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ASTR 400B: Research Assignment 2
Transformation of Energy Budget and Orbital Parameters during The Formation of Major MW-M31 Merger Remnant

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1. INTRODUCTION

Milky Way (MW) along with its largest neighbours the Andromeda galaxy (M31) and the Triangulum galaxy (M33) resides in the known group of galaxies called the Local Group. Based on the current observational data, the future interactions between these galaxies have been studied broadly. One such study was carried out using a combination of collisionless N-body simulations and semi-analytic orbit integrations in van der Marel et al. (2012). According to the collisionless N-body simulation described in van der Marel et al. (2012), the MW and M31 will merge at $t = 5.86^{+1.61}_{-0.13}$ Gyr from now. The major merger remnant of MW-M31 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 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. More specifically, we want to understand the distribution of internal and orbital energies between the three objects before the merger and compare them to the final distribution of internal and orbital energies between the M33 and the Major MW-M31 Merger Remnant, Samyog.

We currently have an understanding of the energy evolution of the system of two galaxies as they merge (e.g. Drakos et al. 2019a,b). For the given system of two galaxies, the total energy remains conserved as they merge into a single remnant (Drakos et al. 2019a) as is obvious in the case of N-body simulation of two-galaxy system. 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

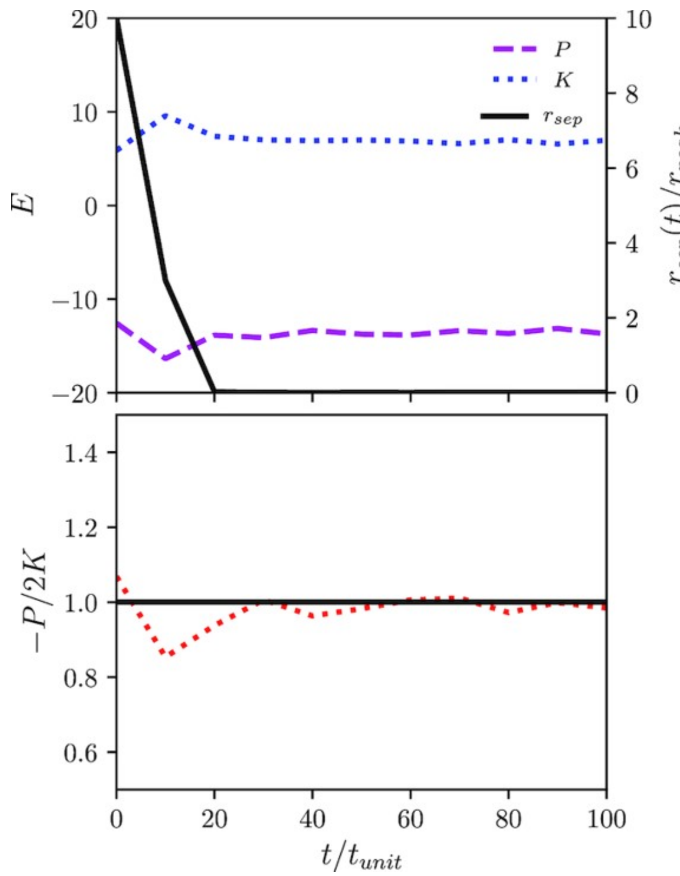

Figure 1. Energy evolution of two galaxies of same mass merging together as shown in (Drakos et al. 2019a). The progenitor galaxies possessed the Einasto density profiles, with the initial conditions of having the orbital parameter of $r_{sep} = 10r_{peak}$ and the radial velocity of $v_0 = 0.8v_{esc}$. The top panel shows the radial separation between the halo centres (solid black line), as well as the potential and kinetic energy of the entire system. The bottom panel shows the virial ratio P/2K (dotted red line), which should be 1 for a virialized system (solid black line).

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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 will help us understand the open problem of understanding galaxy mergers with multiple galaxy systems.

We also propose to investigate whether the merger remnant, Samyog, is supported by rotation or velocity dispersion. As this information corresponds to the internal structure, density profile, and shape of the galaxy, this is something very important to understand Drakos et al. (2019a,b).

The virial ratio of a galaxy is defined as, $-\frac{P}{2K}$, where P is the total internal potential energy and K is the total kinetic energy (Drakos et al. 2019a). It is known that if a merger remnant of two galaxies contains the virial ratio equal to 1, then the galaxy is purely supported by velocity dispersion. Fig. 1, taken from Drakos et al. (2019a), shows the merger of two equal mass galaxies that is dominantly supported by velocity dispersion. It is known that known halo shapes are mostly supported dominantly by anisotropic velocity dispersion as they rotate very slowly (Frenk & White 2012). However, we wish to know whether the merger remnants like Samyog also follow this or not. We will do this by finding a dimensionless spin parameter that is further discussed in Section 2.

2. THE PROPOSAL

For the purpose of understanding the energy evolution of the system, we will investigate where the orbital potential energy being lost between the two galaxies go as they merge. We will do so by finding whether the change in rotation or velocity desperation of the Samyog is enough to account for this energy loss. We will also inquire whether Samyog is dominantly supported by rotation or by velocity dispersion.

To answer these questions, we will first investigate the internal energies of the three galaxies before the merger occurs. This is done by using the equation for internal energy of the particular galaxy,

$$E_{int,g} = K_{int,g} + P_{int,g}, \tag{1}$$

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,

$$\begin{aligned} K_{int,g} &= \Sigma_{i=1}^{N} m_i v_i^2, \\ P_{int,g} &= -\frac{1}{2}\Sigma_{i,j=1}^{N}\frac{Gm_im_j}{r_{ij}^2}, \end{aligned} \tag{2}$$

where N is the total number of particles in the given galaxy.

Now, to find the orbital energies between any two galaxies, we will find the total energy between those two galaxies and subtract the internal energies of these galaxies,

$$E_{orb,g1-g2} = E_{tot,g1-g2} - E_{int,g1} - E_{int_g 2},$$

which reduces to,

$$E_{orb,g1-g2} = -\frac{1}{2}\Sigma_{i=1}^{N_{g1}}\Sigma_{j=1}^{N_{g2}}\frac{Gm_im_j}{r_{ij}^2}, \tag{3}$$

where N_{g1} and N_{g2} are the total number of particles in the respective galaxies.

Now, to calculate the total energy of the system, we will use the equation,

$$E_{tot} = \Sigma_g\, E_{int,g} + \Sigma_{g1\neq g2}\, E_{orb,g1-g2}. \tag{4}$$

Finally, to find the angular momentum of the halo, we use the equation,

$$\mathbf{J} = \Sigma_{i=1}^{N} m_i \mathbf{r_i} \times \mathbf{v_i}. \tag{5}$$

To understand whether the halo is dominantly supported by rotation or velocity dispersion, a dimensionless spin parameter, λ, can be useful. The spin parameter is defined as,

$$\lambda = \frac{J|E|^{1/2}}{GM^{5/2}}, \tag{6}$$

where M is the halo mass, J is the magnitude of its angular momentum, and E is the internal energy of the halo (Frenk & White 2012; Drakos et al. 2019a). According to Frenk & White (2012), for a purely rotationally supported halo, $\lambda = 0.4$. As shown here in Fig. 2, taken from Drakos et al. (2019a), the value of λ of a merger can vary greatly depending on the initial conditions of its progenitors. However as stated before, it is known that halo shapes are mostly supported dominantly by anisotropic velocity dispersion as they rotate very slowly (Frenk & White 2012). Thus, using this parameter, we will be able to understand whether the remnant, Samyog, is supported by rotation or velocity dispersion. Depending on whether M33 gains or loses internal energy after the merger, we will also look at its spin parameter to understand the evolution of its spin parameter as the MW and M31 merges. We will look at the total internal energy of the M33 as well as the orbital energy in between M33 and Samyog to see whether the loss or gain of energy results into change in the internal structure of the M33 or does it only result in getting M33 to be gravitationally bound more or less to the remnant.

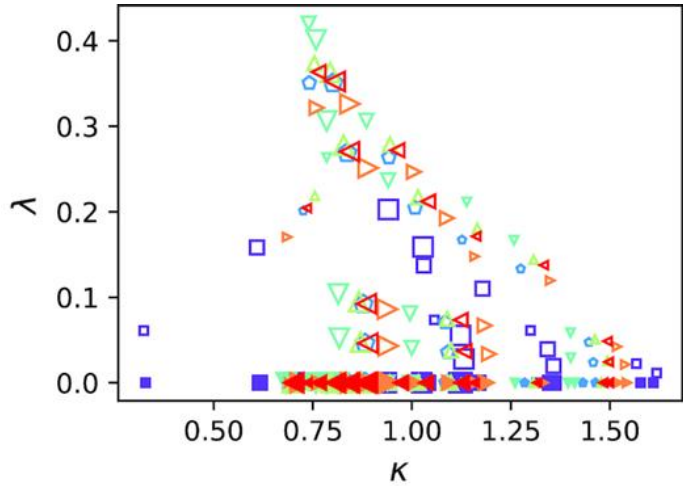

Figure 2. The plot of spin parameter vs energy parameter for various galaxy merger remnants according to different initial conditions as shown in Drakos et al. (2019a). As can be seen in the plot there are a couple of merger remnants that are quite close to $\lambda = 0.4$, attributing to them being purely supported by rotation. The value of λ is very spread out giving us the understanding that the merger remnants can be dominantly supported by rotation, which is in contrast to the statement given in Frenk & White (2012), given that they have some particular initial conditions.

To find these values from our N-body simulation, we will first write a code to find the Center Of Mass of the MW at t=0. We will use this point as the point of origin for all the following calculations using the simulation data. Thus, whenever we read the data from any of the snapshot, we will convert the data to the reference frame of this CoM of the MW at $t = 0$ Gyr.

Then, we will write the codes for finding the internal kinetic energy and the internal potential energy for any galaxy using eq. 2. We will write the code to calculate the total internal energy by utilizing eq. 1. We will also implement the code to find the orbital energy between the two galaxies using eq. 3. Then, we will write the code to find the total energy of the system using eq. 4. We will implement the code to calculate the angular momentum of any given galaxy using eq. 5. Finally, we will implement the code to find the spin parameter of any given galaxy using eq. 6.

Since, we are interested in comparing the outcomes before and after the merger, we will take on the snapshots 0 and 800, corresponding to $t = 0$ Gyr and t 12 Gyr, respectively. Using the 0th snapshot, we will find the internal energies, angular momentum, and spin parameters of all three galaxies. We will also find the orbital energies of the galaxy pairs and then find the the total energy of the system. We will also find the total energy of the MW and M31 system by adding up both of their internal energies with the orbital energy between them. Then, using the 800th snapshot, we will find the internal energies, angular momentum, and spin parameters of both the galaxies, Samyog and M33. We will also find the orbital energy and total energy of this system. Finally, we will compare the internal energy of Samyog at snapshot 800 to the total energy of the MW and M31 system found at snapshot 0 to fins the answer to our first question. Then, we will look at the spin parameters of Samyog to understand whether it is dominantly supported by rotation or velocity dispersion. Finally, we will look at the spin parameter and internal energy of M33 along with the orbital energy of the Samyog-M33 system to understand how the merger has impacted M33.

We hypothesise that we will find the internal energy of the Samyog to be less than the total energy of MW-M31 system as, in our opinion, this system must loose energy to become gravitationally stable within. It is understandable that the merger remnant, Samyog, will be 'hotter' than either MW or M31, however to remain gravitationally bound it will loose some energy to either M33 or their combined orbit. We further hypothesize that Samyog will be dominantly supported by velocity dispersion, as, again, it will be 'hotter' than either M31 or MW, which, if Frenk & White (2012) is to be believed, are supported dominantly by velocity dispersion.

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