# Tidal Tail Velocity Dispersion during the First Encounter of the Milky Way-M31 Merger

Ella Butler

April 10 2025

**ABSTRACT**

The velocity dispersion of tidal tails refers to the spread in velocities among stars in structures formed from major merger events. It is significant as a key indicator of gravitational disruption in galactic interactions. N-body simulations will be used to model the gravitational interactions between particles and calculate the velocity dispersion within the tidal tails. Using these simulations, the formation and evolution of tidal tails during the first encounter of the Milky Way-M31 merger can be studied, and their velocity dispersion can be calculated. During the initial encounter, the velocity dispersion of disk particles in M31 experience a sharp increase around 3.75 Gyr into the future. These findings demonstrate that tidal tails are not just morphological features but dynamically evolving structures, where the increased velocity dispersion reflects the intensity of gravitational disruption. This study enhances the general understanding of how stellar material is redistributed during galaxy evolution and provides a framework for interpreting observational signatures of past merger events.

**Key words:** Tidal Tails – Tidal Bridge – Major Merger – Stellar Disk – Hierarchical Growth

## 1 INTRODUCTION

Studying the evolution of galactic **tidal tails** is essential to gain a better understanding of **major mergers** (define it using mass ratio). Tidal tails are the result of gravitational interactions between galaxies. During the interaction, stars and gas get pulled away from the **stellar disks**, or outer regions, of the galaxies due to tidal forces. These features can stretch for over hundreds of kiloparsecs and can persist for a few billion years. The tidal tails that link the perturbing galaxy to the perturber are known as **tidal bridges**. Tidal bridges and tails are considered a signature of a recent major merger. Major mergers play a role in galactic morphological transformations in that they redistribute material, as well as trigger bursts of star formation. These tidal tails and bridges also serve as crucial observational evidence for the **hierarchical growth** model, suggesting that galaxies form through a series of mergers and other accretion events. Studying the formation and persistence of these tidal features is crucial to understanding the physics that governs galaxy growth and evolution. Studying tidal tails and tidal bridges reveals the interaction history between galaxies. A **galaxy** is a gravitationally bound system of stars whose properties cannot be explained by a combination of baryons (gas, dust, and stars) and Newton's laws of gravity. **Galaxy evolution** refers to the processes by which galaxies grow, interact, and change in structure and composition over time. Tidal tails and bridges can be observed to better understand how they contribute to galaxy evolution. Tidal debris provides astronomers with evidence of gravitational encounters that occurred billions of years ago. By analyzing the distribution, kinematics, and composition of tidal debris, astronomers can use this information to improve already existing models on galactic growth and evolution. Tidal tails and bridges can also serve as dynamical markers of the dark matter halo structure, and can provide a framework for how galaxies continue to evolve in different environments, from isolated pairs to dense galaxy clusters.

Tidal tails and bridges are formed from gravitational physics. These interactions come into play during close encounters. Each encounter is considered to involve only two galaxies. The tidal forces that act on spiral galaxies during a close encounter, as well as their rotational motion, draw out long tails of gas and stars. For the first encounter, tidal forces give the disks enough energy to escape the inner potential well.Mihos (2004) After this near direct passage of the companion galaxy, the outer portions of the disk will deform into a spiral arm that connects the two galaxies, called a bridge. A counterarm will also form on the far side of each galaxy, called a tail. This occurs because of the symmetric nature of tidal forces. If the partner galaxy is equal in mass or more massive, then a tail of escaped debris forms from the perturbed disk. In addition, disk particles from the near side get swept into the perturber galaxy. Toomre & Toomre (1972) Tidal tail formation is strongly correlated to orbital geometry. Mihos (2004) They are strongest in prograde encounters, where spin and angular momentum vectors are aligned to a moderate extent. The tails are weakest in a retrograde encounter. Due to the pair of galaxies' orbital decay, these can cause the galaxies to fall away from their tails as they merge together. Tidal tails change as time passes. Most of the material remains bound to the remnant within loose elliptical orbits. Over billions of years, some of the tidal tail material at the base will fall back into the merger remnant, and the outer portions will continue to expand. This will result in continual stretching of the tidal tail. Mihos (2004)

The test-particle method is one way to explore and understand the kinematics of interacting galaxies, as well as the morphology of the features that form during a merger. One example software that does these simulations is called Identikit. Dynamical models were simulated using this software, and detailed in a paper authored by Privon et al (2013). Within the paper, they simulated a few known mergers that were observed by space telescopes. From their paper, the velocity scaling parameter showed a noticeable bias in the best

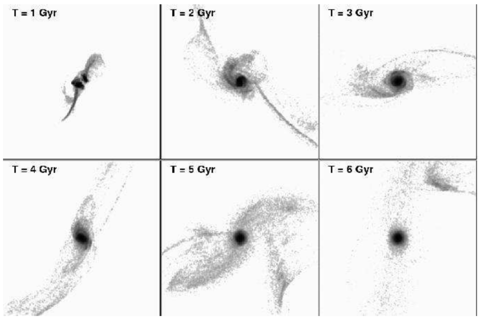


**Figure 1.** Evolution of an equal-mass merger. Note the tidal bridge gets stripped early on, but the tidal tails remain for around 3 Gyr, getting stretched out as the outer portions expand. (Figure 3, Mihos (2004))

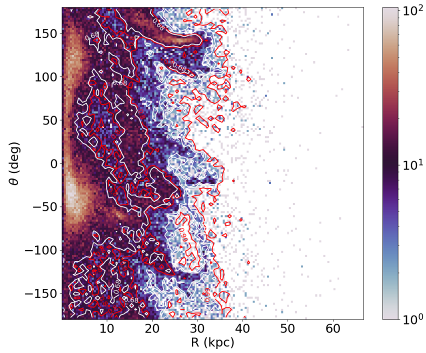


**Figure 2.** A phase diagram of a snapshot of M31 disk particle data. This is from the Lab 7 in-class assignment. Note the arm on the top of the graph; the outstretched material is considered to be prominent tidal debris.

fit values. The bias could be explained by the disk particles they used having zero velocity dispersion, which were used to match tails formed from disks with a non-zero velocity dispersion. The velocity scaling determined by test-particle matching would have to have been inflated in order to compensate for this. Privon et al. (2013) The solution to this discrepancy lies in using test-particle models that can include or calculate velocity dispersion. In reality, particles experience velocity dispersion as they are subject to mergers. In the disk of a galaxy, the dispersion is low; stars make up a majority of the disk and follow circular orbits around the galactic center. When the merger occurs, the velocity dispersion increases, especially in tidal tails.

## 2 THIS PROJECT

In this paper, the velocity dispersion of tidal tails that form during the Milky Way–M31 merger will be studied. These structures can provide insight into redistribution of mass and angular momentum during a merger. Using N-body simulation data, the development of these tidal features throughout different stages of the merger will be tracked. In addition, the change in velocity dispersion of disk particles over time will be calculated and analyzed. By plotting the evolution of velocity dispersion across multiple time steps, the aim is to better understand the dynamical impact of the merger on the structure of the resulting remnant elliptical galaxy. This project addresses the limitations highlighted in the Privon et al. (2013) paper with regard to the lack of velocity dispersion in the test-particle models. Their findings pointed out a bias in velocity scaling in their test-particle models. By focusing on the change in velocity dispersion during the Milky Way–M31 merger, this project will explore how velocity dispersion evolves dynamically, rather than assuming a static or negligible value for test particles. This project will allow for investigation into how dispersion impacts tidal tail morphology and kinematics using a more realistic set of test-particle data. Velocity dispersion plays a key role in determining the structural and kinematic properties of remnant galaxies. If simulations neglect or oversimplify the impact of velocity dispersion, they risk misrepresenting the dynamics of merging systems. This is particularly true in tidal tails, where dispersion increases significantly. By quantifying how velocity dispersion changes over time during the Milky Way–M31 merger, this study provides a more physically realistic perspective on the dynamics of merging disks.

## 3 METHODOLOGY

In this project, N-body simulations will be utilized based on the merger models presented in van der Marel, Besla et al. (2012, *ApJ*, 753, 9). An N-body simulation is a numerical technique used to study gravitational interaction of a system of particles, where each particle represents a portion of mass—such as stars, gas, or dark matter—in the galaxy. These simulations allow for tracking of dynamical evolution in galaxies by solving Newton's laws of motion and gravity for all particles simultaneously. In the van der Marel & Besla model, each galaxy is initially represented by a combination of a dark matter halo and a stellar disk. The dark matter halos follow a Navarro-Frenk-White (NFW) density profile, which is used in cosmological simulations to model the structure of halos formed through hierarchical clustering. The stellar disks are embedded within these halos and are modeled as rotationally supported components with an exponential surface density profile. These initial conditions provide a realistic framework for analyzing the gravitational dynamics of the Milky Way–M31 merger, including the formation of tidal features over time. This study will use the HighRes version of the Milky Way–M31 merger simulation data. This was chosen because the high resolution data provides the spatial and mass resolution essential for capturing interaction dynamics. The analysis focuses on disk particles from both the Milky Way and M31, as these represent the part of the galaxy that is most directly affected by tidal interactions. Using methods adapted from previous coursework, the center of mass (COM) positions and velocities of each galaxy are computed for a shift into a COM framework for kinematic analysis. To identify tidal tails, phase diagrams (theta vs. radius) will be generated to detect kinematic outliers that lie far from the main rotation curve at large radii. For the Milky Way, the outliers are particles considered to be past 30 kpc, and for M31, they are considered to be past 50 kpc. After identifying the tidal tail particles, their time evolution can be tracked across a series of snapshots, and plotted on a graph that shows velocity dispersion over time.

The core calculations in this project involve determining the positions and velocities of disk particles relative to their host galaxy's COM, as well as tracking the evolution of velocity dispersion in the tidal tails over time. To analyze the structure and kinematics of each galaxy, we first shift into a COM frame, computing both the position and velocity of the stellar disk relative to the COM using the methods developed in prior coursework. The total spatial separation of each particle from the galaxy center is calculated using the Euclidean distance formula:

$$r = \sqrt{(x - x_{COM})^2 + (y - y_{COM})^2 + (z - z_{COM})^2} \tag{1}$$

where x, y, and z are the particle's coordinates and $x_{COM}$, $y_{COM}$ and $z_{COM}$ are the coordinates of the galaxy's center of mass. The total velocity relative to the galaxy's bulk motion is computed as:

$$v = \sqrt{(v_x - v_{x,COM})^2 + (v_y - v_{y,COM})^2 + (v_z - v_{z,COM})^2} \tag{2}$$

where $v_x$, $v_y$, and $v_z$ are the particle's velocity components and $v_{x,COM}$, $v_{y,COM}$, and $v_{z,COM}$ are the velocity components of the galaxy's COM. To identify tidal tails, phase diagrams will be made by plotting particle velocities against the galactic radii. To do this, their coordinates will be converted from Cartesian to cylindrical, using these equations: Particles that deviate from the expected distance are interpreted as members of tidal tails. After selecting tidal tail particles based on their phase-space positions, their data will be used to compute the velocity dispersion at each time step:

$$\sigma^2 = \frac{1}{N}\Sigma(v_i - \bar{v})^2 \tag{3}$$

where $v_i$ are individual particle velocities, $\bar{v}$ is the mean velocity of the group, and N is the number of particles in the tail. This allows for tracking the particles in the tidal structures across snapshots, and better understanding of how the merger affects their kinematics. To investigate how tidal tails evolve during the Milky Way–M31 merger and how their velocity dispersion changes over time, two types of plots will be generated. The first type is a phase diagram (theta vs. radius) for disk particles in both galaxies. This type of plot was developed in Lab 7, and will be used to identify outlier particles that lie beyond a certain distance. The second type of plot will graph velocity dispersion for tidal tail particles of both galaxies over the time period which the snapshot represents. This figure will be generated using a function that tracks the same set of disk particle indices across successive snapshots and calculates their velocity dispersion at each time step. The plot will display velocity dispersion over time. This will allow for testing of the hypothesis that tidal tails gain internal velocity spread as a result of repeated gravitational interactions. Together, these two plots will answer the core research question by showing both the *structure* of the tidal tails (via phase space) and the *dynamical evolution* of their kinematics (via dispersion growth). The hypothesis for this project is that tidal tails gain internal velocity spread after the first encounter as a result of repeated gravitational interactions. This prediction is motivated by the expectation that repeated gravitational encounters and tidal stripping events will dynamically heat the outer regions of each galaxy's disk. As stars are pulled into tidal tails, they become more susceptible to gravitational forces that are not only from the interaction with the companion galaxy, but also from the evolving potential of the system as a whole. Unlike the inner disk, where stars follow relatively ordered, circular orbits, stars in the tails are no longer bound in a coherent structure and are more likely to exhibit random motion. This should manifest itself as an increase in velocity dispersion.

## 4 RESULTS

The first heatmap visualizes the distribution of disk stars in the Milky Way based on their radial distance (R, in kpc) and angular position ($\theta$, in degrees) at simulation snapshot 350. The color scale represents the number density of stars on a logarithmic scale, with darker shades indicating higher densities. Most stars are concentrated at radii less than 15 kpc, with a fairly symmetric spread in $\theta$. The low-density regions at large radii beyond $\tilde{3}$0 kpc represent potential tidal features, including stars that have been ejected or disrupted during the merger. The main takeaway is that while the Milky Way disk remains mostly intact at this stage, there is visual evidence of low-density stellar material extending to large radii. This is consistent with the early formation of tidal tails. The second heatmap visualizes the distribution of disk stars in M31 based on their radial distance (R, in kpc) and angular position ($\theta$, in degrees) at simulation snapshot 350. The color scale represents the number density of stars on a logarithmic scale, with darker shades indicating higher densities. Most stars are concentrated at radii less than 20 kpc, with a fairly symmetric spread in $\theta$. The low-density regions at large radii beyond $\tilde{5}$0 kpc represent potential tidal features, including stars that have been ejected or disrupted during the galactic interaction. The main takeaway is that the M31 disk remains somewhat intact at this stage, but its extent is less so than that of the Milky Way. It has a thicker radius, but there is more visual evidence of low-density stellar material extending to large radii, out past 50 kpc. This is consistent with the early formation of tidal tails. The plotted figure shows the time evolution of the velocity dispersion of tidal tail stars for both the Milky Way (red line) and M31 (blue line) from shortly before to after their first encounter, over a time span of roughly 3.5 to 5 Gyr. The y-axis shows the velocity dispersion in km/s, and the x-axis shows time in gigayears (Gyr). The dispersion values were computed based on stars identified as part of the tidal tails via phase space analysis. The plot highlights a pronounced spike in velocity dispersion for M31 near 4.20 Gyr, going from around 15 km/s to around 60 km/s. This suggests a strong dynamical response to the first passage in the merger. The Milky Way's disk particles show more fluctuations in the plot's time frame, with increases in dispersion being observed between the time frames of 3.50 Gyr to 3.80 Gyr, 4.00 Gyr to 4.30 Gyr, and 4.40 Gyr to 4.70 Gyr. Decreases in dispersion were observed as well, from the time frames of 3.80 Gyr to 4.00 Gyr, 4.30 Gyr to 4.40 Gyr, and a slight decrease from 4.70 Gyr to 4.80 Gyr. At the 5.00 Gyr mark, both galaxies' disk particles appear to have the same velocity dispersion. The main takeaway is that the tidal tail particles from M31 experience a sharper increase in velocity dispersion during the first encounter, indicating a more violent disruption compared to the Milky Way disk.

## 5 DISCUSSION

The results from the velocity dispersion plot show that after the first encounter between the Milky Way and M31, the tidal tails of both galaxies experience a noticeable increase in internal velocity dispersion. In particular, M31 exhibits a sharp rise in velocity dispersion around 4.20 Gyr, peaking significantly before a slight decline, while the Milky Way shows a more moderate but consistent elevation in dispersion during the same time frame. This trend supports the original hypothesis: repeated gravitational interactions and tidal forces during and after the first encounter dynamically heat the outer stellar populations, leading to a loss of ordered motion and an increase in random stellar velocities. The observed rise in dispersion is consistent with the expectation that stars pulled into tidal tails increase in

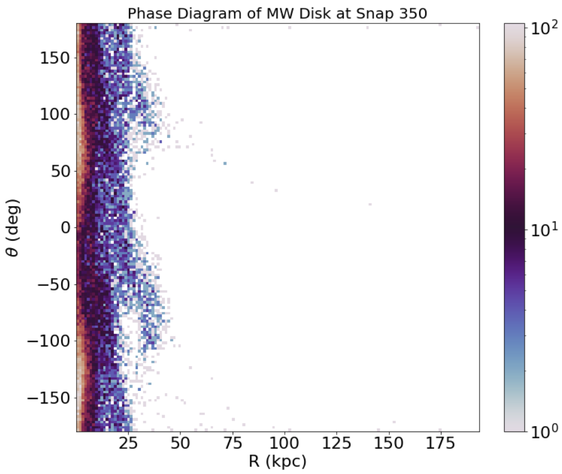


**Figure 3.** Distribution of disk stars in the Milky Way based on their radial distance (R, in kpc) and angular position ($\theta$, in degrees) at simulation snapshot 350. The color scale represents the number density of stars on a logarithmic scale. Note that while the Milky Way disk remains mostly intact at this stage, there is visual evidence of low-density stellar material extending to large radii—consistent with the formation of tidal tails.

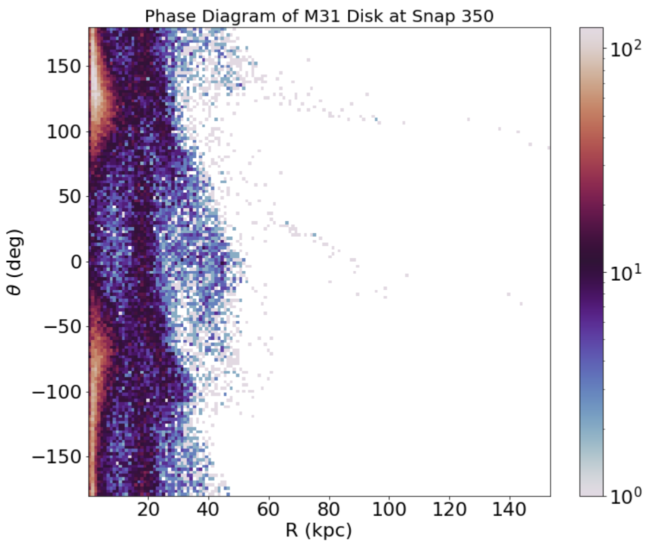


**Figure 4.** Distribution of disk stars in M31 based on their radial distance (R, in kpc) and angular position ($\theta$, in degrees) at simulation snapshot 350. The color scale represents the number density of stars on a logarithmic scale. Note that the M31 disk remains mostly intact at this stage, but there is visual evidence of low-density stellar material extending to large radii—consistent with the formation of tidal tails.

kinematic disorder over time as the system evolves, confirming the idea that tidal tails are dynamically heated structures formed through repeated gravitational disturbances during a major merger. The observed increase in velocity dispersion of tidal tail stars following the first encounter is consistent with prior theoretical and simulation-based studies on galactic interactions. As described by Mihos (2004), tidal forces during close passages of galaxies inject energy into the disk, stretching material into tails and bridges. The results support

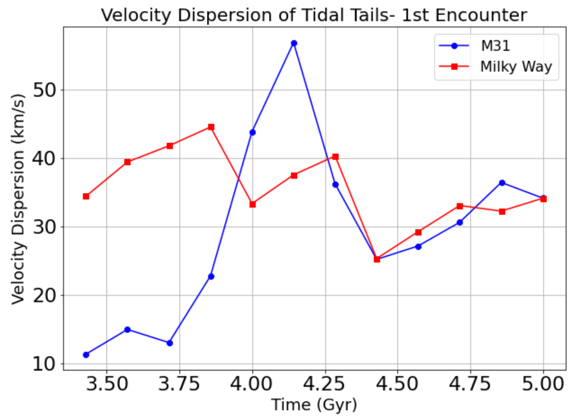


**Figure 5.** Time evolution of the velocity dispersion of tidal tail stars for both the Milky Way (red line) and M31 (blue line) from shortly before to after their first encounter. The y-axis shows the velocity dispersion in km/s, and the x-axis shows time in gigayears (Gyr). M31's tidal tail particles experience a sharp increase in velocity dispersion during the first encounter, going from 15 km/s to 55 km/s, indicating a more violent disruption compared to the Milky Way disk particles.

this, showing that stretching is accompanied by dynamical heating, as measured by a rise in velocity dispersion. Furthermore, the results resonate with the foundational work of Toomre & Toomre (1972), which established that the outer disk is most susceptible to tidal deformation during prograde encounters—precisely where dynamically hot tidal features are expected to form. Importantly, our findings also reinforce the critique raised by Privon et al. (2013), where test-particle simulations failed to capture realistic kinematics due to the omission of velocity dispersion. The use of particle-tracked velocity dispersion illustrates the physical process that Privon et al. (2013) stated must be included for more accurate modeling. This result deepens the understanding of galaxy evolution by emphasizing that tidal tails are not just morphological features, but dynamically complex structures that have evolving internal kinematics as a consequence of repeated gravitational interactions. Recognizing this helps constrain models of stellar redistribution and star formation in merger remnants, contributing to a more complete picture of how large-scale structures form in the universe. There are several sources of uncertainty in this analysis. One uncertainty arises from the identification of tidal tails by visual inspection of 2D histograms and phase diagrams. Since this step is subjective, it introduces the possibility of inconsistent or biased particle selection across snapshots, in that what may actually be a disk particle is missed due to its location on the phase diagram. In addition, identifying outliers in phase space is dependent on the definition that is set in place of what constitutes a significant deviation from the rotation curve. Thresholds will vary across snapshots due to the evolving structure of the disks. Temporal resolution of the simulation is another factor; if the time between snapshots is too large, dynamical events that are differential but still contribute to changes in velocity dispersion will be missed or undersampled. Since the data was collected and graphed over intervals of 10 snapshots, the dispersion values themselves may be sensitive to contamination from disk particles that were not fully stripped, especially if the number of particles in the tidal tails is small. Lastly, some velocity measurements may include contributions from bulk motions rather than internal dispersion, which can artificially inflate the measured values. These uncertainties highlight the importance of refining selection criteria and implementing automated or statistical methods to improve robustness of models.

## 6 CONCLUSION

Velocity dispersion of tidal tails refers to the spread in velocities among stars in structures formed from major merger events. It is significant as a key indicator of gravitational disruption in galactic interactions. N-body simulations were used to model the gravitational interactions between particles and calculate the velocity dispersion within the tidal tails. Using these simulations, the formation and evolution of tidal tails during the first encounter of the Milky Way–M31 merger can be studied, and their velocity dispersion can be calculated. One key finding from the analysis is the sharp increase in velocity dispersion observed in M31's tidal tail stars shortly after the first encounter, peaking around 4.20 Gyr into the simulation. This result supports the original hypothesis that repeated gravitational interactions during a major merger dynamically heat the outer disk, leading to increased random motions among stars that are stripped into the tails. The rise in dispersion confirms that tidal tails evolve not only morphologically but also kinematically. This finding reinforces the idea that velocity dispersion can serve as a tool for identifying and characterizing tidal features in both simulations and observations. Future work could involve automating the identification of tidal tail particles using machine learning or clustering algorithms to reduce subjectivity and increase consistency across snapshots. Additionally, incorporating gas dynamics and star formation into the simulation would provide a more complete picture, as current N-body methods omit hydrodynamic forces and feedback processes. Improvements can also be made by accounting for the COM motion and correcting for projection effects to better isolate internal dispersion from bulk motion. Expanding the analysis to include later merger stages would help track whether the velocity dispersion continues to evolve or stabilizes, offering further insights into how long tidal tails remain dynamically distinct features in a merger remnant.

## 7 ACKNOWLEDGEMENTS

For this project, Van Rossum & Drake (2009) was the programming language used to compute the velocity dispersion over the merger. Within the program, the numpy Harris et al. (2020) and matplotlib Hunter (2007) imports were used to run calculations and make plots. ChatGPT OpenAI (2024) was used to generate examples of improved readability within in-line comments and function docstrings, and some of these improved comments were implemented within the program. The author would like to thank Himansh Rathore for providing insights as to the method of the program from the in-class coding hack days. The author would like to extend thanks to her life partner, Roswell Roberts IV, for his assistance in debugging the program and for overall support of the author throughout the project. *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.*

## REFERENCES

Harris C. R., et al., 2020, Nature, 585, 357
Hunter J. D., 2007, Computing in Science & Engineering, 9, 90
Mihos J. C., 2004, Symposium - International Astronomical Union, 217, 390–399
OpenAI 2024, Code comments explanation, https://chatgpt.com/share/6816ad28-1024-8000-80e7-68afa5762da3
Privon G. C., Barnes J. E., Evans A. S., Hibbard J. E., Yun M. S., Mazzarella J. M., Armus L., Surace J., 2013, The Astrophysical Journal, 771, 120
Toomre A., Toomre J., 1972, The Astrophysical Journal, 178, 623
Van Rossum G., Drake F. L., 2009, Python 3 Reference Manual. CreateSpace, Scotts Valley, CA

This paper has been typeset from a TEX/LATEX file prepared by the author.