Draft version May 7, 2020
Typeset using LATEX default style in AASTeX63

Tidal Debris from M33: Stellar Streams of M33

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ABSTRACT

This paper studies the changes of MW and M33 systems and M31 and MW systems R_j during the collision of MW, M31, and M33. The change in R_j can help us know how many stars M33 has been ripped out into a star stream. This can help us understand how small-mass galaxies contribute to the halo of massive galaxies. It can also help us explain the formation of similar structures. We found that R_j is positively related to the centroid distance of each galaxy, but the change is not as dramatic as the centroid distance. The final of Simulation M33 lost around 90% of its mass and gradually disintegrated to form a sub-structure.

Keywords: Galaxies Interaction: Kinematics and Dynamics — Galaxies Merger: MW, M31 and M33 System — Merger Remnant — Jacobi Radius — Tidal Stripping/Sharing

1. INTRODUCTION

Our Milky Way (MW) is located in a small group of galaxies called the Local Group. The three most massive galaxies in LG are all spirals: MW, Andromeda Galaxy (M31), and Triangular Galaxy (M33). These three galaxies account for most of the mass of the local group, their mass ratio is about 10: 10: 1 (Guo et al. (2010)). Besides, the distances between M33 and M31 from the Milky Way are almost the same, with a difference of only 0.8 Mpc.

The orbits and interactions of the MW, M31, and M33 have been examined in several previous studies. van der Marel et al. (2012) indicates that the MW and M31 will merge at t = 5.87 Gyr. The most likely result is that MW and M31 merge first, and M33 evolves on a decaying orbit around the MW+M31 combined galaxy, and will eventually also merge. Before M31 reaches MW or collides with MW, M33 has a 9% probability of directly hitting MW at its first center point. In addition, the probability of M33 popping out of the local group temporarily or permanently is 7%.

In van der Marel et al. (2012)'s Monte Carlo simulation, at t = 10 Gyr, MW and M31 have been merged, and M33 has lost 23.5% of its star into a tidal stream. These streams do not lie along with the location of the orbit (Figure 1).

Before losing stars, more massive satellites sink deeper into the host's gravitational potential. Conversely, low-mass satellites have a longer survival time, but dynamical friction cannot drag them into the innermost area, and there is a significant separation (Amorisco (2017)). In the Monte Carlo simulation of the MW-M31-M33 merger, we can observe this process, and the tidal debris of M33 remains at large radii (Figure 1). In addition, he claims that the material deposited by low-mass satellites maintains a large number of low mass satellites continue to make multiple orbits about the host and that the radial velocity dispersion of tidal is also high due to the extension of the orbit.

Through tidal processing, the escaped ejecta in the leading (trailing) tail continues to be decelerated (accelerated) by the satellite 's gravity leading to large offsets of the ejecta orbits from the satellite 's original orbit (Choi et al. (2007)). And they discuss this process that this is related to the Hill-Jacobi theory, which is suitable for satellites in circular orbits. In particular, the impact of the satellite's self-gravity on the tail will only decrease slightly as the satellite's mass decreases. For satellites of limited mass, the morphology of the leading and tailing tails will be different due to gradient of the host's gravitational potential from one end of the satellite to the other.

The study of tidal debris from M33 in the merger of MW-M31-M33 allows us to understand how relatively small mass galaxies contribute to the stellar halo of massive galaxies and can be an example to help us understand the formation of similar structures in other galaxies. In addition, this study can also help us understand the evolution of substructures in the Milky Way, such as the formation of the leading and training arms of the Sagittarius Stream (Law & Majewski (2010)).

In this process, we can also understand the influence of the distribution of dark matter on the tidal debris distribution of M33, how the dark matter of M33 is incorporated into the MW-M31 system, and it affects the final stellar halo merger of MW and M31.

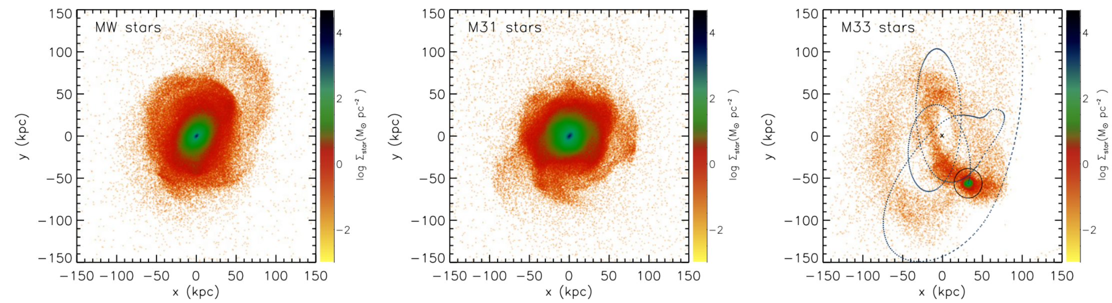

Figure 1. van der Marel et al. (2012)'s distribution of luminous particles at the end of the N-body simulation (t = 10 Gyr) for the canonical model with, from left to right, particles originating in the MW, M31, and M33. The color scale indicates the surface mass density. The MW and M31 have formed a merged remnant. However, the remnant is not yet fully relaxed, since particles originating from the two different galaxies still have a somewhat different spatial distribution. M33 maintains its own identity, but has lost 23.5% of its stars into tidal streams.

2. THIS PROJECT

In this article, we want to study how M33 formed a star stream and influenced the merger process during the merger of M31 and MW. This includes how the Jacobi Radius of M33 changed during the merger of M31 and MW, and how many stars of M33 were torn apart, and how the mass-loss rate changed over time.

This project can help us understand how relatively small mass galaxies contribute to the stellar halo of massive galaxies and how substructures in galaxies have evolved.

If we know how the Jacobi Radius of M33 changes during the galaxy merger, this can better help us know the process of formation of the stellar stream. We can combine the loss of M33 mass with time to help us understand the history of galaxy halo formation. In addition, by comparing the M33 stars velocity dispersion profile and merged remnant, it helps us understand the dynamics of the substructure.

3. METHODOLOGY

An N-body simulation is a simulation of a dynamical system of particles, usually under the influence of physical forces, such as gravity. In this project, we treat each star as a particle and study the gravitational force received by each star in the MW-MW-M33 system and how it moves under the influence of force (van der Marel et al. (2012)).

The Jacobi Radius for a satellite on a circular orbit about an extended host, where the host is assumed to be well modeled as an isothermal sphere halo:

$$R_j = r\left(\frac{M_{sat}}{2M_{host}(<r)}\right)^{1/3} \tag{1}$$

R_j is Jacobi Radius, M_{sat} is the satellite mass, in this project, the M_{sat} is the total mass of stars within the previous snap R_j. r is the distance between satellite and host galaxy. $M_{host}(<r)$ is total mass of host galaxy stars within the r.

In this project, we need to calculate the Jacobi Radius of M33 under the influence of M33 and M31 at each time in N-body simulation, and then pick out the stars of M33 outside Jacobi Radius. These stars are the members of the star stream. The first figure is the change chart of Jacobi Radius of M33, including M33 under the influence of M31, M33 under the influence of MW. The second graph is the change of the mass loss of M33 with time. The loss of mass should be inversely related to R_j. When R_j is larger, the loss is smaller. When R_j is gradually smaller, the loss will be more and more, which means that more stars are torn from M33. The third picture is the relative distance change of M33, M31 and MW center of mass position. Through this picture we can judge when these three systems start to

Figure 2. This picture describes the logic of the entire project, the most important thing is to calculate Jacobi Radius. Based on each time Jacobi Radius selects the stars that become streams' star and calculates the mass-loss rate function.

collide. In addition, I also intend to make a picture of the spatial position of the center of mass of these three galaxies moving with time. This picture allows us to see the fusion process more clearly. The last picture is the space position map of M33's detached stars. We can choose a few different times to see how these torn stars change.

I think that as the two galaxies get closer, their R_j will become smaller and smaller. As can be seen from Equation 1, R_j is inversely proportional to the distance, and distance dominates the influence. Also, if R_j is made smaller, more and more mass will be lost, and more stars belonging to M33 will be outside R_j.

4. RESULTS

When the time starts, the R_j of M31 and M33 gradually decreases, and when the time is about 1.5 Gyr, it gradually increases again. This is most likely due to a collision between M31 and M33, and then they bounced off again. Before 3 Gyr, the R_j of MW and M33 became smaller and smaller, but after 3 Gyr became larger temporarily, it was also possible that a collision occurred and then bounced off. After 3 Gyr, R_j oscillates periodically, but the general trend is to gradually decrease. This also reflects the gradual collision and fusion of M33 and MW and M31. Around 8 Gyr, the R_j of the M33 and MW systems and the M33 and M31 systems decrease sharply at the same time, and then the rebound increases. It is very likely that during this period the three galaxies had a violent collision at the same time. (Fig. 3)

When the time starts, the mass loss of MW and M33 systems is gradually increasing, especially after 1.5 Gyr, the mass loss of M33 is growing very quickly. And at this time, the mass loss of the M31 and M33 systems suddenly had a peak. Combining with Fig. 3, I think that M31 and M33 collided and R_j suddenly became smaller, and then the combination of M33 and M31 accelerated closer to MW to cause the MW and M33 systems The mass loss growth suddenly accelerated. Also, at 8 Gyr, the mass losses of the MW and M33 systems and the MW and M31 systems are very close to 1, which means that the collision of these three galaxies is likely to crash M33. R_j is very small, almost all the stars belonging to M33 are outside R_j. (Fig.4)

In this figure, we can also see that when R_j becomes smaller, the mass loss becomes larger because more stars are belonging to M33 outside R_j. Similarly, when R_j becomes larger, the mass loss becomes smaller. At the end of the evolutionary process, the mass loss is stable at around 0.9, which means that at the end of the galaxy collision, M33 may be torn out 90% and become a star stream, and only 10% belong to it.

At the beginning of the simulation, the centroid positions of M31 and M33 are very close to MW and M33, only about 200kpc. At about 1.5 Gyr, the distance between M31 and M33 is reduced to less than 100kpc, and they are likely to collide. And near the four Gyr, the MW and M33, MW and M31, and M31 and M33 centroid distances all suddenly dropped, which means they collided one after another during the fusion process. This trend of successive collisions did not stop until around 6 Gyr. The distance between MW and M31 becomes 0, they complete the merge, and the curves of the centroid distances of MW and M31 and MW and M33 overlap. In Fig.3 and Fig.4, the curves of MW and M31 and MW and M33 also overlap near 6 Gyr. It can also indicate that the merger of MW and M31 is

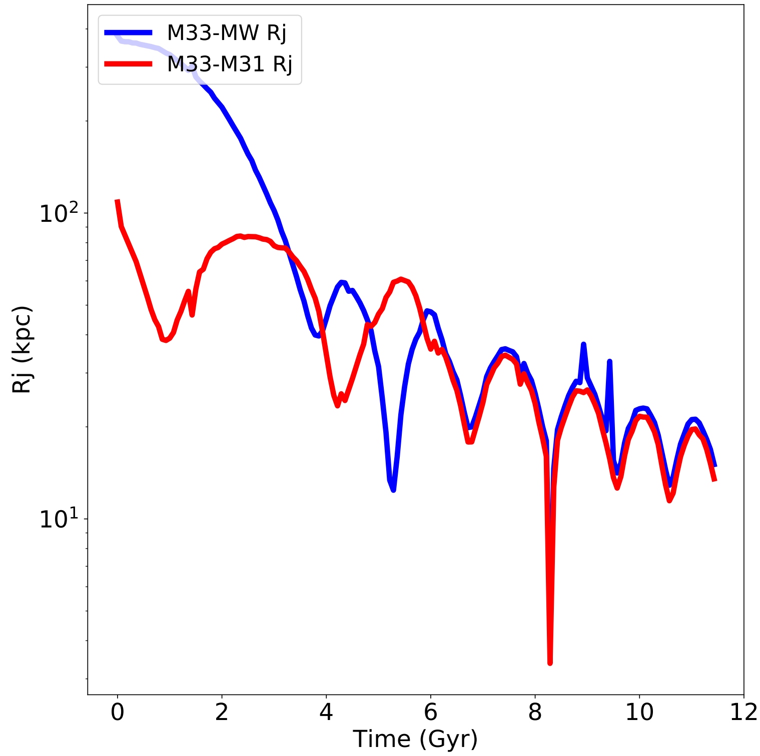

Figure 3. This figure is the R_j changing with time. The R_j of M33 MW system and M33 M31 system both gradually became oscillating and smaller.

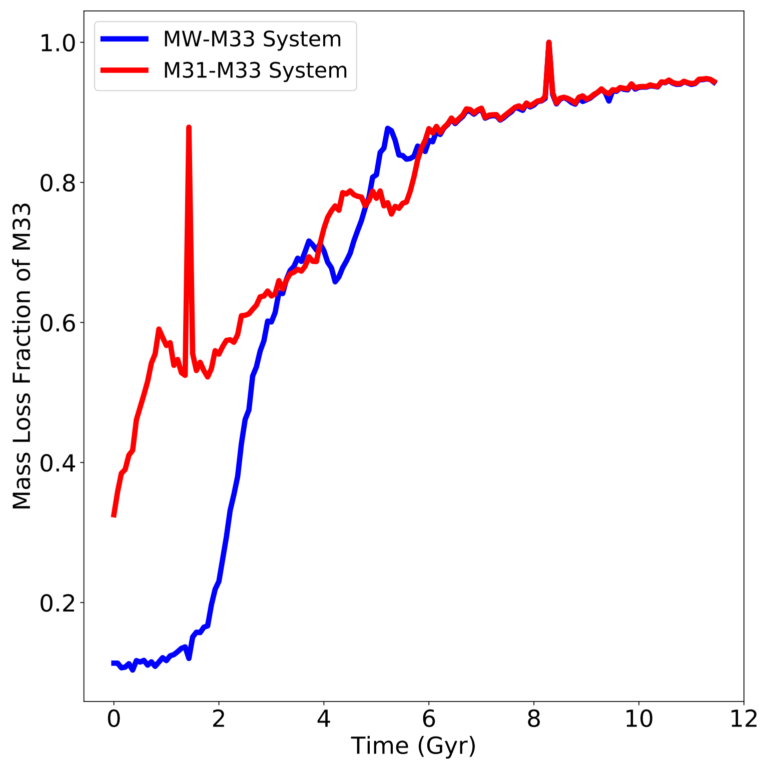

Figure 4. This figure is the Mass Loss fraction of M33 changing with time. The Mass Loss fraction of M33 in M33 MW system and M33 M31 system both gradually increasing.

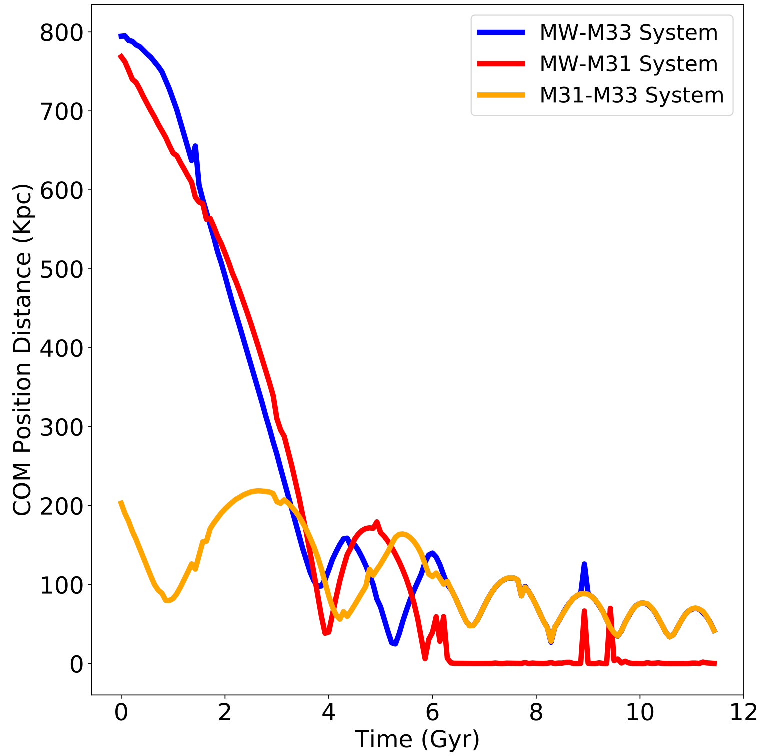

Figure 5. This picture is the center of mass position distance between MW and M31 system, MW and M33 system and M31 and M33 system.

completed. In addition, the position of the center of mass and R_j both tend to become smaller, and the position of the center of mass changes more drastically than the change of R_j. (Fig.5)

I also made a graph of the changes in the centroid positions of MW, M31, M33 in space. It can be seen that M33 is gradually spirally merged into the MW and M33 systems, with several collisions and bounce off trajectories. These trajectories can well explain the phenomenon that R_j becomes smaller and then becomes larger. It can also be seen in this figure that M33 and M31 have a very close center of mass (-200, 375, 0) shortly after the start of evolution. This should correspond to the fact that the collision between M33 and M31 near 1.5 Gyr caused a sudden drop in R_j. In this figure we can also see that the centroids of MW and M31 gradually merge and overlap. This can also explain the completion of the merger of MW and M31 after 6 Gyr. And we can also see that the center of mass of M33 rotates around the trajectory after the merger of MW and M31. Therefore, M33 is not fully incorporated, which can explain the oscillation of R_j at the end of evolution in Fig. 3.

The Fig. 6 is the spatial distribution of M33's star stream. I chose 6 times, namely 0 Gyr, 2.2 Gyr, 4.3 Gyr, 6.5 Gyr, 8.6 Gyr, 10.7 Gyr. At the beginning of evolution, there are relatively few member stars in M33, and there are not many stars at 2.2 Gyr. However, at 2.2 Gyr, the stream members of M33 became significantly denser, and there was a drift in position relative to 0 Gyr. This is most likely caused by the collision of M31 and M33 at 1.5 Gyr. When there were 4.3 Gyr, members of the M33 stream pulled out a certain structure. This is most likely caused by the collision of three galaxies near 4 Gyr. And with the extension of time, this structure was torn away and spread. It can be seen from Fig. 5 that after the merger of MW and M31, the trajectory of M33 revolves around MW and M31. In the process, M33 is constantly torn and the stars that are torn out are thrown away. This process is likely to cause the formation of this structure.

5. DISCUSSION

In this simulation, the change in R_j is consistent with the change in centroid distance, but the change in centroid is more dramatic than the change in R_j. This should be because R_j is related to the 1/3 power of mass. Moreover, the lost mass ratio of R_j and M33 is negatively correlated, because larger R_j means fewer stars belonging to M33 are outside R_j, and the lost mass is relatively smaller. This result is in line with expectations.

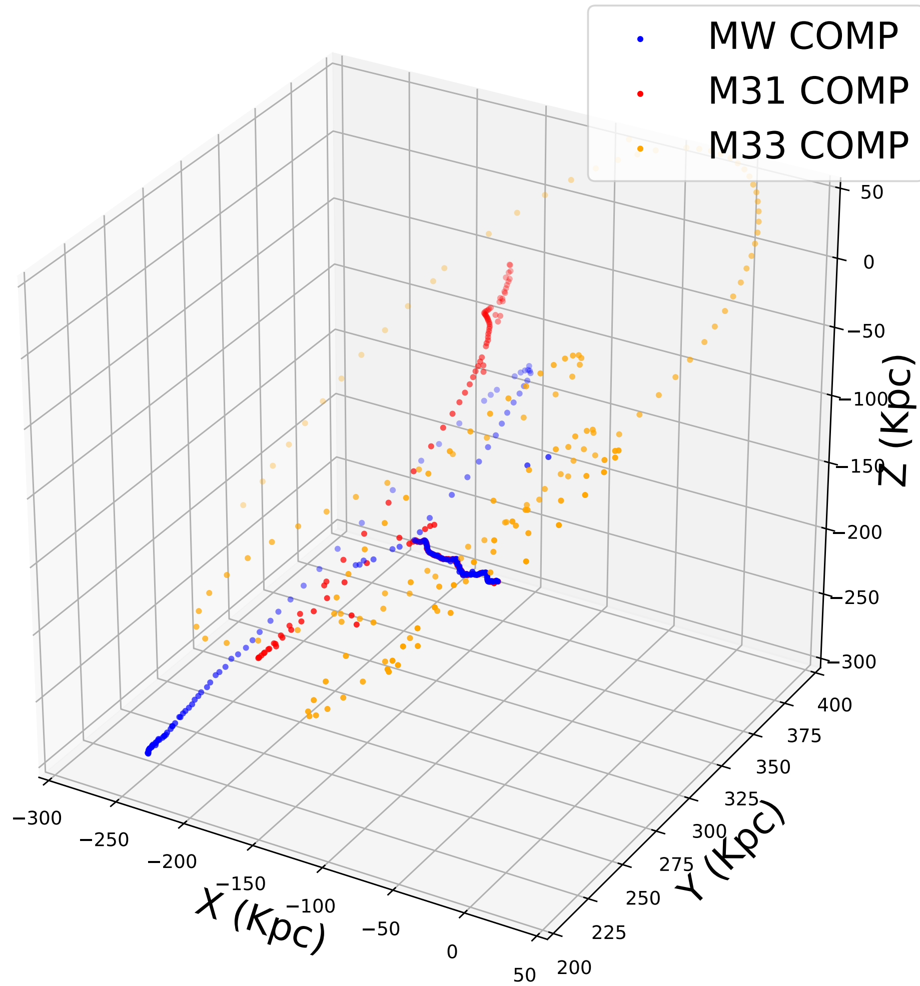

Figure 6. This figure is the center of mass position of MW, M31 and M33 moving in the space.

Through the change of R_j, we can also k that MW and M31 are merged around 6 Gyr. This result can also be seen from the mass loss ratio of M33, because of Fig. 3 and Fig. 4 mean that the blue lines of MW and M33 systems overlap with the red lines of M31 and M33 systems. Moreover, from Fig. 5 it can also be obtained that when more than 6 Gyr, the distance between the center of mass of MW and M31 becomes 0. This result is in line with 5.87 Gyr of van der Marel et al. (2012).

As can be seen from Fig. 4, the final mass loss of M33 is as high as 90%. This means that it is very likely that only 10% still belongs to M33 itself, and 90% of the parts belonging to M33 are thrown out. This situation is partially consistent with the Sagittarius star stream, but from Fig. 6 there is no structure similar to the leading and training arms of the Sagittarius star stream (Law & Majewski (2010)). This may be because the mass of M33 is much larger

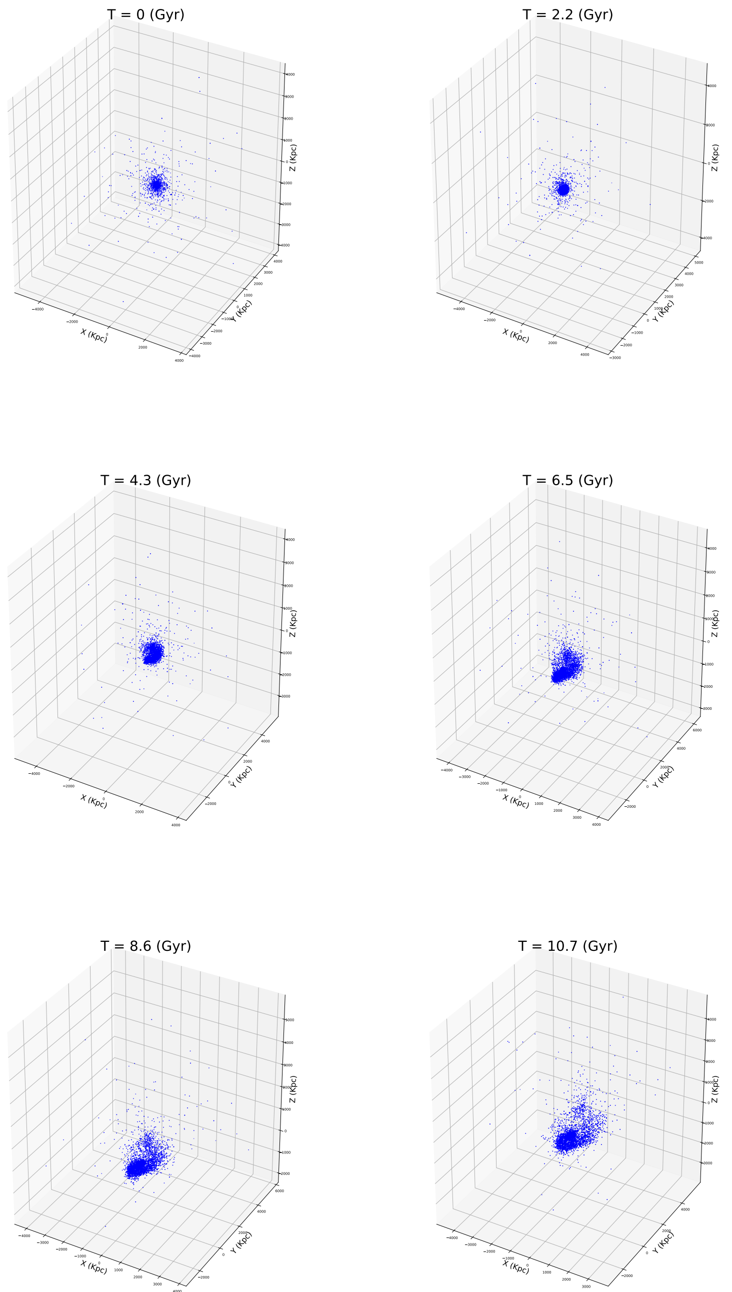

Figure 7. This figure is M33 stream position distribution at T = 0, 2.2, 4.3, 6.5, 8.6, 10.7 Gyr.

than the Sagittarius dwarf galaxy, and in the end of the simulation, M33 still rotates and merges around the center of mass after the merger of MW and M31, and has not been completely merged.

However, van der Marel et al. (2012) believes that simulation time near 10Gyr, M33 lost 23.5% of the stars, and these stars became its star stream. It can be seen from Fig. 4 that the mass loss of M33 has exceeded 80%. I suspect that it may be that the massive stars are thrown out but the lighter ones will merge back into the M33 system. These massive stars account for 23.5% of the stars but 80% of the mass. But this requires further study.

6. CONCLUSIONS

This paper studies the changes of MW and M33 systems and M31 and MW systems R_j during the collision of MW, M31, and M33. The change in R_j can help us know how many stars M33 has been ripped out into a star stream. This can help us understand how small-mass galaxies contribute to the halo of massive galaxies. It can also help us explain the formation of similar structures. This allows us to have a deeper understanding of the merger of galaxies and the formation of substructures.

In this simulation, we can get that R_j is positively related to the change of the center of mass of the galaxy, but the change is not as dramatic as the change of the center of mass of the galaxy. This is most likely because R_j is also related to the mass ratio. When a galaxy collides, R_j will decrease drastically, but after the collision, the galaxy will bounce off, R_j will increase, but it will continue to oscillating and decrease gradually. Moreover, the change of R_j is inversely related to the mass loss of the galaxy. When R_j decreases, there will be more stars outside the R_j in the galaxy, and the mass of the loss will be more, and vice versa.

After the merger of MW and M31, the trajectory of the center of mass of M33 still rotates around the common center of mass of MW and M31, collide and bounce off. This process will cause the M33 star to become a stellar stream and gradually diffuse, contributing to the formation and extension of the substructure. This also shows that gravity and collisions between galaxies can change the shape of substructures.

In further research, I can use the Hernquist profile instead of the isotropic model, so that I can get a more accurate R_j formula to calculate R_j. I can also count the number of lost stars and compare it with the result of van der Marel et al. (2012). Check if they are consistent.

7. ACKNOWLEDGEMENTS

1. Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018 doi: 10.3847/1538- 3881/aabc4f)
2. matplotlib Hunter (2007),DOI: 10.1109/MCSE.2007.55
3. numpy van der Walt et al. (2011), DOI : 10.1109/MCSE.2011.37
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