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

Jay Motka [1,2]

[1] Department of Astronomy and Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
[2] Department of Physics, University of Arizona, Tucson, AZ 85721, USA

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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 has 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 studied in van der Marel et al. (2012), we propose to study the evolution of energy budget 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 properties 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 would effect the structure of halos the most. 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 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

Corresponding author: Jay Motka
jaymotka@arizona.edu

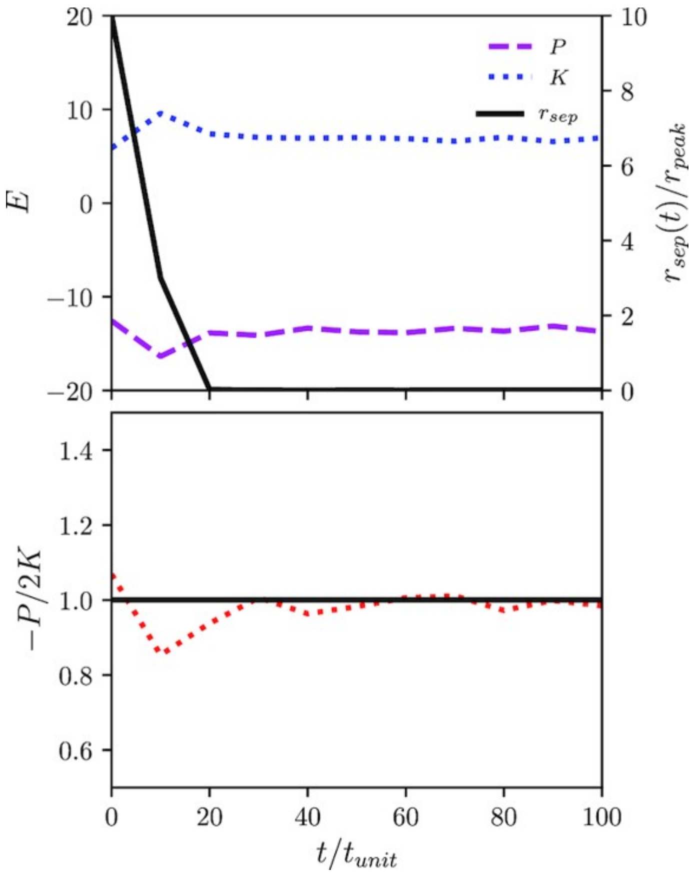

Figure 1. Energy evolution of the system of two halos of same mass, merging together, as shown in Drakos et al. (2019a). The progenitor galaxies possessed the Einasto density profiles. As can be seen in the bottom panel, after the merger, virial ratio (dotted red line) of the merger halo is nearly equal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

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 will help 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 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 galaxy clusters. Finding answers to these open questions is essential to further understand the galaxy evolution 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 will also look at the 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 will find out whether the halo of Samyog is dominantly dispersion supported or dominantly rotation supported. We will 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 energy budgets of all the separate halos at a given time. Using those energy budgets, we can find the virial ratios for all the halos, which is the direct indicator of whether the halo is 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 gravitational force.

To answer these questions, we will calculate the internal energies of the various halos according to the flowchart as shown in Fig. 2. We will first calculate the internal energies of MW, M31, and M33 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 will calculate the internal energies of Samyog and M33 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 will compare the virial ratios of MW and M33 at $t = 0$ Gyr with Samyog's virial ratio evolution to understand the halo structure of a galaxy major merger compared to its progenitors. Finally, we will look at the evolution of M33's virial ratio through-

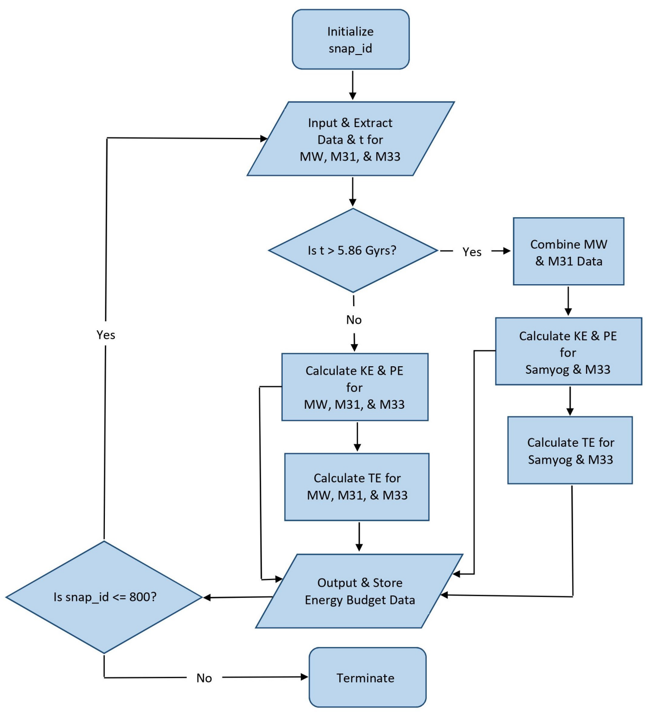

Figure 2. Flowchart showing the process of calculating internal energy budgets of different halos evolving with time. Note that the MW M31 data is combined to calculate energy budgets of the halo of Samyog after time $t > 5.86$ Gyr, according to van der Marel et al. (2012).

out the merger process to understand merger's impact on the satellite galaxy.

We will investigate the total internal energies of the three galaxies before 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 kinetic energy of the halo and $P_{int,g}$ is the potential energy of the halo. 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 given two dark matter particles. By comparing the internal energies of M33 before and after the merger will allow us to understand how it evolves as the merger takes place.

We will be plotting four figures as part of our results. The first two figure will contain the plots of virial ratios and internal energies, similar to Fig. 1, of MW and M31 before the merger. The third figure will contain the similar plot of Samyog after the merger. The final figure will contain 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 we will find that Samyog is nearer to virial equilibrium compared to the initial conditions of MW and M31. It is understandable that 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 also gain 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 $\lambda_{vir} = 0.834$ 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.

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 $\lambda_{vir} = 0.796$ at $t = 0$ Gyr and $\lambda_{vir} = 0.030$ at $t = 11.429$ Gyrs. This virial ratios indicate that M33 is dominantly supported by dispersion before the merger and by rotation after the merger. We

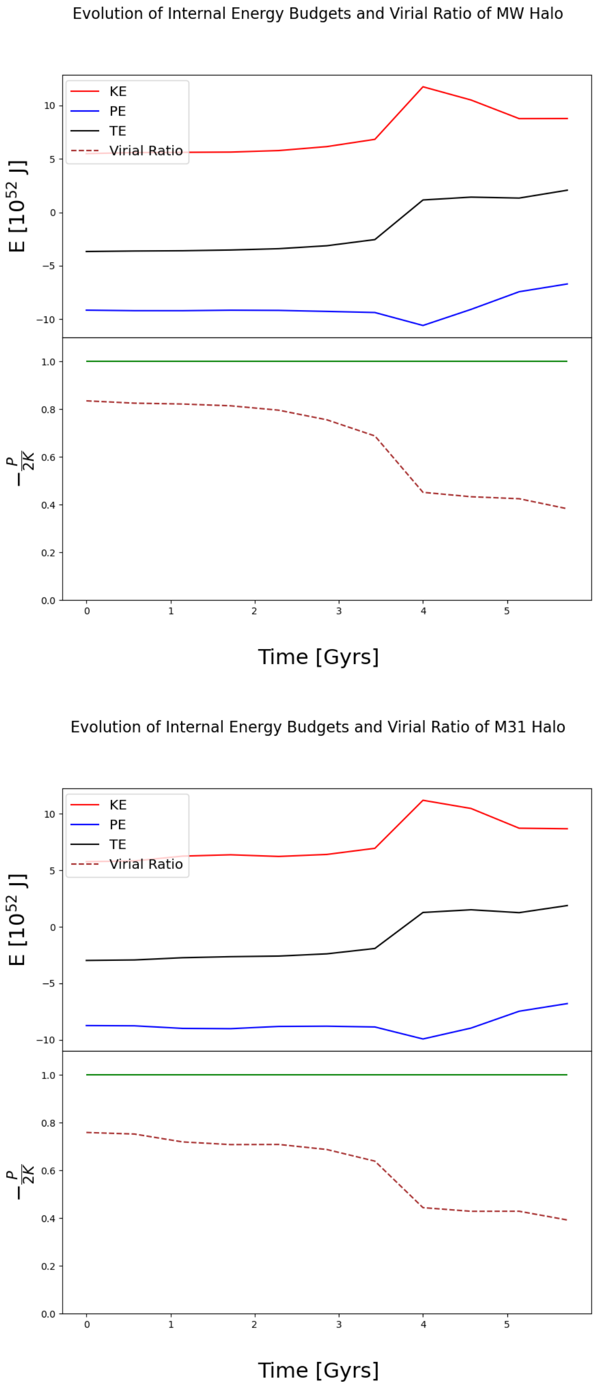

Figure 3. Internal energy and virial ratio evolution of MW (upper) and M31 (lower) before t = 5.86 Gyr, when the merger takes place. The x-axis of both plots show time in Gyrs. The upper part of both plots show the evolution of kinetic energies (red lines), potential energies (blue lines), and total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

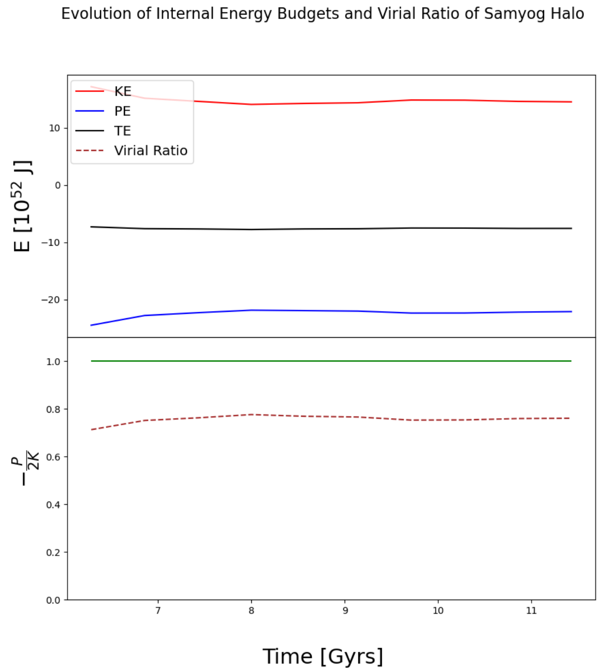

Figure 4. Internal energy and virial ratio evolution of Samyog after t = 5.86 Gyr, when the merger takes place. The x-axis of the plot show time in Gyrs. The upper part of the plot shows the evolution of kinetic energy (red line), potential energy (blue line), and total energy (black line) in $10^{52}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

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 virial ratio of λ_{vir} = 0.760. Thus, Samyog is dominantly supported by velocity dispersion. This is similar to what we hypothesized. We also find 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 virially 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.

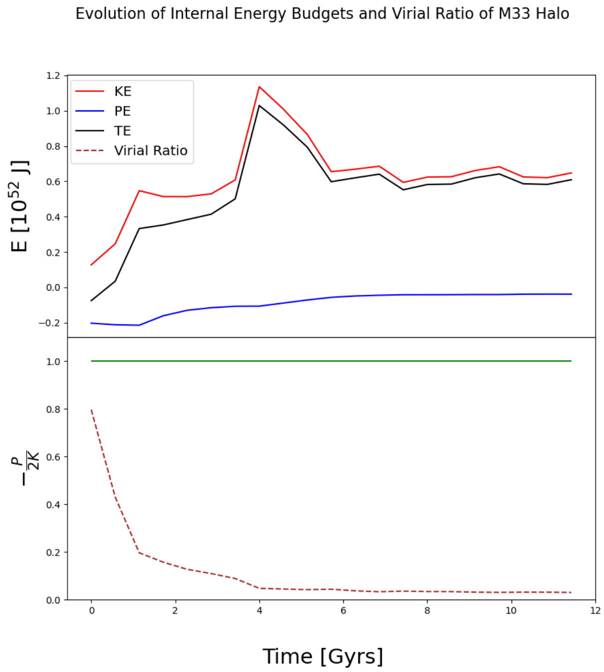

Figure 5. Internal energy and virial ratio evolution of M33. The x-axis of the plot shows time in Gyrs. The upper part of the plot shows the evolution of kinetic energy (red line), potential energy (blue line), and total energy (black line) in $10^{52} J$. The lower part of the plot shows the evolution of the virial ratio (dashed brown line). The reference of virial ratio equal to 1 (green line) is given. 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.

As stated in Section 4, M33 has virial ratios of $\lambda_{vir} = 0.796$ at $t = 0$ Gyr and $\lambda_{vir} = 0.030$ at $t = 11.429$ Gyrs, indicating that M33 is dominantly supported by dispersion before the merger and by rotation after the merger. 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, changing its internal structure significantly.

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. For more accurate result, we need to define the radius of M33 after the merger and calculate internal energies only using particles within that radius.

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