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Evolution of M33's Bound Mass in the Future MW-M31-M33 System

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ABSTRACT

Tidal interactions drive satellite galaxy evolution via mass stripping and structural changes. To understand this process in the future Local Group, we analyze N-body simulations of the MW-M31-M33 system (across ~ 11.5 Gyr), focusing on the M31-M33 interaction. We quantify the stellar mass gravitationally bound to M33 within its time-varying Jacobi Radius (R_J). We find M33 loses 28.4% of its initial stellar mass residing within R_J. This loss commences after the first close pericenter passage ($t \approx 4.5$ Gyr) and correlates strongly with subsequent encounters where R_J shrinks significantly. Our results quantify the predicted tidal stripping efficiency for M33, confirming close encounters as the primary driver of stellar mass loss within the Jacobi Radius in this evolving environment.

Keywords: Tidal Stripping — Jacobi Radius — Local Group — Satellite Galaxy — Galaxy Evolution

1. INTRODUCTION

Galaxies are thought to grow within large **Dark Matter Halos**; massive, invisible structures providing the foundation for galaxy formation and evolution (Mayer et al. 2001; Semczuk et al. 2018; Varela-Lavin et al. 2023). Within galaxy groups, interactions are a key part of evolution, and smaller **Satellite Galaxies** orbiting a larger host are particularly affected. As a satellite travels through its host's gravitational field, it experiences intense tidal forces causing **Tidal Stripping/Sharing**, pulling material away (Mayer et al. 2001; Lokas et al. 2015). This process can significantly alter the satellite's stellar disk and create tidal tails (Mayer et al. 2001; Semczuk et al. 2018). We study these interactions to understand how galaxies, especially smaller ones, are shaped by their environment.

A **Galaxy** is broadly defined as a gravitationally bound system containing stars, gas, dust, and dark matter (Mayer et al. 2001; Pardy et al. 2016). Tidal stripping directly impacts **Galaxy Evolution** – the study of how galaxies form and change properties over cosmic time – within host environments. Mass loss and redistribution crucially alter a galaxy's kinematics and morphology. These interactions can also affect satellite star formation activity, potentially triggering starbursts or removing gas needed for future star formation, sometimes leading to **Quenching** (Mayer et al. 2001; Semczuk et al. 2018). Understanding tidal effects thus clarifies how galaxies evolve and assemble mass, particularly within environments like the **Local Group** (van der Marel et al. 2012).

Current understanding derived from numerical simulations indicates tidal stripping is highly effective during close passages (pericenters) of a satellite around its host (Mayer et al. 2001; Lokas et al. 2015). Simulations show satellites on prograde orbits experience significantly stronger tidal effects, including mass loss and morphological changes, compared to retrograde orbits (Lokas et al. 2015). Figure 1 demonstrates this orbital dependence, showing the faster decrease in outer disk stellar density for prograde orbits compared to retrograde ones. The efficiency of stripping is also linked to resonance effects, occurring when stellar orbital periods within the satellite align with the satellite's orbital period around the host, maximizing tidal impact (Lokas et al. 2015).

Despite significant progress, several open questions remain regarding the tidal evolution of satellite galaxies. While simulations show interactions trigger morpho-

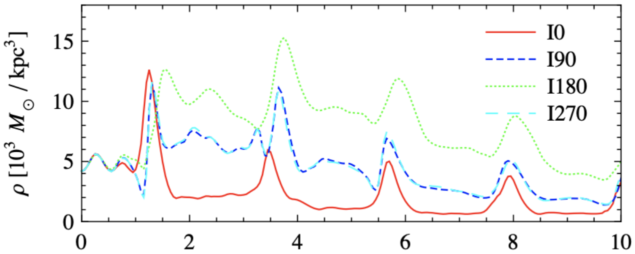

Figure 1. The time evolution of the average stellar density, ρ, within an outer radial shell (between 2 and 4 kpc) for a simulated dwarf galaxy orbiting a Milky Way-like host. Different lines show the results for distinct initial orientations of the satellite's stellar disk relative to its orbit: prograde (I0), retrograde (I180), and two perpendicular orientations (I90; I270). The pericenter passages occur roughly every $\sim$ 2.0 Gyr (visible as density dips for the prograde case). Figure adapted from Lokas et al. (2015).

logical and star formation changes (Mayer et al. 2001; Lokas et al. 2015), precisely predicting long-term fate and detailed transformation timescales for satellites under different conditions is still challenging. A key specific question, relevant to understanding the future evolution of the **Local Group**, is how much mass will a satellite galaxy like M33 lose over time as it interacts with M31 in the lead-up to the M31-Milky Way merger, and what physical processes dictate this mass loss rate (Semczuk et al. 2018; van der Marel et al. 2012). Researchers answer these questions using numerical simulations (N-body and hydrodynamical codes) to model the gravitational interactions and gas physics involved.

2. THIS PROJECT

In this paper, we investigate the future mass loss of M33, a significant **Satellite Galaxy** within the **Local Group**. Using simulation data from van der Marel et al. (2012) modelling the future MW-M31-M33 interaction, we aim to quantify the stellar mass M33 loses over $\sim$11.5 Gyr. Our method tracks the stellar mass remaining **Gravitationally Bound** within M33's time-varying **Jacobi Radius** (R_J). The **Jacobi Radius** approximates the boundary of M33's gravitational dominance against M31's tidal influence.

This project directly addresses the open question regarding the challenge of predicting precise mass loss rates for specific satellites in complex, evolving environments. While general principles of **Tidal Stripping** are understood (Mayer et al. 2001; Lokas et al. 2015), quantifying the exact amount and rate of mass loss for a galaxy like M33, subject to time-varying tidal forces from both M31 and the Milky Way during their future merger (van der Marel et al. 2012), remains a specific predictive challenge simulations can address.

Quantifying M33's future mass loss is important for understanding **Galaxy Evolution** within the **Local Group**. It provides insight into satellite survival prospects and quantifies the potential contribution of stripped stars to the **Stellar Halo** (a diffuse stellar component around a galaxy, often from disrupted satellites) of M31 or the MW-M31 remnant (Mayer et al. 2001). Measuring this loss rate also informs models of satellite **Quenching** or altered star formation (Mayer et al. 2001; Semczuk et al. 2018). This study addresses this open question by quantitatively measuring the **Gravitationally Bound** stellar mass evolution within the **Jacobi Radius** using the van der Marel et al. (2012) simulation, offering a prediction for M33's fate and tidal stripping efficiency in this dynamic environment.

3. METHODOLOGY

We use an N-body simulation, a computational technique modelling many discrete objects interacting primarily via gravity (Mayer et al. 2001; Lokas et al. 2015). Stars and dark matter are represented by particles whose positions and velocities evolve based on calculated gravitational forces. Initial conditions model MW, M31, and M33 with realistic components, including extended **dark matter halos** and **stellar disks** (van der Marel et al. 2012).

Our approach involves analyzing snapshots from the van der Marel et al. (2012) simulation to track the evolution of M33. For this analysis focused on mass loss, we use the stellar particles identified as initially belonging to the M33 galaxy. We are using the **LowRes** resolution version of the simulation data provided for this course. By selecting only M33's stellar particles at each timestep, we can calculate properties specific to that **galaxy** as it evolves within the simulation.

First, the code determines the M31 and M33 centers of mass (COM) using an iterative shrinking-sphere method

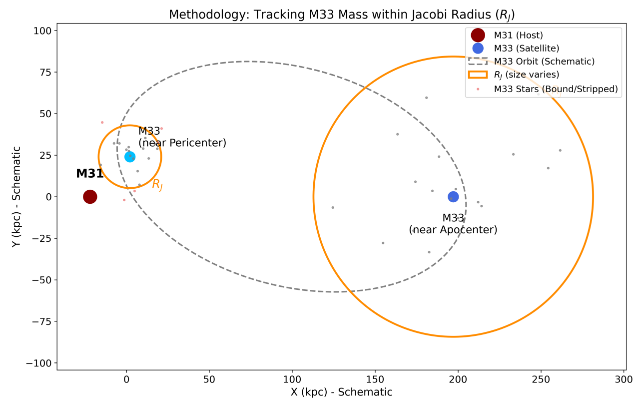

Figure 2. The diagram shows the host galaxy M31 (dark red circle) and the **satellite galaxy** M33 (blue circles) at two representative points along its simulated orbit (dashed grey ellipse): near apocenter (right, larger separation) and near pericenter (left, smaller separation). The orange circles depict M33's **Jacobi Radius** (R_J) calculated at these two points. Note that R_J is significantly smaller near pericenter, where M31's tidal influence is stronger, compared to apocenter. The small dots represent M33 stellar particles schematically, showing particles both inside (grey) and potentially outside (light red) the R_J boundary, especially near pericenter where stripping is expected to be most effective.

for robustness (logic from P2CenterOfMass.py). Let the COM positions be $\vec{r}_{\rm M31}(t)$ and $\vec{r}_{\rm M33}(t)$. Their separation $R(t)$ (kpc) is the Euclidean distance:

$$R(t) = |\vec{r}_{\rm M33}(t) - \vec{r}_{\rm M31}(t)|$$

Next, masses for the **Jacobi Radius** formula are calculated. The host mass, $M_{\rm host}(R(t))$, is the mass of M31 particles (types 1, 2, 3) within $R(t)$ from M31's COM (using P3MassProfile.py). The satellite mass, $M_{\rm sat}$, is approximated as M33's total mass (types 1, 2, 3) within 300 kpc (from P4JacobiRadius.py). The **Jacobi Radius** (R_J, in kpc) is then (Lokas et al. 2015):

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

where $M_{\rm sat}$ is M33's total mass ($M_\odot$) and $M_{\rm host}(R(t))$ is M31's enclosed mass ($M_\odot$) within radius $R(t)$.

Finally, M33 stellar particles (types 2, 3) within $R_J(t)$ from M33's COM are identified. The **gravitationally bound** stellar mass, $M_{\rm bound}(t)$ ($M_\odot$), is the sum of their individual masses m_i:

$$M_{\rm bound}(t) = \sum_{i \in \text{M33 stars}} m_i$$

$$\text{where} \quad |\vec{r}_i(t) - \vec{r}_{\rm M33,COM}(t)| < R_J(t)$$

where $\vec{r}_i(t)$ is the position of the i-th M33 star particle (kpc). The bound fraction is $f_{\rm bound}(t) = M_{\rm bound}(t)/M_{\rm initial}$, where $M_{\rm initial}$ is the initial total stellar mass. This process repeats for each snapshot.

Two primary plots are generated. Figure 3 displays the M31-M33 separation $R(t)$ and M33's calculated **Jacobi Radius** $R_J(t)$ versus time, illustrating orbital dynamics and how R_J shrinks during close passages, highlighting periods of intense **tidal stripping**. In Figure 4, the primary result shows the fraction of M33's initial stellar mass remaining bound within $R_J(t)$ versus time ($f_{\rm bound}(t)$), directly quantifying M33's cumulative mass loss. Figure 3 is based on a combination of class material and my own code. Figure 4 relies on a code flow built from scratch.

Based on previous studies of tidal interactions involving **satellite galaxies** (Mayer et al. 2001; Lokas et al. 2015) and simulations of the specific M31-M33 system (Semczuk et al. 2018), we hypothesize that M33 will experience significant stellar mass loss over the ~11.5 Gyr duration of the van der Marel et al. (2012) simulation. We expect the mass loss to occur episodically, concentrated around the times of pericenter passage when the M31-M33 separation distance $R(t)$ is minimized and the **Jacobi Radius** $R_J(t)$ consequently shrinks, leaving previously bound stars outside M33's gravitational dominance. Given the results for similar tidally interacting systems (Mayer et al. 2001), we anticipate a total stellar mass loss possibly exceeding 20% of M33's initial stellar mass by the end of the simulation, primarily driven by **tidal stripping** during these close encounters with M31.

4. RESULTS

Figure 3 illustrates the dynamical context of the M33-M31 interaction over the simulated period of approximately 11.5 Gyr. The plot displays the separation distance $R(t)$ between the centers of mass (COMs) of the two galaxies and the calculated **Jacobi Radius** $R_J(t)$ for M33 as functions of time. M33 is clearly on an evolving, eccentric orbit around M31. It experiences a relatively distant first pericenter passage near 1 Gyr ($R \approx 80$ kpc), and then undergoes a significantly closer second pericenter passage around 4.4 Gyr ($R \approx 40$ kpc). The subsequent orbits show decreasing apocenter and pericenter distances. M33's **Jacobi Radius** (R_J) closely tracks the separation distance throughout the simulation. The main takeaway from this figure is the identification of multiple close encounters, particularly the one at $t \approx 4.5$ Gyr, during which M33's calculated sphere of gravitational dominance (R_J) significantly decreased, setting the environment for enhanced **tidal stripping**.

The primary result, the quantification of M33's stellar mass loss, is presented in Figure 4. This figure plots the fraction of M33's initial stellar mass remaining **gravitationally bound** within $R_J(t)$ as a function of time. Initially, for approximately the first 4.5 Gyr, virtually no stellar mass is lost from within R_J, with the bound fraction remaining at 1.0. A significant and continuous phase of decline begins around 4.5 Gyr, coinciding precisely with the closest pericenter passage identified in Figure 3 where R_J reached its minima points. The subsequent mass loss appears episodic, with the rate of decline visibly increasing following later pericenter passages and slowing during apocenter phases. By the end of the simulation ($\approx$ 11.5 Gyr), the fraction of bound stellar mass drops to approximately 0.716. The main takeaway result from this figure is that M33 loses a substantial fraction, 28.4%, of its initial stellar mass from within its **Jacobi Radius** over the simulated timeframe, with this mass loss clearly triggered and driven episodically by the close pericenter encounters with M31.

5. DISCUSSION

Figure 4 displays our primary result, quantifying the stellar mass loss of M33 within its calculated **Jacobi Radius** (R_J) throughout the future interaction with M31 (van der Marel et al. 2012). We found that M33 loses 28.4% of its initial stellar mass. This loss was not gradual; we observed significantly more **tidal stripping** during encounters near pericenter, correlating with pe-

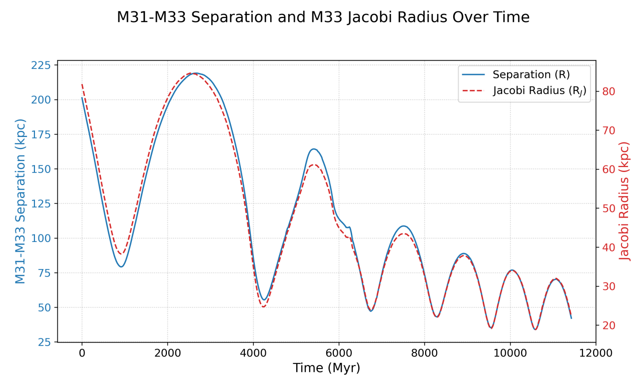

Figure 3. The time evolution of the M31-M33 separation distance $R(t)$ (solid blue line, left axis) and the calculated **Jacobi Radius** $R_J(t)$ for M33 (dashed red line, right axis) over approximately 11.5 Gyr of simulated time. Pericenter passages correspond to minima in separation, while apocenters correspond to maxima. Note the significant decrease in R_J during the close pericenter passage near $t \approx 4.5$ Gyr.

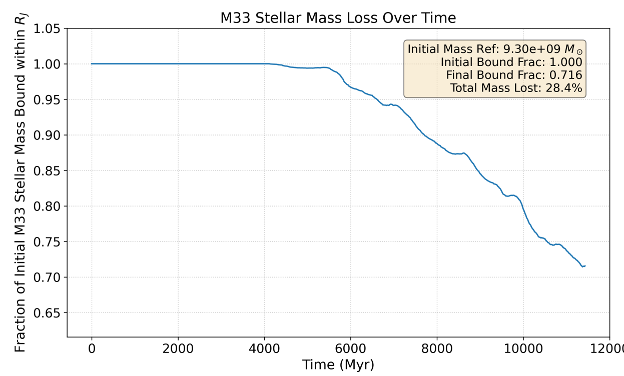

Figure 4. The fraction of M33's initial stellar mass ($M_{\text{initial}} \approx 9.30 \times 10^9 M_\odot$) remaining **gravitationally bound** within its calculated **Jacobi Radius** (R_J) as a function of time. The bound fraction remains near 1.0 until $t \approx 4.5$ Gyr, after which significant, episodic mass loss occurs, correlating with pericenter passages seen in Figure 3. The annotation summarizes the initial mass, initial/final bound fractions, and the total percentage lost (28.4%).

riods where the R_J value shrinks. This result agrees with the hypothesis made in the methodology section.

The conclusion that M33 undergoes substantial episodic mass loss aligns with the established picture of **tidal stripping** driven by satellite-host interactions. This mechanism minimcs the "tidal stirring" concept explored by Mayer et al. (2001), where repeated encounters transform dwarf galaxies. While Semczuk et al. (2018) simulated the M31-M33 system focusing on reproducing current morphology from a potential past encounter, our work focuses on the future evolution depicted in the van der Marel et al. (2012) simulation. This result is important for understanding **galaxy evolution** in the **Local Group** for several reasons: it provides a quantitative estimate for the survivability of M33-like satellites in dense environments, constrains the amount of stellar material M33 might contribute to the **stellar halo** of M31 (or its merger remnant), and establishes a benchmark for the effectiveness of tidal stripping in intricate multi-body interactions predicted by models such as van der Marel et al. (2012).

There are a few uncertainties that must be discussed. Firstly, the calculation relies on the R_J formula, which is an approximation based on assumptions such as a point-mass host and often a circular orbit (Lokas et al. 2015), whereas the tidal field in this complex interaction is more intricate. Secondly, as an N-body simulation, the one utilized here does not take into account hydrodynamics, star formation, or feedback processes. These baryonic physics components, explored in studies like Mayer et al. (2001) and Semczuk et al. (2018), could potentially influence M33's internal structure, its response to tides, and thus the overall mass loss over the $\sim$11.5 Gyr timeframe. Thirdly, the results depend on the specific initial conditions and assumed orbital parameters inherent in the van der Marel et al. (2012) simulation data. As demonstrated in studies like Semczuk et al. (2018), different orbital assumptions can lead to drastically varying interaction outcomes.

6. CONCLUSIONS

Tidal interactions within galaxy groups fundamentally shape the evolution of **satellite galaxies** by stripping mass and altering their structure. Understanding **tidal stripping** is crucial for explaining the observed properties of satellite populations, the build-up of host galaxy halos, and the influence of environment on galaxy transformation. We utilize N-body simulation data modeling the future interactions within the **Local Group**, specifically between M31 and M33, to investigate this process. Our primary goal is to quantify the amount of stellar mass that remains **gravitationally bound** to M33 within its time-varying **Jacobi Radius** (R_J) over approximately 11.5 Gyr.

In our analysis, a key finding was made regarding M33's future evolution: it is predicted to lose 28.4% of its initial stellar mass from within its time-varying **Jacobi Radius** (R_J) over the $\sim$11.5 Gyr timeframe. We conclude that this loss is episodic and is triggered by close pericenter passages where M31's tidal forces become more dominant and R_J shrinks. This provides quantitative evidence for the efficiency of **tidal stripping** in the future **Local Group** environment and informs predictions about the survivability of M33 and its potential contribution to the **stellar halo** of the M31-Milky Way merger remnant. Our findings strongly agree with our hypothesis.

Future work could build on this by using a hydrodynamical simulation rather than purely an N-body simulation. This would allow for the inclusion of gas physics, star formation, and feedback processes, all of which can alter the satellite's response to tidal forces (Mayer et al. 2001; Semczuk et al. 2018). Exploring more sophisticated techniques that do not rely on a sharp cut-off at R_J to define bound mass may also lead to a more refined mass loss estimate.

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