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Transformations of Internal Energy Budgets during the Formation of Major MW-M31 Merger Remnant Samyog

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ABSTRACT

We investigate the evolution of internal energy budgets of the dark matter halos in the initial three-galaxy system of Milky Way (MW), Andromeda galaxy (M31), and Triangulam galaxy (M33) during the formation of major MW-M31 merger remnant, Samyog. The exchange of energies within the system governs the structural evolution of the halos within the system. By looking at the evolution of the internal energy budgets and virial ratios of the halos, we investigate whether the halo of the major merger remnant Samyog is dominantly supported by velocity dispersion or rotation. We also investigate whether the M33 halo gains or loses energy during the formation of Samyog and how it changes its internal structure. Through this investigation, we get a better understanding of the evolution of halos of major merger remnant as well as the smaller satellite in a complex system of galaxies as the merger takes place. We found the final virial ratio of Samyog to be $\lambda_{vir} = 0.760$. This indicates that the major merger remnants like Samyog are dominantly dispersion supported in such complex systems after the mergers take place. We also found that M33 gains an abundance of energy such that its total energy becomes positive and its virial ratio becomes very small after the merger. This indicates that many dark matter particles are tidally stripped from the halos of small satellite galaxies like M33 in such complex systems as the mergers take place.

Keywords: Local Group; Galaxy Merger; Merger Remnant; Major Merger; Dark Matter Halo; Virial Equilibrium

1. INTRODUCTION

Milky Way (MW) along with its largest neighbour the Andromeda galaxy (M31) and a collection of the satellite galaxies that orbit them make up a group of galaxies called the Local Group. The largest of these satellite galaxies is the Triangulum galaxy (M33). According to van der Marel et al. (2012), the MW and M31 will merge at $t = 5.86^{+1.61}_{-0.13}$ Gyr from now. A galaxy merger happens when a system of interacting galaxies collide with each other. This system is defined to be merged once their nuclei have coalesced and there is only one central luminosity peak that remains. This merged system is known as merger remnant. When the interacting galaxy pairs have the luminosity ratio of $L_2/L_1 > 0.33$, the galaxy merger is known as major merger and the merger remnant is known as major merger remnant (Lambas et al. 2012). The MW-M31 merger is a major merger, and the major merger remnant of MW-M31 system is often called Milkomeda or Milkdromeda in popular sources. On the account of preserving the integrity of the originality in naming cosmological objects in the astronomy community, for the purposes of this paper, we name the major merger remnant of MW-M31 system as the Sanskrit word "Samyog", translating to English as "a merger" or "an union". Using the N-body simulation described in van der Marel et al. (2012), we propose to study the evolution of internal energy budgets in the system made of MW, M31, and M33 as the merger between MW and M31 takes place.

As defined in Willman & Strader (2012), "A galaxy is a gravitationally bound collection of stars whose prop-

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erties cannot be explained by a combination of baryons and Newton's laws of gravity". A Galaxy evolves over time through many ways, including the changes in its structure, gas mass, stellar mass, or color. However, a galaxy merger can speed this process of galaxy evolution many folds. The distribution of internal and orbital energy of the system can tell us a lot about the structure of individual galaxies as well as system as a whole. The spherical distribution of dark matter (DM) that surrounds the baryonic disk or spheroid of a galaxy is known as the dark matter halo, simply referred to as halo from now on. As the halos are the most massive components of galaxies, the exchange of energies is an excellent tracer of the evolution of the structures of halos. Thus, it is important to understand the evolution of various energy budgets of a DM halos in a system during a merger.

We currently have an understanding of the energy evolution of the halos in a system of two galaxies as they merge (e.g. Drakos et al. 2019a,b). The virial ratio of a galaxy is defined as,

$$\lambda_{vir} = -\frac{P}{2K}, \tag{1}$$

where P is the total internal potential energy and K is the total kinetic energy (Drakos et al. 2019a). When the virial ratio equals to 1, the galaxy is in virial equilibrium and is purely supported by velocity dispersion. Fig. 1, taken from Drakos et al. (2019a), shows the merger remnant of two equal mass galaxies that is dominantly supported by velocity dispersion.

For a system of two galaxies, the total energy of the two galaxies remains conserved as they merge into a single remnant as is obvious in the case of the simulation of two-galaxy system (Drakos et al. 2019a). However, we do not yet have a sound understanding of how the energy evolves in a more complex system containing more than two galaxies, which is the case in most galaxy mergers. As the given simulation contains a three-galaxy system, it is possible that the total energy of the MW and M31 may not remain conserved as there may be energy loss or gain from their interaction with M33. Understanding this interaction helps us understand the open problem of understanding galaxy mergers in systems with multiple galaxies. Furthermore, It is known that known halo shapes are mostly supported dominantly by anisotropic velocity dispersion as they rotate very slowly (Frenk & White 2012). However, do the halos of major merger remnants like Samyog also follow this theory? It is also unknown how the structure of small satellite galaxies change as the major merger occurs in the complex galaxy systems. Finding answers to these open questions is essential to further understand the galaxy evolution

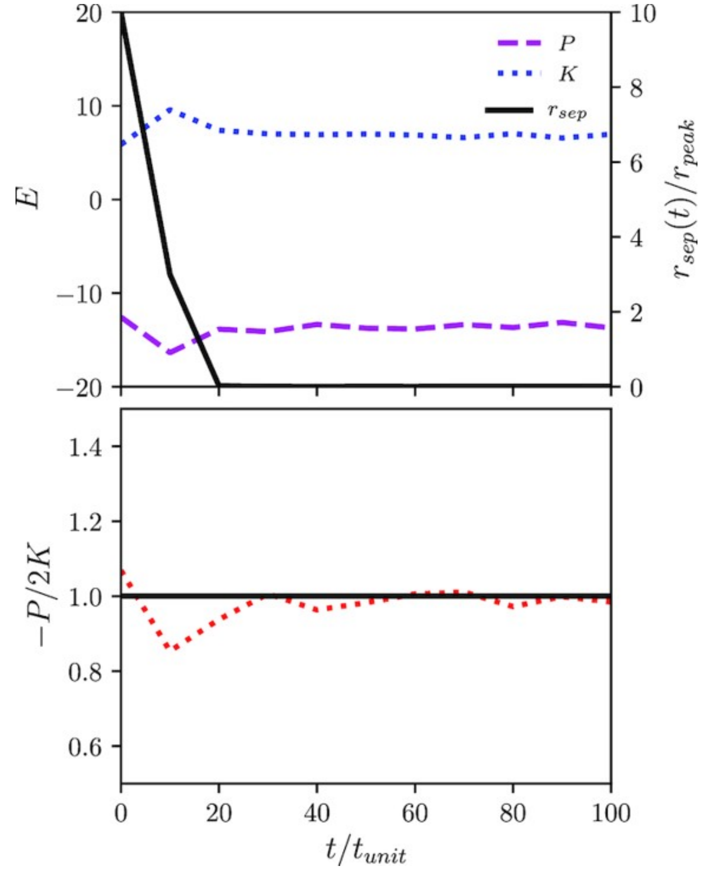

Figure 1. Energy evolution of the system of two halos of the same mass, merging together, as shown in Drakos et al. (2019a). The progenitor galaxies possessed the Einasto density profiles. As can be seen in the bottom panel, after the merger, virial ratio (dotted red line) of the merger halo is nearly equal to 1.

through mergers occurring within complex systems like our local group.

2. THIS PROJECT

In this paper, we propose to investigate whether the halo of major merger remnant Samyog is supported by rotation or velocity dispersion by looking at its virial ratio. We also look at the internal energy budgets of M33 as it evolves over time. For these purposes, we want to understand the distribution of internal energies of the three halos before the merger and compare them to the final distribution of internal energies of the halos of Samyog and M33.

This project addresses both the open questions mentioned in Section 1. We find out whether the halo of Samyog is dominantly dispersion supported or dominantly rotation supported. We also investigate whether the halo of M33 gains energy or looses energy and how that changes its internal structure in terms of it being more dispersion depended or more rotation depended as the merger takes place.

The information of whether the galaxy halo is dispersion supported or rotation supported corresponds to the internal structure, density profile, and shape of the galaxy (Drakos et al. 2019a,b). Thus, answering the proposed questions is something very important in understanding galaxy evolution through a major merger. This project addresses these questions by looking at the different internal energy budgets of all the separate halos at a given time. Using those internal energy budgets, we find the virial ratios for all the halos, which are the direct indicators of whether the halos are dominantly supported by dispersion or not.

3. METHODOLOGY

Based on the current observational data, the future interactions between MW and M31 galaxies have been studied broadly. One such study was carried out using a combination of collisionless N-body simulations and semi-analytic orbit integrations for the three-galaxy system of MW, M31, and M33 in van der Marel et al. (2012). Here, the N-body simulation means a dynamical simulation of system of many particles governed by the gravitational force. In this paper, we utilize this N-body simulation to investigate our questions.

To answer these questions, we calculate the internal energies of the various halos according to the flowchart shown in Fig. 2. We first calculate the internal energies of MW, M31, and M33 halos at given times before the merger occurs, i.e. at $t < 5.86$ Gyr (see van der Marel et al. 2012). After the merger, we calculate the internal energies of Samyog and M33 halos at given times. We then calculate the virial ratios of Samyog's halo, at given times to see how it evolves after its formation. We compare the virial ratios of MW and M33 halos at $t = 0$ Gyr with the virial ratio evolution of Samyog's halo to understand the halo structure of a galaxy major merger compared to its progenitors. Finally, we look at the evolution of M33 halo's virial ratio throughout the merger process to understand merger's impact on the satellite galaxy. Comparing the internal energies of M33 before and after the merger allows us to understand how it evolves as the merger takes place.

We investigate the total internal energies of the halos as the merger occurs. This is done by using the equation for internal energy of the particular galaxy,

$$E_{int,g} = K_{int,g} + P_{int,g}, \tag{2}$$

where $K_{int,g}$ is the internal kinetic energy of the halo and $P_{int,g}$ is the internal potential energy of the halo.

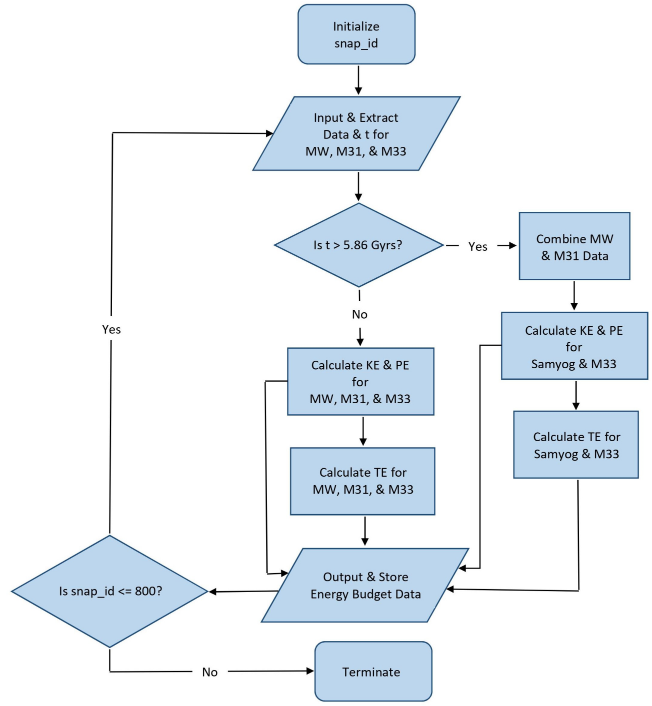

Figure 2. Flowchart showing the process of calculating internal energy budgets of different halos evolving with time. Note that the MW and M31 data is combined to calculate the internal energy budgets of the halo of Samyog after time $t > 5.86$ Gyr (van der Marel et al. 2012).

These can be found using,

$$K_{int,g} = \frac{1}{2}\Sigma_{i=1}^{N} m_i v_i^2,$$
$$P_{int,g} = -\Sigma_{i\neq j}^{N} \frac{G m_i m_j}{r_{ij}}, \tag{3}$$

where N is the total number of particles in the given galaxy, m_is are the masses of individual dark matter particles, v_is are their speeds, and $r_{i,j}$s are the separations between the two given dark matter particles.

We plot four figures as part of our results. The first two figures contain the plots of virial ratios and internal energies, similar to Fig. 1, of MW and M31 before the merger. The third figure contains the similar plot of Samyog after the merger. The final figure contains the similar plot of M33 over the entirety of the simulation time. Looking at the internal energy budgets evolution as well as the evolution of the virial ratios as the merger occurs would help us understand where the energy goes as well as how the internal structures of the galaxies change as the merger occurs.

We hypothesize that Samyog will be found to be nearer to the virial equilibrium compared to the initial conditions of MW and M31. It is understandable that

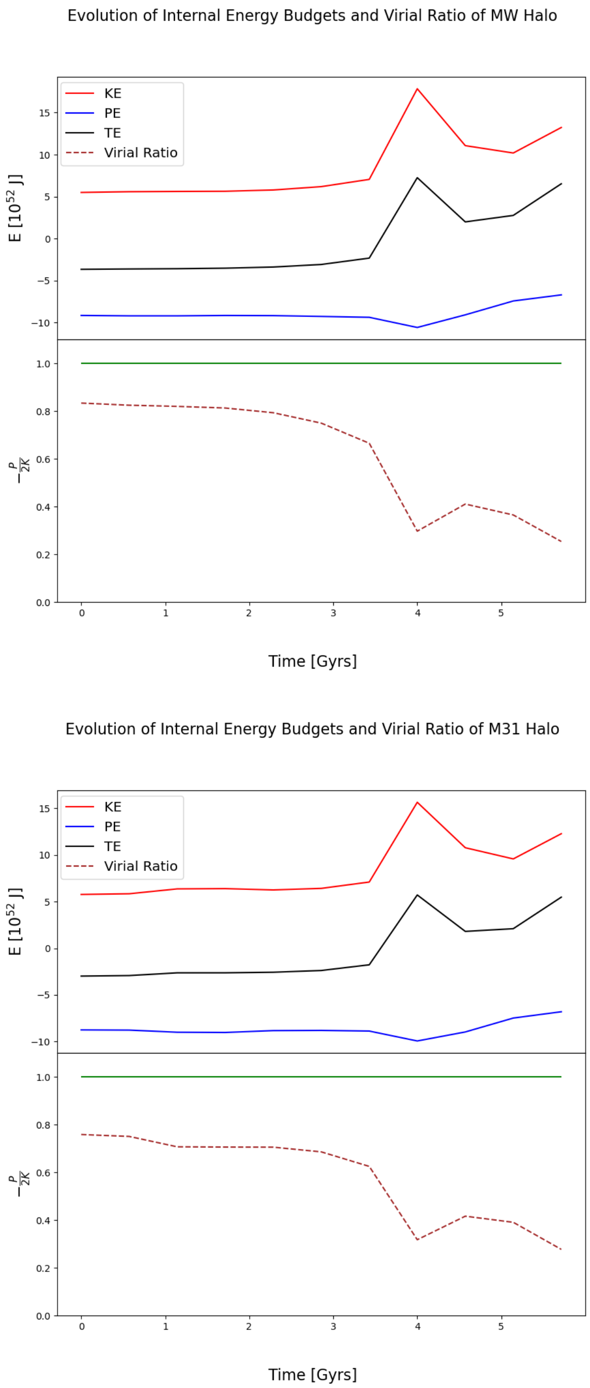

Figure 3. Internal energy and virial ratio evolution of MW (upper) and M31 (lower) before $t = 5.86$ Gyrs. The x-axis of both plots show time in Gyrs. The upper part of both plots show the evolution of kinetic energies (red lines), potential energies (blue lines), and total energies (black lines) in 10^{52} J. The lower parts of both plots show the evolution of the virial ratios (dashed brown lines) and the references of $\lambda_{vir} = 1$ (green lines). As can be seen, both MW and M31 have initial virial ratios that indicate their high dispersion dependence before the merger.

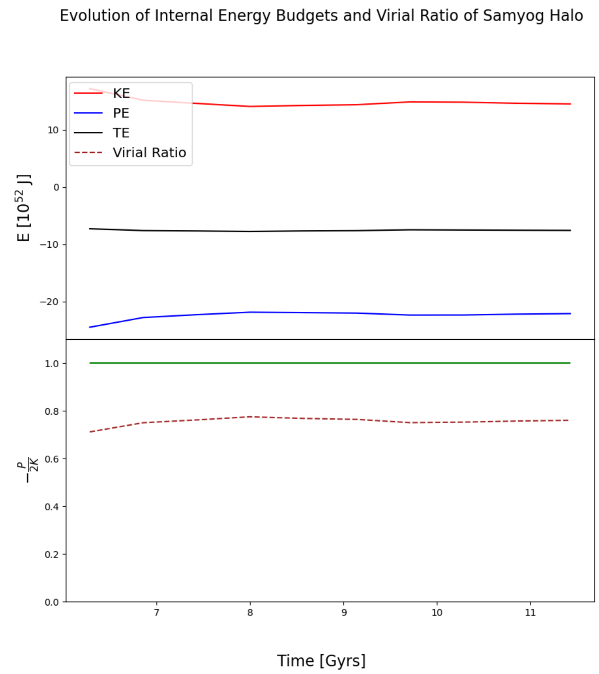

Figure 4. Internal energy and virial ratio evolution of Samyog after $t = 5.86$ Gyr. The x-axis of the plot show time in Gyrs. The upper part of the plot shows the evolution of kinetic energy (red line), potential energy (blue line), and total energy (black line) in 10^{52} J. The lower part of the plot shows the evolution of the virial ratio (dashed brown line) and the reference of $\lambda_{vir} = 1$ (green line). As can be seen, Samyog has the final virial ratio that indicates its high dispersion dependence after the merger.

the major merger remnant, Samyog, will be 'hotter' than either MW or M31 at $t = 0$ Gyr. This means that the motion of dark matter particles within the halo is more random, giving us a virial ratio for the halo of Samyog to be nearer to 1. Thus, Samyog would be dominantly supported by velocity dispersion. We also hypothesize that M33 will gain internal energy and become more random as it is loosing its orbital energy due to dynamical friction.

4. RESULTS

Using the method shown in Section 3, we produced four different plots of the evolution of internal energies and virial ratios of the various halos as the merger occurs. The plots of the evolution of internal energies and virial ratios for MW and M31 are given in Fig. 3. As can be seen in Fig. 3, at $t = 0$ Gyr, the virial ratio of MW halo is $\lambda_{vir} = 0.833$ and the virial ratio of M31 halo is $\lambda_{vir} = 0.758$. These initial virial ratios indicate that both MW and M31 are dominantly supported by dispersion before the merger.

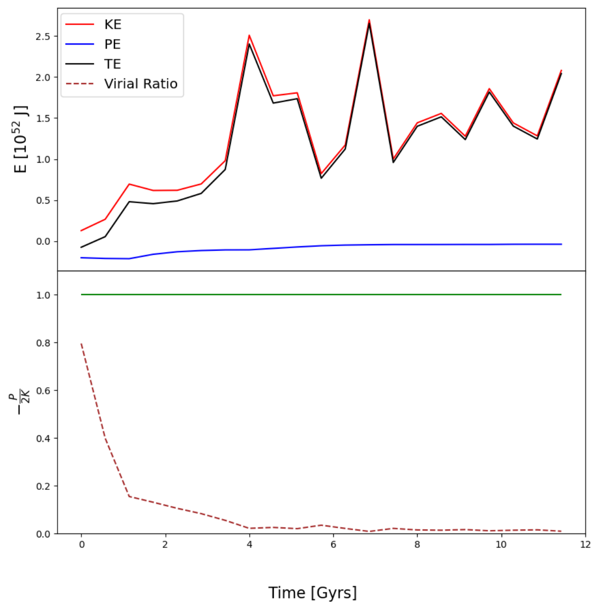

Figure 5. Internal energy and virial ratio evolution of M33. The x-axis of the plot shows time in Gyrs. The upper part of the plot shows the evolution of kinetic energy (red line), potential energy (blue line), and total energy (black line) in 10^{52} J. The lower part of the plot shows the evolution of the virial ratio (dashed brown line) and the reference of $\lambda_{vir} = 1$ (green line). As can be seen, M33 has the initial virial ratio that indicates its high dispersion dependence before the merger and the final virial ratio that indicates its high rotation dependence after the merger.

The plot of the evolution of internal energies and virial ratio of Samyog are given in Fig. 4. As can be seen in Fig. 4, at $t = 11.429$ Gyrs, the virial ratio of Samyog halo is $\lambda_{vir} = 0.760$. This final virial ratio of Samyog indicates that Samyog is dominantly supported by dispersion after the merger. Compared to MW before the merger, Samyog has a lower virial ratio, indicating that Samyog is less dispersion dependent than MW. Compared to M31 before the merger, Samyog has very similar but slightly higher virial ratio, indicating that Samyog is slightly more dispersion dependent than M31.

The plot of the evolution of internal energies and virial ratio of M33 are given in Fig. 5. As can be seen in Fig. 5, the virial ratios of M33 are $\lambda_{vir} = 0.795$ at $t = 0$ Gyr and $\lambda_{vir} = 0.009$ at $t = 11.429$ Gyrs. This virial ratios indicate that M33 is dominantly supported by dispersion before the merger and appears to be supported by rotation after the merger. We also see that the M33 is gaining significant amount of energy as the merger takes place.

5. DISCUSSION

As stated in Section 4, Samyog has the final virial ratio of $\lambda_{vir} = 0.760$. Thus, Samyog is dominantly supported by velocity dispersion. This is similar to what we hypothesized. We also found that it is less dispersion dependent compared to MW before the merger and slightly more dispersion dependent compared to M31 before the merger. This means that two dispersion dependent galaxy halos merge to create a merger halo that is dominantly supported by velocity dispersion. However, it is not necessarily true that it will be more dispersion dependent compared to both of its progenitors.

These calculations of virial ratios are done by calculating total internal energies of various halos instead of average internal energies. Thus, while these virial ratios gives us an understanding of the big picture, more accurate results would be obtained if we calculate the average internal energies.

As stated in Section 4, M33 has virial ratios of $\lambda_{vir} = 0.795$ at $t = 0$ Gyr and $\lambda_{vir} = 0.009$ at $t = 11.429$ Gyrs, indicating that M33 is dominantly supported by dispersion before the merger and appears to be supported by rotation after the merger. We see that the total energy of the M33 is positive after the merger, indicating that the halo of M33 is gravitationally unbound. This indicates that there are many dark matter particles that were stripped from M33. We can see this in Fig. 6, where we see the tidally stripped dark matter particles at $t = 11.4$ Gyrs. In Fig. 5, we also see that the M33 is gaining significant amount of energy as the merger takes place. This is according to what we hypothesized. This means that, in a three-galaxy complex system like MW-M31-M33, when a major merger takes place, the satellite galaxy usually gains energy, resulting in tidal stripping and changing of its internal structure significantly.

The bipolar velocity distribution seen in the plots of M33 halo at $t = 11.4$ Gyrs in Fig. 6, is the effect of the stripped dark matter particles, which gives us the found rotational dependence of all the dark matter particles within the initial halo of the M33, indicated by the low virial ratio. This explains the final virial ratio of M33 halo being very low. For more accurate result, we need to define the Jacobi radius of M33 after the merger and calculate internal energies only using particles within that radius.

6. CONCLUSIONS

We investigate the evolution of internal energy budgets of the dark matter halos in the initial three-galaxy system of Milky Way (MW), Andromeda galaxy (M31), and Triangulam galaxy (M33) during the formation of major MW-M31 merger remnant, Samyog. The ex-

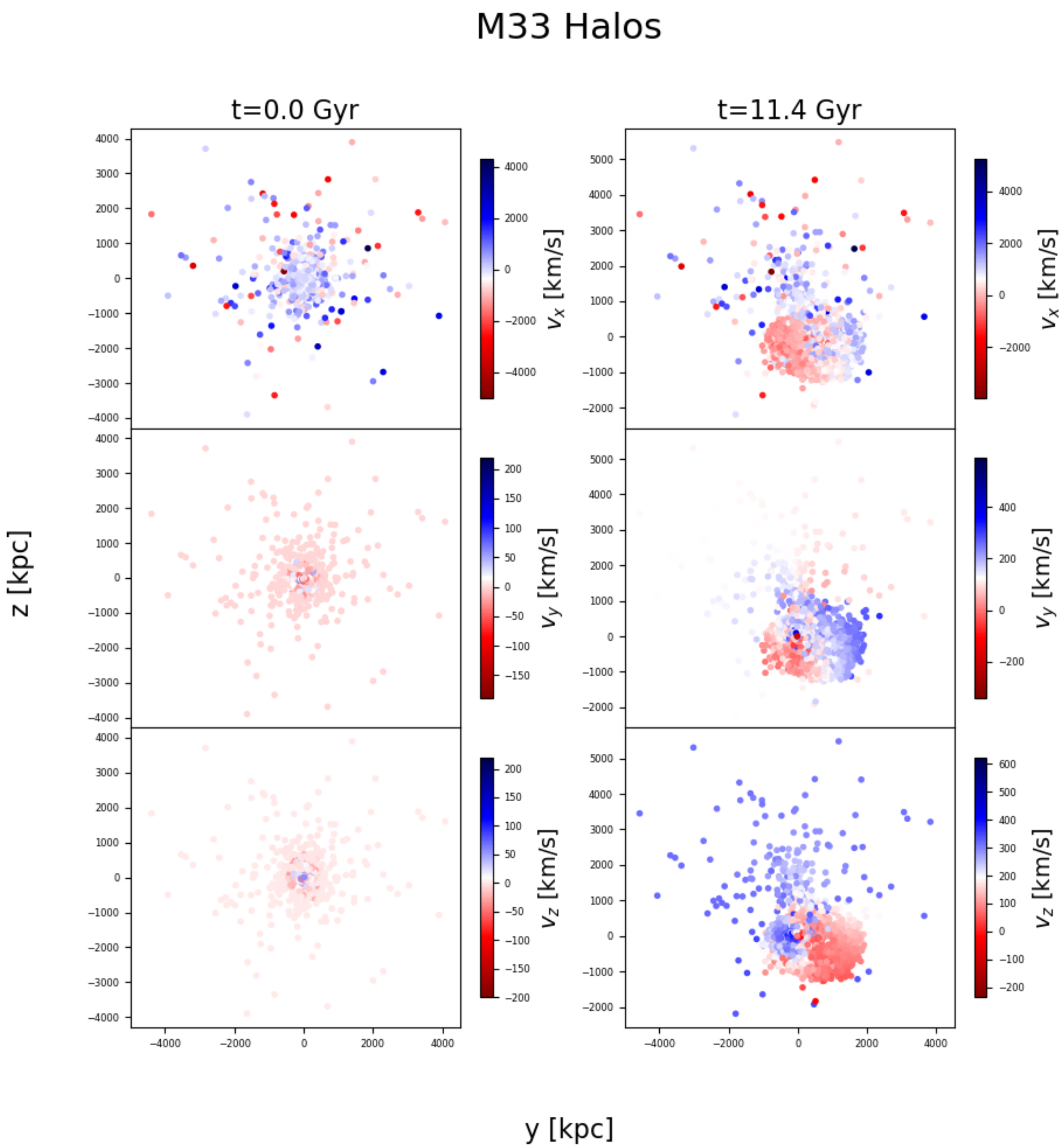

Figure 6. Dark matter halos of the M33 galaxy. The left three plots and the right three plots are at the snapshot at $t = 0$ Gyr and at the snapshot at $t = 11.4$ Gyrs, respectively. The x-axis and the y-axis of the plots show y-coordinates and z-coordinates, respectively, in kpc. The upper two plots, the middle two plots, and the lower two plots are color coded to show x-velocities, y-velocities, and z-velocities, respectively, in km/s. M33 halo after the merger, at $t = 11.4$ Gyrs, have high velocity particles compared to the M33 halo before the merger, at $t = 0$ Gyr. The tidally stripped dark matter particles after the merger are apparent in the right three plots. The apparent bipolar distribution of velocities in the right three plots is due to the stripping of dark matter particles from M33 halo and is responsible for lower virial ratio.

change of energies within the system governs the structural evolution of the halos within the system. By looking at the evolution of the internal energy budgets and virial ratios of the halos, we investigate whether the halo of the major merger remnant Samyog is dominantly supported by velocity dispersion or rotation. We also investigate whether the M33 halo gains or loses energy during the formation of Samyog and how it changes its internal structure.

We found the final virial ratio of Samyog to be $\lambda_{vir} = 0.760$. This indicates that the halo of Samyog is dominantly dispersion supported, which is in agreement with our initial hypothesis. We also found that it is less dispersion dependent compared to MW before the merger and slightly more dispersion dependent compared to M31 before the merger. This means that two dispersion dependent galaxy halos merge to create a merger halo that is dominantly supported by velocity dispersion. However, it is not necessarily true that it will be more dispersion dependent compared to both of its progenitors.

We further found that M33 gains an abundance of energy such that its total energy becomes positive, which is in agreement with our initial hypothesis. This indicates that many dark matter particles are tidally stripped from the M33 halo as the merger takes place. We also find that the virial ratio of the M33 halo becomes very small after the merger, contrary to our hypothesis. We attribute this feature to the bipolar velocity distribution in the dark matter particles of M33, an effect of the tidal stripping of dark matter particles from the initial halo of M33. We conclude that in a three-galaxy complex system like MW-M31-M33, when a major merger takes place, the satellite galaxy is likely to gain energy, resulting in tidal stripping and changing its internal structure significantly.

To gain more accurate results of virial ratios, we further propose to repeat this investigation by calculating average internal energies instead of total internal energies. By using the dark matter particles only within the Jacobi radius to investigate the internal energies of the M33 halo after the merger can also give us more information. For future works, the investigation of the evolution of orbital energies within the system will also give us more holistic view of how the system in its entirety evolve as the merger takes place.

7. ACKNOWLEDGEMENT

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