

# Tidal Features and Remnants in the Milky Way-M31 Merger

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## ABSTRACT

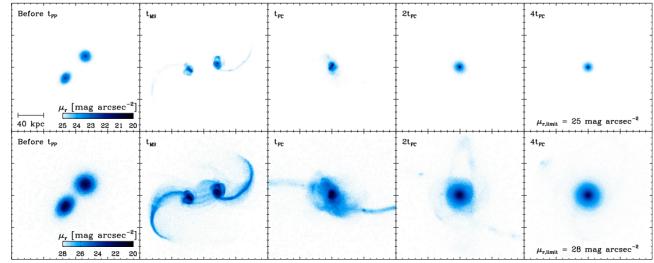
Tidal bridges and tails are physical features that resemble extended swept-out spiral arms created by strong tidal forces throughout the merging of galaxies. The examination of these tidal features provides significant insight into galaxy evolution in terms of kinematics and orbital geometry; however, far less is understood about the creation and evolution of these tidal features themselves and how their evolution coincides with the merging process. We examined high-resolution data from an N-body simulation of the merger of the Milky Way and M31 created by [van der Marel et al. \(2012\)](#) with a particular focus on snapshots surrounding the apoapsis and periapsis of the galaxies' decaying orbits and the end state of the simulation. With these data, we identified particles associated with tidal features and tracked their location to the end of the simulation in an effort to determine the fate of these features. Through this investigation, it was found that these tidal features are mostly transient to the merger process and are primarily created at points of apoapsis and periapsis in the decaying orbit after the first close encounter. Further, a majority of the mass comprising these tidal features remains gravitationally bound and within the main body of the merger remnant at the end of the simulation. These findings play an important role in beginning to understand when galaxy mergers produce these tidal features and what happens to the matter that comprises them after they are no longer visible. This first step will provide a framework for more in-depth and thorough investigation of the transient lifetime of tidal bridges and tails and characterization of mass distribution throughout the merger process.

**Key words:** Tidal Tails – Tidal Bridges – Local Group – Stellar Disk – Gravitationally Bound

## 1 INTRODUCTION

Galaxy merging events are the underlying principle of hierarchical galaxy formation theory which proposes accretion of smaller satellites play a significant role galaxy evolution [Wang et al. \(2012\)](#). These events involve extreme tidal forces which often result in the creation of unique structures within these interacting systems. **Tidal tails** and **tidal bridges** are streams or spindles of stars and gas or dust which are ejected from their host galaxies throughout the merger process due to gravitational forces exerted on the material. They often resemble extended spiral arms which reach out towards (bridge) and away (tail) from the companion satellite [Toomre & Toomre \(1972\)](#). The study of this form of mass loss and tidal debris provides significant insight into the initial conditions of merging systems, the fate of stripped material, and the tidal forces involved in these events.

**Galaxies** are "gravitationally bound sets of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity" as defined in [Willman & Strader \(2012\)](#). The study of tidal remnants such as tidal bridges or tails created during merging events is vital to better understand how galaxies grow and change over time due to both internal and external events—**galaxy evolution**. In particular, these structures can serve as a galactic fossil record of past interactions of galaxies and their satellites [Wang et al. \(2012\)](#). Based on the shape, prominence, and other physical characteristics of tidal tails and bridges it is possible to determine the strength of tidal forces, pro- and retrograde interactions, and how strongly **gravitationally bound**, or held by the galaxy, the tail initially was to the host galaxy



**Figure 1.** Mock images of a simulation of two mass ratio 1:1 mergers taken from [Ji et al. \(2014\)](#). Tidal tails and bridges can be seen forming throughout the merger process yet fade somewhat quickly. This shows that these features are created during close encounters of the merging galaxies and are transient features which we hope to show in this investigation.

with implications on star formation [Privon et al. \(2013\)](#). By studying objects which present these features, it is possible to improve current models of galaxy evolution, structure, and merging events.

Current research on galaxy mergers has shown the ubiquitous nature of tidal tails and bridges in these systems and has helped to relate physical properties of these structures to characteristics of the merging system. The orientation of these tails has been related the inclination of the **stellar disks** – the flat rotating body of the galaxy composed of gas, dust, and stars – during the encounters between the two objects and overall orbital geometry of the system [Mihos](#)

(2004). Prograde and retrograde encounters also have been shown to create noticeable differences in the strength of the formed tails; prograde encounters create more significant tidal structures compared to retrograde Privon et al. (2013). The length and symmetry of these structures created in both interacting galaxies during a merge has also been shown to largely be determined by the speed or severity of the encounter as well as the mass ratio of the objects Ji et al. (2014); Toomre & Toomre (1972). It has been shown that slower encounters tend to create more significant tails and that smaller mass ratios result in more significant tidal features as seen in Fig. 1. However, to what extent these remnants can be used to reconstruct all aspects of merging events or identify past events remains open.

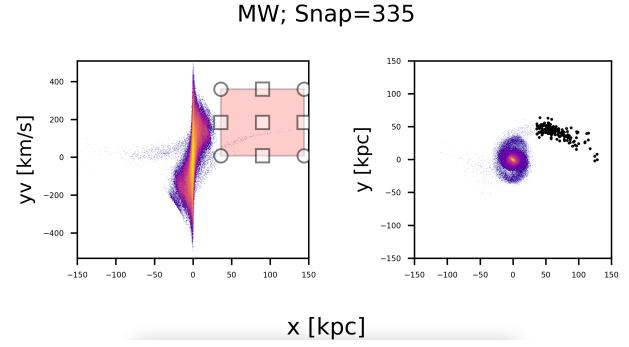
While many advances have been made in understanding these structures, there are several questions which remain unanswered. Perhaps one of the largest is how long these tidal debris exist, and what their fate is as the system evolves. The relatively faint nature of these structures has made them difficult to detect and therefore absent in many shallow surveys of galaxy populations. Thus, it is unknown whether tidal remnants persist long after the coalescence of merging galaxies or that major mergers which produce these features remain relatively rare. Further, there has been very little exploration as to what becomes of these structures post-merge as they are mostly considered to be transient to the merge; however, some research suggest they could seed stellar streams Wang et al. (2012). Addressing these questions as well as how to better identify these features is vital for furthering models of galaxy evolution.

## 2 THIS PROJECT

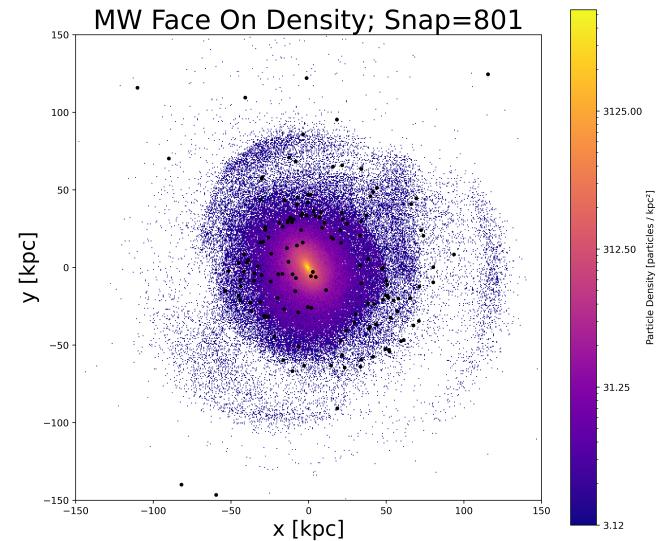
In this investigation, we will examine the creation of tidal tails and bridges during the Merger of M31 and the Milky Way. The specific snapshots used in this investigation will be determined by the orbital motion of the centers of mass of the Milky Way and M31 shortly after the periapsis and apoapsis of their orbit. These snapshots include: 275, 280, 285, 335, 340, 345, 410, 420, 425, 430, 435, 470, 475, and 480. Using this information, it will then be possible to identify disk particles that are within these tidal structures using velocity phase diagrams and track them as the simulation progresses.

Through this investigation, we seek to better understand when in the process of merging these tidal structures are created and in the process identify the fate of this material after the merge has completed. By tracking the identified particles throughout the simulation, it will be possible to determine the lifespan of tidal tails and bridges, as well as if this material remains gravitationally bound to the merge remnant.

Identifying when these structures form, their lifetime, and where this matter eventually ends up will greatly advance our understanding of how galaxies evolve after major merges. By examining simulation of major objects within the **Local Group**, all galaxies and objects which are gravitationally bound to the Milky Way despite the expansion of the universe, this study will help to further increase our understanding of the timeline of tidal structure formation by placing bridge and tail formation events concretely within the simulated merger. Further, by identifying the particles which create these features it is possible to recreate the life of these transient structures to identify lifetime and fate of the matter involved.



**Figure 2.** A phase diagram and face-on column density plot of the Milky Way at snap 335 using HiRes Data. The transparent red box in the phase plot diagram is a plotting tool used to identify the index of particles within the specified region. These particles are then plotted as black dots on top of the face-on density plot in order to ensure that the selected particles are part of a tidal feature. As particles selected within the box are clearly associated with a tidal feature, this methodology holds merit.



**Figure 3.** A density plot of Milky Way disk particles at snap 801 looking face-on to the disk. Black dots in this image are disk particles that were identified to be in the tidal tail or bridge in snap 335 shown in Fig. 2. Most identified particles have re-accreted with the remnant disk particles however, some remain distinctly separate from the main body.

## 3 METHODOLOGY

The simulation used in this investigation is an N-body simulation of the three major objects of the Local Group – the Milky Way, M31, and M33 – produced by van der Marel et al. (2012). In this simulation, gravitational forces between all particles are approximated with the accuracy of this approximation being primarily determined by the distance between the particles. Further, three major components of these galaxies were modeled: the disk, bulge, and dark matter halo. For the galaxies modeled in this simulation, exponential profiles with scale length  $R_d$  were used for disk profiles, bulge profiles where scaled with  $R^{1/4}$ , and dark matter halos were modeled using a Hernquist profile. Further, M33 was modeled without a bulge due to its insignificant mass.

In order to identify these tidal structures phase diagrams of both

the Milky Way and M31 will be created using HiRes data in order to depict the velocity of particles along one axis vs their position in the body of the galaxy. Clusters of particles which are outliers from the general shape of the phase plot are likely to be tidal tails or bridges and their comprising particles identified as shown in Fig. 2. To ensure these particles are part of a tidal feature their position is plotted within the disk of the Milky Way. These particles can then be tracked to later stages of the simulation, most notably to the end show in snap 801 as shown in Fig. 3 to determine where the particles comprising these features end up.

Phase diagrams of both the Milky Way and M31 will be created at snaps 275, 280, 285, 335, 340, 345, 410, 420, 425, 430, 435, 470, 475, and 480. Each plot will be manually analyzed to determine the presence of tidal tails and bridges as shown in Fig. 2. Disk particles which comprise the identified structures can then be recorded using their indices and tracked through the simulation and ultimately to its conclusion in snap 801 as shown in Fig. 3. By tracking these stars through the simulation it will be possible to determine the transient lifetime of these tidal structures during the merger process as well as determine where the disk particles which created these structures resided when the simulation ended. To do so, the fraction of particles identified as being part of a tidal tail or bridge and are beyond a radius which encloses most of the galaxy's mass, are tracked over the simulation snapshots of interest. This ratio is defined by the following equation:

$$M(R_{95})/M_{tot}$$

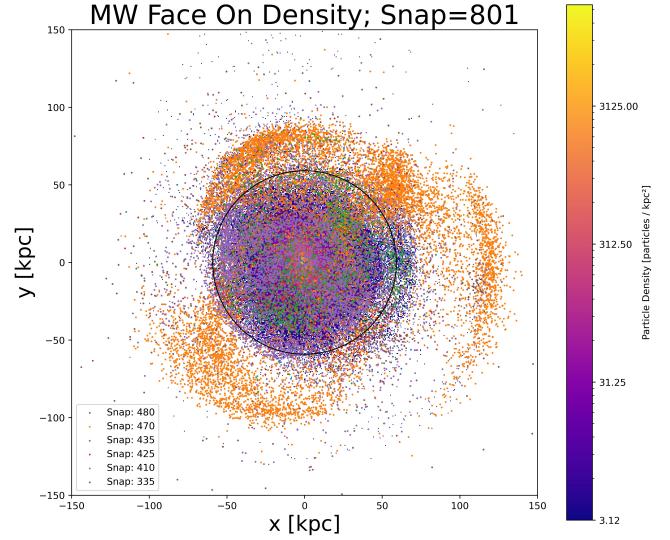
This will present a view of how these tidal features evolve over the course of the simulation.

During the Milky Way-M31 merger sequence, tidal tails of various prominence will form at each of the close encounters of the system. The most pronounced of these features will persist throughout the length of the simulation. Further, while the material will for the most part remain bound to the merger remnant, these tidal structures will potentially remain as seeds for tidal streams as M33 is tidally stripped.

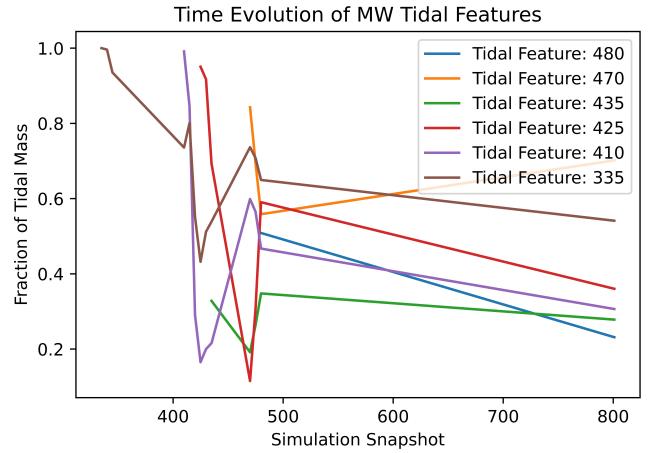
## 4 RESULTS

Through this investigation plots were created to show the location of all particles identified as part of a tidal feature within the key snapshots examined at the end state of the simulation. This was plotted upon a 2D-histogram of the face-on column density of the galaxy in order to examine the location of these particles relative to the merger remnant. As shown in Figs. 4 and A1 visually distinguishable tidal features were identified in snaps 335, 410, 425, 435, 470, and 480 for the Milky Way while they were only identified in snaps 335, 410, 425, and 470 for M31. It appears that most disk particles identified in tidal features throughout the simulation reside within the body of the merger remnant. In both cases visually it appears as if a majority of disk particles that are outside of the body of the merger remnant are from the most recent tidal features identified in snap 470. Further, there is much more significant distribution of disk particles associated with tidal features from the Milky Way, compared to M31. This suggests that because of the unequal disk masses of the Milky Way and M31, more material is ejected from the body of the Milky Way and it has taken longer for the material to re-accrete.

By tracking these identified particles throughout the simulation as well as calculating radii which enclose close to all the mass of each galaxy at each snapshot of interest, it is possible to determine a fraction these tidal features which remains distinct and beyond the



**Figure 4.** A density plot of Milky Way disk particles at snap 801 looking face on to the disk. Colored dots plotted over this represent disk particles associated with tidal features identified in snaps: 335, 410, 425, 435, 470, and 480. The circle centered on the center of mass represents the radius within which 95% of the Milky Way's mass is contained. It is clear that the majority of tidal features which remain at the end of the simulation are mostly due to the tidal features identified in snap 470



**Figure 5.** Depicts the time evolution of each tidal structure after they are initially identified as defined by the fraction of the initial mass identified in the tidal structure that stays outside of the remnant defined by the radius enclosing 95% of the mass of the Milky Way for each snapshot of interest in this investigation. This figure supports the qualitative data in Fig. 4 in that tidal feature 470 is the most distinctly separable from the disk and shows.

main body of the galaxy. These results are shown in Figs. 5 and A2. In order to provide the most conclusive results, different values for the percentage of mass enclosed were chosen for each galaxy: 95% for the Milky Way and 99% for M31. These values were chosen experimentally by determining which produced results that clearly showed the evolution of these features throughout the simulation. From these figures, it is clear to see that there are rapid changes in the fraction of particles which exist beyond this critical radius shortly following both periapsis and apoapsis of the center of mass

orbits of each galaxy. Further, there appear to be some tidal features which have a significantly larger portion of their component particles beyond this radius throughout the simulation and these appear to be from very early tidal features formed. It is also clear that shortly after these features are identified, the critical radius identified increased significantly due to additional disk particles being swept out from the center of the galaxy resulting in the dramatic decrease in the ratio of each tidal feature shortly after they are created.

## 5 DISCUSSION

Analyzing the distribution of disk particles associated with tidal features in the Milky Way at the end of the simulation, it is clear that the tidal feature identified in snap 470 remains the most prominent at the end of the simulation. There are prominent tidal structures which are present beyond the body of the galaxy and the critical radius containing 95% of the mass of the Milky Way. This indicates that this feature which was created around the same time as the merging of the Milky Way and M31 persists until the end of the simulation. This supports the hypothesis of this investigation that major merger events will produce tidal features that persist until the end of the simulation.

These data suggest that that tidal features are indeed created during the merging process of galaxies. The final merging process has the slowest relative speed of the centers of mass of each galaxy due to dynamical friction. This seems to correspond with the most prominent tidal features created around snap 470 as seen in Figs. 4 and A1. This supports findings by Ji et al. (2014) which found that more significant tidal tails are created when encounters happen at slower relative velocities. Further, Ji et al. (2014) also suggests that less massive galaxies in the merger process will have much more significant tidal features. While The Milky Way and M31 are approximately the same mass, the disk of the Milky Way is less massive potentially suggesting why tidal features are more prominent at the end of the simulation for the Milky Way compared to M31. Overall, this finding improves our understanding of both the prominence and longevity of tidal features throughout the merger process as well as potentially how mass ratios of galaxy components may impact the strength of these features.

While these results are promising, there are some major limitations as well. Most notably, as these features were identified visually and the particles selected using a rather unrefined technique of box selection, it is quite likely that some tidal features were not identified, that some particles comprising identified tidal features were not tracked, or that particles not comprising these tidal features were erroneously included in these features. Further, due to formatting limitations it is not feasible to depict all snapshots where tidal features were identified significantly hindering the data which can be used to draw conclusions.

To better understand how these tidal features evolve over the course of the simulation, Figs. 5 and A2 show the prominence of each tidal feature beyond a radius enclosing 95% of the mass of the Milky Way and 99% of the mass of M31 respectively. This was done to show when these features become prominent beyond the body of the galaxy in a dynamic manner that would change as the form of these galaxies evolved over the course of the merger. While it would be expected that the fraction of mass beyond this radius for each tidal feature would reach 1 at some point in the simulation, this is not the case. Instead, while many approach 1, the selection of particles comprising these tidal features was done without regards to the enclosing radius determined at each snapshot, resulting in fractions less than 1 in cases

where the disk particles of the galaxy are very dispersed primarily as the merger progresses. In Fig. 5 it is clear that particles associated with tidal features 335 and 410 are primarily beyond the critical radii identified in these snapshots. The first apoapsis of the merge occurs around snapshot 335 and coincides with the identification of tidal feature 335 which is almost entirely beyond the  $R_{95\%}$ . More noticeable is the final apoapsis and merge of the two galaxies around snapshots 425 and 470. Here it is clear to see that around 425 there was a significant number of particles associated with tidal feature 425 which formed a distinct tidal feature separate from the main body of the galaxy. As the disk particles of the galaxies spread during the process of the merger, many of the fractions decreased while those of 335 and 410 again increased. Finally, at the end of the simulation it is clear to see that a majority of the particles in tidal feature 470 and 335 both exist beyond the merger remnant while closer to a third of the particles associated with the other tidal features are in this region.

These data show that quite a large fraction of the material identified as comprising tidal features created early in the merger process can be found in the outer regions of the galaxy while later mergers produced tidal features comprised of disk material that was initially closer to the center as shown by the initial fractions of tidal feature mass. Further, these features are indeed created during both the periapsis and apoapsis points in the decaying orbit of the galaxies as they merge, similar to what is shown in Fig. 1. Finally, it is clear that a significant amount of the material which comprises these features remains gravitationally bound to the merger remnant, shown by rather low fractions for tidal features 410, 425, 435, and 480 as well as visually in Fig. 4. However, a significant amount of material attributed to major tidal features created during the last stages of the merger remains beyond the body of the merger at the end of the simulation indicating that not all matter remains bound.

There are several limitations to these data which draws into question the validity of these results. Most notably, the method used to identify particles belonging to a tidal structure allowed for particles to be counted as a part of more than one tidal feature. This could potentially lead to the similar trends found in tidal features are created at very different points in the merging process, most notably some similarities between tidal features 470 and 480 as well as 425, 435, and 410. Without accounting for this double counting it becomes far more difficult to determine the extent of the accuracy of these data. Further, as the body of the galaxy becomes less cohesive throughout the merger, while calculating the radius within which a majority of the galaxy's mass is present does provide a dynamic radius for which it is possible to determine whether tidal features have been re-accreted into the galaxy, it is a rather crude method. This method works best when the body of the galaxy is very circular which in many snapshots is not the case due to extreme tidal forces. This likely plays a major role in sharp changes in Fig. 5 as well as the sharp decrease shortly after being identified that can be seen in the evolution of most tidal features. This is likely due to the additional disk particles being thrown away from the main body of the galaxy. Finally, the limited time resolution of his data makes it difficult to determine when these features are created exactly and when they are no longer prominent within the system. This makes it difficult to estimate when these features are created, when they are "destroyed", and how quickly these processes take place.

## 6 CONCLUSIONS

Tidal bridges and tails are physical features that resemble extended swept-out spiral arms created by strong tidal forces throughout the

merging of galaxies. The examination of these tidal features provides significant insight into galaxy evolution in terms of kinematics and orbital geometry; however, far less is understood about the creation and evolution of these tidal features themselves and how their evolution coincides with the merging process. We examined high-resolution data from an N-body simulation of the merger of the Milky Way and M31 created by [van der Marel et al. \(2012\)](#) with a particular focus on snapshots surrounding the apoapsis and periapsis of the galaxies' decaying orbits and the end state of the simulation. With these data, we identified particles associated with tidal features and tracked their location to the end of the simulation in an effort to determine the fate of these features.

Through this investigation, tidal features were identified in snapshots surrounding the periapsis and apoapsis of the decaying orbits of the Milky Way and M31. Tidal features were identified in snapshots 335, 410, 425, 435, 470, and 480. Tidal features 435 and 480 were less separated from the majority of the galaxy's disk particles, shown by the lower tidal mass fraction when they were identified. Further, tidal feature 480 was found to be the most prominent remaining feature at the end of the simulation. These results agree with the hypothesis that these tidal features would be created throughout the merger and that the most prominent features, notably tidal feature 470, would remain distinct from the remnant disk particles. This can be seen both in the visual distribution of particles as well as the mass fraction time evolution increasing at the end.

From the examination of the time evolution of the tidal features, it is clear a significant portion of material which comprises tidal features remains within the body of the merger remnant. This can clearly be seen as all mass fractions have values of over 0.2 at the end of the simulation. Moreover, while around 70% of the particles comprising tidal feature 470 remain outside of the radius containing 95% of the Milky Way's mass, it is clear from examining the distribution of these particles that a majority remain gravitationally bound to the merger remnant. Therefore it is highly likely that continuing the simulation would result in the mass ratio of tidal feature 470 falling to be more in line with the other tidal features. However, these results indicate that between 20% and 60% of mass found in tidal features remains beyond the merger remnant at the end of the simulation. This finding partially support the hypothesis that these tidal structures will remain outside of the remnant however it does not provide enough information regarding the location or orbital kinematics of these particles to conclude whether they remain gravitationally bound nor if they seed tidal streams from M33.

While these results represent an important step forward in understanding the tidal structures created as galaxies merge, there are many potential avenues of improvement. Identification of tidal features relied on a visual analysis of the galaxies phase diagram and a face on view of the galaxies disk. While sufficient for the purposes of this investigation, this method ignores the three dimensional nature of the simulation and thus could potentially have missed identifying some tidal features. Similarly, to calculate mass fractions for tidal structure evolution, the radius calculated is a sphere measured from the center of mass of the galaxy. Thus it is highly likely that particles that could be distinguished from the main body of the galaxies or merger remnant in terms of the third dimension instead were included as part of the main body. In order to improve how the evolution of these tidal features were measured one possible method would be constructing a KDTree for the particles within the simulation and using this determine for each disk particle identified as part of a tidal feature, the surrounding density of non-tidal feature disk particles within a radius of 0.5 kpc. If this density where to reach a critical value, potentially determined based on threshold below the central density of the

galaxy, then it would be considered re-accreted into the main body of the galaxy. This would allow for greater precision in determining the evolution of tidal features measured by the fraction of their mass which is distinct from the main galaxy. Further, by examining more snapshots at higher time resolutions it would be possible to see how the features evolve in greater detail potentially allowing estimates of transient lifetime. Finally, in order to gain a better understanding of how the orbital mechanics of the merger effect the creation of these tidal features, the mass of identified tidal features could be plotted against the velocities of the galaxies in order to determine how this impacts tidal structure formation.

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I would like to thank Professor Besla and Mr. Himansh for their support and advice given throughout the semester to make this investigation more thorough and clear. Further, the use of generative AI such as ChatGPT in this project was limited to formatting of matplotlib figures and occasionally the troubleshooting of code. In these instances, all code was originally written by myself and only small edits were made by the generative to fix potential errors (in most cases these changes did not work but inspired my own troubleshooting ideas).

This work made use of the following software packages: `matplotlib` ([Hunter 2007](#)), `numpy` ([Harris et al. 2020](#)), and `python` ([Van Rossum & Drake 2009](#)).

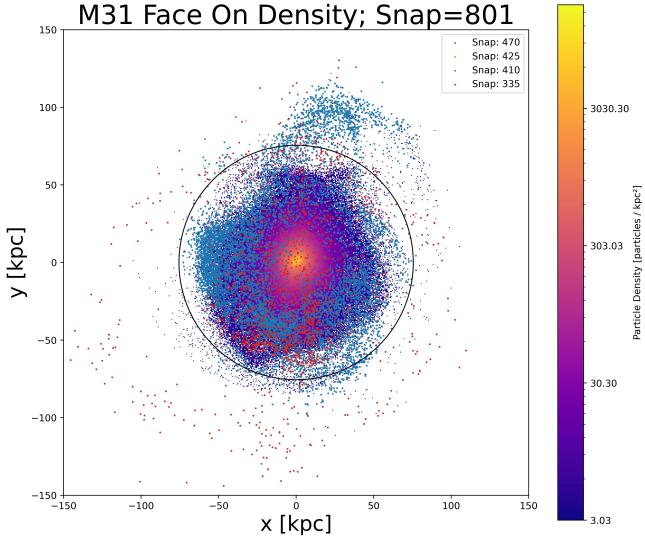
Software citation information aggregated using [The Software Citation Station](#) ([Wagg & Broekgaarden 2024](#); [Wagg et al. 2024](#)).

## Land Acknowledgment

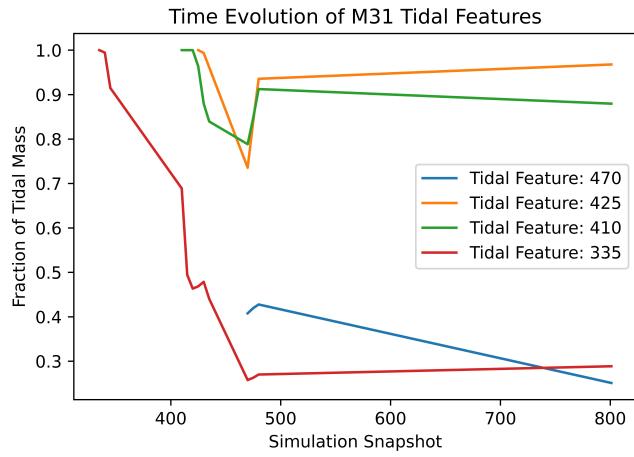
We respectfully acknowledge the University of Arizona is on the land and territories of Indigenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. The university strives to build sustainable relationships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

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**Figure A1.** A density plot of M31 disk particles at snap 801 looking face on to the disk. Colored dots plotted over this represent disk particles associated with tidal features identified in snaps: 335, 410, 425, and 470.



**Figure A2.** A figure depicting the fraction of particles identified in each tidal feature which are beyond a radius enclosing 99% of the mass of M31 for each snapshot of interest in this investigation. The circle centered on the center of mass represents the radius within which 99% of the M31's mass is contained. Few particles associated with tidal features remain distinct from the disk at the end of the simulation; an exception to this is particles in snap 470.

## APPENDIX A: M31 FINAL DATA FIGURES

### A1 Tidal Particle End of Simulation Distribution

### A2 Tidal Feature Evolution

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.