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On a Downward Spiral: Understanding the Morphological Changes of M33 Under the Tidal Influence of M31*

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ABSTRACT

Spiral arms have been observed to be induced by tidal interactions between galaxies, particularly in the case of M31 and M33 in the Local Group. The tidally induced spiral arms of M33 are an important topic of research because their proximity to our galaxy is convenient for us to observe and build upon our theory of galaxy evolution and galactic morphological changes. Our project uses N-body simulations to track the evolution of spiral arms in M33 to see when the spiral arms first sprang up and how long they would last as M33 orbits M31. These details will allow us to construct a complete evolutionary picture of how M33's spiral arms developed. We find that our simulated M33 begins to show traces of spiral arm structures when it reaches pericenter at around 4.29 Gyr, and these structures slightly subside at apocenters but become prominent again at the next pericenters. This suggests a strong correlation between the magnitude of the tidal force (which is inversely proportional to the cube of distance) and the formation and stability of spiral arms.

Keywords: Local Group — Spiral Galaxy — Satellite Galaxy — Tidal Stripping/Sharing — Galaxy Interaction

1. INTRODUCTION

The Local Group is a group of galaxies of which the three largest members in terms of extension are M31 (also known as the Andromeda Galaxy), the Milky Way, and M33 (also known as the Triangulum Galaxy), respectively. All three have been confirmed to be spiral galaxies because they exhibit structures consisting of stars, gas and dust, and extending from the galaxy's center to the flat, rotating disk. M33, in particular, is also believed to be a satellite galaxy of M31 because it orbits the much more massive M31 on gravitationally bound orbits; however, details are not clear regarding the history of their interaction (van der Marel et al. 2012; Tepper-García et al. 2020). By interaction, we are referring to the gravitational effects that galaxies can have on one another due to their proximity, including tidal effects wherein a galaxy's material is pulled towards or away from the other galaxy due to the other galaxy's tidal forces.

The topic of galaxy interaction is currently a focus in astronomical research as it offers insights into galaxy evolution. For the term "galaxy" itself, we are adopting the definition by Willman & Strader (2012) wherein a galaxy is a gravitationally bound system of stars "whose properties cannot be explained by a combination of baryons and Newton's laws of gravity" (Willman & Strader 2012). With this definition in mind, we also define galaxy evolution to be the changes of these bound systems of stars over time, not just in their kinematics and stellar components but also in their size and their morphology, most notably the formation of spiral arms like those in the Local Group. If a connection is found between the evolution of a Local Group galaxy like M33 and its interactions with its neighbors, we will be able to construct a vivid picture of the Local Group's history, where the shapes that we observe today can be traced back to distant points in time where processes inside and between galaxies triggered changes in their morphology.

There are works in the current literature which demonstrate that morphological structures like spiral arms can be induced by tidal interactions between galaxies. Hydrodynamic simulations of the grand spiral galaxy M51 by Dobbs

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et al. (2010) have shown that M51's spiral arms are most realistically the result of tidally-induced kinematic density waves that wind up over time. Other N-body simulations by Semczuk et al. (2017) found that when a Milky Way-like galaxy orbits a Virgo-like cluster, that galaxy can develop two temporary spiral arms during pericenter passages, as seen in Fig. 1. While M33 does not possess well-defined grand design spirals like M51 and is not similar in size to the Milky Way, it has been observed to possess a two-armed spiral structure. Semczuk et al. (2018) has shown from their simulations of the Local Group that these arms of M33 were mostly likely excited by tides from its host galaxy, M31.

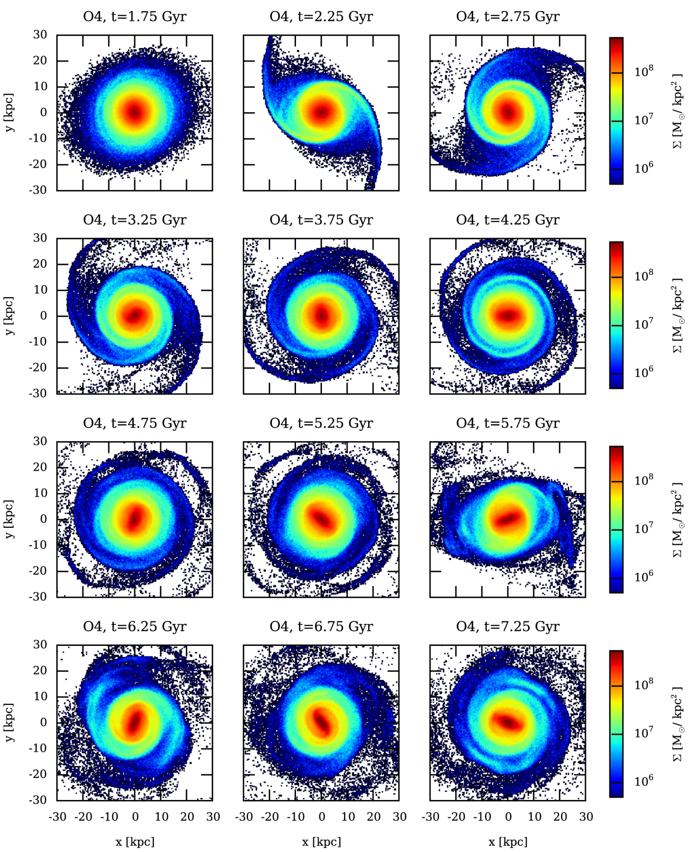


Figure 1: Face-on view of the surface density distribution of stars in the Milky Way-like galaxy from Semczuk et al. (2017), showing two distinct spiral arms.

As of today, the process through which the two-armed spiral structure of M33 was induced by tides from M31 has not been fully understood. Using N-body simulations that took into account star formation, feedback and cooling processes, Semczuk et al. (2018) noted that a pericenter passage of M33 near M31 could induce spiral arms and tidal distortion features in the gaseous and stellar disks that lasted 0.75 Gyr after M33 left the pericenter. This result does confirm what simulations of galaxies more massive than M33 have shown, which is that spiral arms could be induced during pericenter passages. However, it is unclear as to what happens after M33's pericenter passage, or even after the period of 0.75 Gyr that Semczuk et al. (2018) mentioned. Do M33's spiral arms gradually dissipate until the next pericenter massage, where the galaxy is once again spiralized? Such re-spiralizations have been observed by Dobbs et al. (2010) in simulated Milky Way-mass galaxies, but have yet been focused upon in the current literature on M33.

2. THIS PROJECT

In this project, we will focus only on the evolution of M33's spiral structures. We aim to track changes in M33's morphology at the same time as its distance with regards to M31, which, according to our expectations, will be tidally interacting with M33.

The goal of the project, as evidenced from the previous paragraph, will be to fill in the gaps in our understanding of what happens to M33's tidally induced spiral arms over time. Do they dissipate as M33 gets further, only to form again during the next pericenter passage? If they do dissipate, how long do they last in our simulations compared to the 0.75 Gyr noted by Semczuk et al. (2018)? On the other hand, if they do not dissipate, how are the spiral arms retained as M33 gets further away, thus experiencing less tidal force from M31 because the tidal force is inversely proportional to the cube of the distance?

Our study, despite its limited focus only on M33's spiral arms, is expected to contribute to the understanding of galaxy evolution. With technological advances, from more detailed simulations to the proposed launch of the Nancy Grace Roman Space Telescope in 2027, astronomers will be able to observe more galaxies with various morphological structures. Being able to retrace such structures to the history of the Local Group not only improves our understanding of our own cosmic neighborhood, but also provides the theoretical and empirical basis to reconstruct the history of the more distant systems that we will come across with more cutting-edge equipment.

3. METHODOLOGY

For the project, we will be using a set of models of the Local Group from van der Marel et al. (2012). The models are "N-body simulations", meaning that they simulate the behavior of a dynamical system of N particles as these particles interact amongst themselves gravitationally. In our simulations, the motions of M31, M33 and the Milky Way will be tracked over all snapshots across time.

Motivated by such results as those of Dobbs et al. (2010) and Semczuk et al. (2018), we aim to study the morphology of M33 during and after its pericenter passage with respect to M31. This morphology will be examined visually by plotting the distribution of the stellar particles in cylindrical coordinates and then using density contours to delineate any possible structures like spiral arms. An example of a density contour plot of M33 in our simulations, albeit in x-y coordinates, can be found as Fig. 2. Our goal is that by keeping track of this stellar particle distribution at different pericenters and apocenters along M33's orbit around M31, we will be able to make inferences regarding how the galaxy's structures appear and disappear as it goes around M31.

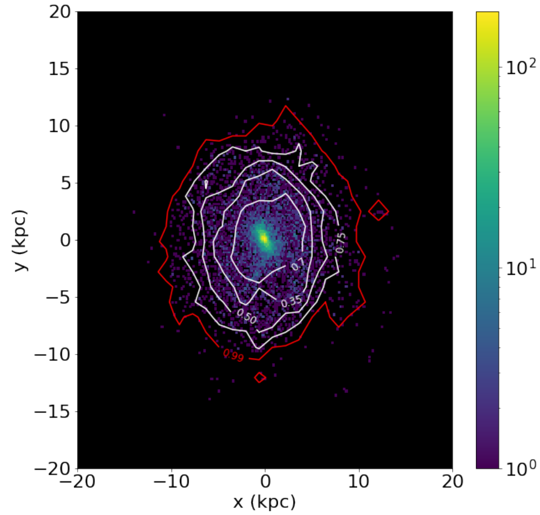


Figure 2: Plot of M33 in x-y coordinates, including density contours. The numbers next to the contour lines show the ratio of the star's mass that is enclosed by each line.

To locate the pericenters and apocenters of M33's orbit, we first compute the center of mass (COM) of both M33 and M31 in the x, y and z directions at each snapshot. This COM can be computed as:

$$x_{COM} = \frac{\sum x_i m_i}{\sum x_i} \tag{1}$$

where x_i is the distance of a particle within the disk of each galaxy as measured in the x, y and z direction from the center of said galaxy, and m_i is the mass of said disk particle. Both x_i and m_i have been provided in the simulations' output data files. With the COMs of both galaxies calculated, we subtract the position of M31's COM by the position of M33's COM for each snapshot to obtain the separation of the two galaxies. We plot all the separations with respect to time, then locate the pericenters and apocenters during successive intervals of time. It is the snapshots at these pericenters and apocenters that we will use to compute the stellar particle distribution in M33.

Next, we reuse the COM calculations to correct the disk particle vector measurements in both galaxies. With the vector measurements corrected, we rotate them such that the disk angular momentum is aligned with the z axis. We then convert the x and y coordinates of the stellar particles' locations into cylindrical coordinates r and θ.

In the end, we should be expecting at least two types of plot. The first plot shows M33's separation from M31 with respect to time, and also marks the pericenters and apocenters that we have chosen to analyze. This plot is to help visualize where all the points are along M33's orbit, which will facilitate the analysis of M33's shape at said point. The second plot, or type of plot, is the stellar particle distribution of M33 at each of the pericenters and apocenters in cylindrical coordinates. To avoid potentially analyzing particles that belong in irrelevant outer region structures like tidal tails, we focus only on the stellar particles within the inner regions limited by r = 15 kpc. Having limited the range of the distribution plots, we apply density contours in search of any galactic structures.

Generally, we expect to find traces of spiral arms at the pericenter, just like Dobbs et al. (2010) and Semczuk et al. (2018) have noted in their simulations. These traces will not look as distinct as M33 gets further away from M31, because the tidal force will then be reduced gradually and have less effect on M33, thus destabilizing the tidally induced spiral structure. By the time M33 is at apocenter, we expect there to be little to no sign of spiral arm densities on the stellar particle distribution plot.

4. RESULTS

The plot of M33's separation from M31 with respect to time is provided as Fig. 3. We see from the figure that M33 is slowly falling into M31, with each of its apocenters getting closer to M31 than the preceding apocenter, and the same goes for pericenters. There are in total 6 apocenters and 6 pericenters up until the last snapshot available.

Fig. 4 shows the stellar particle distribution of M33 at the pericenters and apocenters marked in Fig. 3. We see that at the first pericenter at 0.86 Gyr (Fig. 4a) and first apocenter at 2.71 Gyr (Fig. 4b), there does not appear to be any peculiar structure of stellar particle concentration. However, at pericenter 2 at 4.29 Gyr (Fig. 4c), we begin to see the density contours mark out a horn-shaped region of high density in the middle of the stellar particle distribution, which confirms the existence of spiral arm structures. This horn shape slightly flattens at the next apocenter (Fig. 4d), but juts out again at the pericenter after that. This behavior repeats over the next pericenters and apocenters, but is not shown in the last pericenter and apocenter after 10.2 kpc because the snapshots in this region have centering issues. While it is possible to fix the centering and obtain results for the last pericenter and apocenter, we have decided not to do so due to the limited scope of the project.

5. DISCUSSION

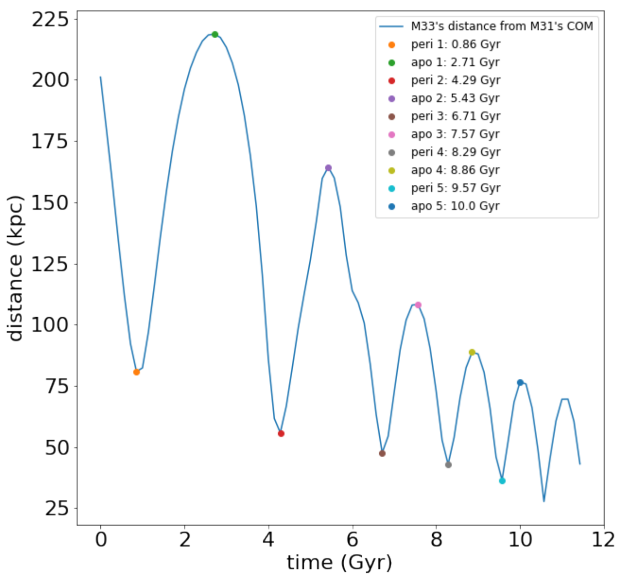


Figure 3: M33's distance from M31 in kpc with respect to time in years. The dots represent the pericenters and apocenters at which the analysis is doable. The last pericenter and apocenter (those after 10.2 Gyr) cannot be analyzed with precision due to a centering issue in the snapshots.

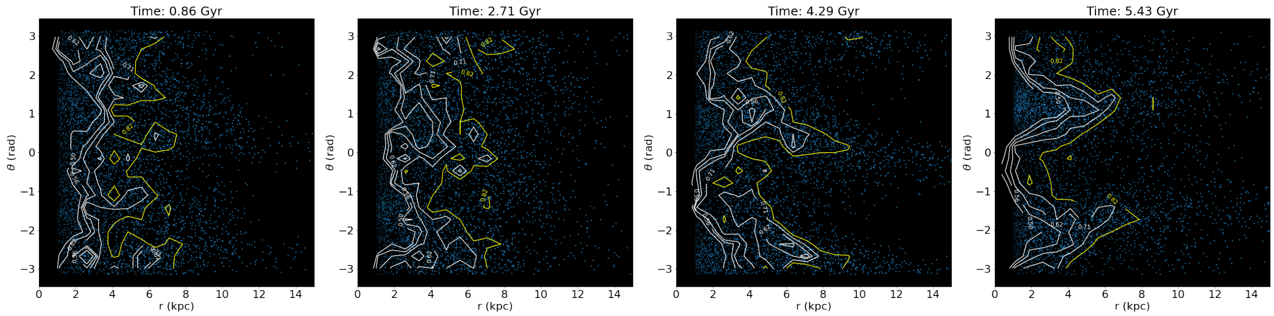
Our results agree with our initial hypothesis that spiral arm structures would form as M33 approaches pericenter. This is the same result that Semczuk et al. (2018) have found. In the broader context of galaxy evolution, this similarity of results strengthens the idea that galactic tidal interactions can induce spiral arms. Additionally, we also note that these signs of spiral arms persist–albeit not as prominently–as M33 leaves the pericenter and reaches the apocenter. If we assume the time of each apocenter to be the time at which each appearance of spiral arm structures disappears, we can subtract this time by the time of the pericenter just before it (i.e. time of apocenter 2 subtracted by time of pericenter 2) to see how long the spiral arms last on average. Doing this calculation on all the points we have except pericenter 1 and apocenter 1 (because they are too early), we get an average of 0.75 Gyr for each spiral arm structure appearance, which is exactly the duration that Semczuk et al. (2018) noted from their simulations. In other words, not only does our analysis confirm the idea that galactic tidal interactions can induce spiral arms at pericenter, but it also independently confirms the duration of M33's tidally-induced spiral arms as noted in the previous literature.

There are some noticeable uncertainties in our analysis. Firstly, only pericenters and apocenters are picked along M33's orbit around M31, so the 0.75 Gyr duration of a spiral arm structure appearance is only a rough estimate based on simplified calculations that do not take into account all the non-pericenter, non-apocenter snapshots. Furthermore, due to centering issues with the snapshots after 10.2 Gyr, we are missing out on crucial information as to what becomes of the spiral arms in the present-day, when M33 has gotten very close to M31.

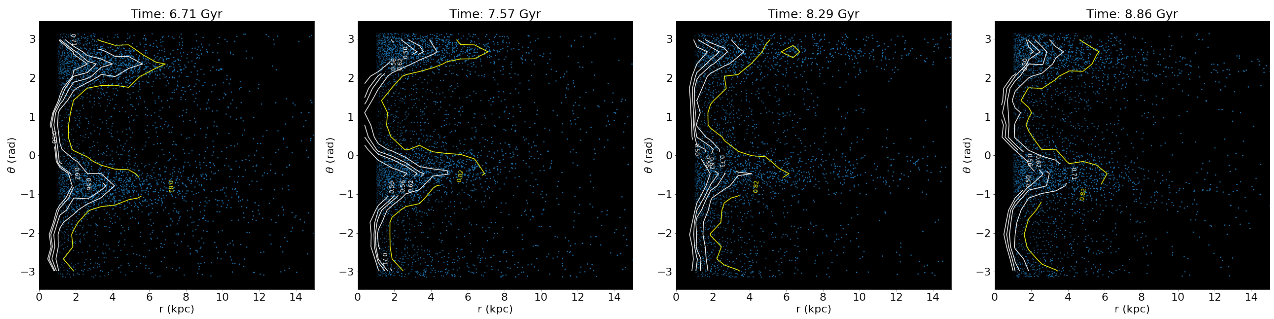
6. CONCLUSIONS

M33 is a satellite galaxy of M31 and is known to exhibit tidally induced spiral arms in simulations (Semczuk et al. 2018). Researching M33 thus provides us with an opportunity to understand how spiral arms evolved in the universe and whether tidal forces could influence this process.

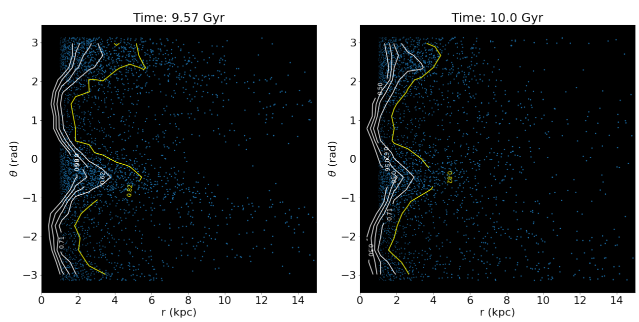
In our project, we discovered density regions of stellar particle distribution that flared up on both sides of M33 as it approached M31, which implies not only the formation of spiral arms, but also an influence by tidal force, which is inversely proportional to the cube of distance. This agrees with not only our hypothesis, but also studies in the current literature like that of Semczuk et al. (2018). We also found that the duration of each spiral arm, if taken to be the time between a pericenter and an apocenter, is on average 0.75 Gyr, which also matches the calculations by Semczuk et al. (2018). However, due to centering issues with the most recent snapshots, we are unable to tell what



(a) Pericenter 1 (0.86 Gyr) (b) Apocenter 1 (2.71 Gyr) (c) Pericenter 2 (4.29 Gyr) (d) Apocenter 2 (5.43 Gyr)



(e) Pericenter 3 (6.71 Gyr) (f) Apocenter 3 (7.57 Gyr) (g) Pericenter 4 (8.29 Gyr) (h) Apocenter 4 (8.86 Gyr)



(i) Pericenter 5 (9.57 Gyr) (j) Apocenter 5 (10.0 Gyr)

Figure 4: Stellar particle distribution of M33 at different snapshots with density contours added. The axes are in cylindrical coordinates: the horizontal axis is r, the magnitude of distance of each particle from M33, and the vertical axis is θ, representing the angle that the particle of distance r makes with the x-axis of the Cartesian coordinates. The contour lines have their own numbers indicating the ratio of number of particles enclosed by each line. We find that as M33 reaches pericenter on its orbit around M31, the stellar particle distribution condenses in a region in the middle of the plot that indicates spiral arm structures. This sign of spiral arm becomes less pronounced at apocenters, but is present nonetheless.

becomes of these spiral arms as M33 gets closer to M31 in the present day. As a result, more needs to be done to look into this stage in M33's morphological evolution.

In the future, we are hoping to fix the centering issues in some of the snapshots in order to track M33's spiral arm structures to the present day. Last but not least, we want to find distinct characteristics of spiral arm particle distributions to automate the code and reduce the human factor when we have to look at the stellar particle distributions and determine which contour lines we should fit onto them. We hope that by following these new suggestions, our analysis will become more thorough and bring us to a more in-depth understanding of how M33's spiral arms behave.

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