.

Paragraph 2: Link to Open Questions.
As stated in the introduction, the question includes whether or not M33's disc might transition to a spheroidal morphology, how quickly the disc might warp or truncate, and to what extent minor mergers or hot halo gas expedite these processes. This project directly addresses the first two. We are going to quantify the disc's progressive thickening or transformation, which will allow us to examine if its outer layers become severely warped or tidally stripped by pericenter passages.

Paragraph 3: Importance for Galaxy Evolution.
It is important to resolve these issues to understand how dwarf spiral galaxies in dense environments, such as the one we are analyzing, can either retain their discs or evolve into more dispersion-supported systems. By linking M33's morphological changes to specific orbital events, this project offers a clearer way of understanding and interpreting the fates of other satellites in the **Local Group** and beyond. In doing so, we refine our broader picture of **galaxy evolution** while under the influence of repeated tidal interactions.

3. METHODOLOGY

Paragraph 1: Simulation Overview.
We are using data from the future MW–M31–M33 interaction scenariovan der Marel et al. (2012), which provides snapshots of an **N-body** simulation covering almost 12 gigayears. In this **N-body** simulation, a galaxy is approximated by a large number of collisionless particles (for example, dark matter, stars), each obeying Newton's laws of gravitation. The positions and velocities of these particles evolve over time under their mutual gravitational influences. In this setup, both the MW and M31 are modeled using extended halos, which are often **NFW** or **Hernquist** profiles, whereas M33 is embedded in its own halo and includes a rotating stellar disc.

Paragraph 2: Data and Particle Types.
For this project, we are using the normal-resolution files as opposed to the high-resolution ones, since the needs of this project (mass loss, morphology, tidal changes) can be met with the normal files. We extract only the stellar particles that lie within a fiducial radius of $r < 30\,\mathrm{kpc}$ around M33's center of mass. We do not focus on the gas particles in the current analysis, so that we can better concentrate on stellar morphological changes.

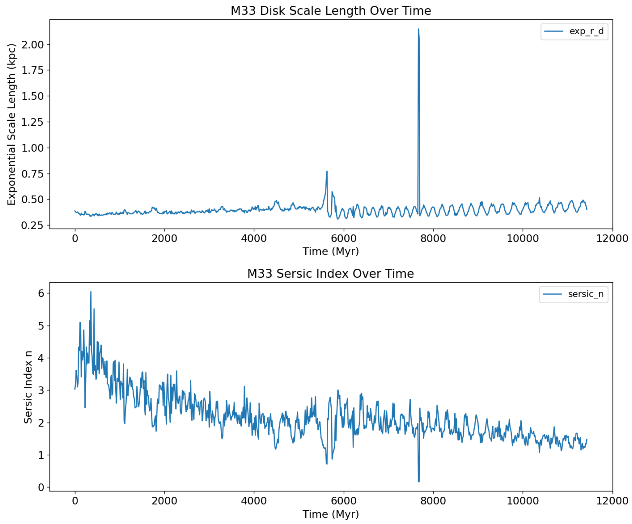

Figure 2. Schematic overview of our analysis pipeline. After reading each snapshot (top), we identify M33's center of mass, filter stellar particles within a chosen radius, and compute structural/kinematic diagnostics (disk profile fitting, velocity dispersions, etc.). Finally, we store and plot these results to assess tidal transformations over time.

We also keep the M31 and MW halos in the background, providing the external tidal fields.

Figure 2: Method Diagram.

Paragraph 3: Equations and Calculations.
For each snapshot, we compute the **Jacobi Radius** R_J using:

$$R_J \approx R \left(\frac{M_{\rm sat}}{2\, M_{\rm host}(R)} \right)^{1/3}, \qquad (1)$$

where R is the instantaneous distance between the satellite (M33) and host (M31), $M_{\rm sat}$ is the total mass of M33 within R_J, and $M_{\rm host}(R)$ is the enclosed mass of M31 out to radius R. We also measure velocity dispersions by binning stars in annuli:

$$\sigma_r^2 = \frac{1}{N} \sum_{i=1}^{N} (v_{r,i} - \langle v_r \rangle)^2, \qquad (2)$$

and fit M33's stellar surface density $\Sigma(r)$ using an exponential or Sérsic law:

$$\Sigma(r) = \Sigma_0 \exp\left(-\frac{r}{r_d}\right). \qquad (3)$$

Paragraph 4: Intended Plots.
We aim to produce several plots. The first is a bound mass fraction vs. time plot, revealing how **tidal** stripping affects M33. The second is a radial velocity dispersion plot to track the heating of the disc, and the third is a stellar density profile fit to check for **tidal** truncation over time. As we can see in Figures 2 and 3, we have successfully generated these graphs.

Paragraph 5: Hypothesis.
Based on prior work(Mayer et al. 2001; D'Onghia et al. 2010; Lokas et al. 2015), we expect M33's stellar disc to lose about 20% of its mass by the final snapshot due to close encounters. We also anticipate a pronounced warp or flare in the outskirts of the disc, with the possibility of a mild instability if the orbit remains prograde. The reasoning is that repeated **pericenter** passages supply a strong **tidal** series of shocks that strip material and internally heat the disk.

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