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Average Specific Angular Momentum of Haloes of Milky Way, M31, and their Merger Remnant

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1. INTRODUCTION

1.1. *Discussion of General Physical Background and Definition of the Topic*

The first evidence of Dark Matter (DM) came with Zwicky's analysis of fast-moving galaxies in the Coma Cluster (Zwicky 1933). Later, while analyzing the rotation curve of the Andromeda galaxy, Vera Rubin provided yet another evidence for the existence of DM haloes surrounding galaxies (Rubin & Ford 1970). In the following years, several extensive studies were carried out and DM haloes were identified as the breeding grounds for galaxies (see e.g., White & Rees 1978). Since then, the scientific community has aimed to better constrain the properties of the DM haloes (see e.g., Davis et al. 1985, analyze the triaxial shape of DM haloes). This paper focuses on another specific property of these DM haloes- their Average Specific Angular Momentum (ASAM), i.e., their average spin. We aim to study the ASAM of haloes surrounding the Milky Way galaxy, the M31 galaxy, and their merger remnant.

1.2. *Overview of Current Understanding of the Halo Spin*

With the help of numerical simulations, it had been established very early that the haloes tend to rotate (Barnes & Efstathiou 1987). Though more massive haloes appear to spin slowly, the exact strength of the spin and the halo mass depends on the definition of the halo (Bett et al. 2007). The internal distribution of specific angular momentum inside a halo follows a rather simple trend – it increases with the distance from the center (Frenk & White 2012). The alignment of the spin axis of haloes with their three principal axes assumes a broad distribution (see e.g., Shaw et al. 2006; Bett et al. 2007). Moreover, the direction of the angular momentum inside the halo also varies with the distance from the center (Bett et al. 2010).

Drakos et al. (2019) analyzed the merger remnant of two equal-massed haloes (without baryons) with various density profiles. The authors find that the remnant halo may assume a complicated spin. Figure 1 shows how the spin of the remnant halo varies with the dimensionless energy parameter (K; tells the energy of the colliding haloes) analyzed in Drakos et al. (2019). Abadi et al. (2010) examine the effects of the formation of a central galaxy on its surrounding halo. When the baryons were included, the authors found that both baryons and halo had comparable angular momenta initially, but baryons lost a significant amount of their angular momentum to the surrounding halo. Thus, in their simple model, the baryons moved inwards and their central galaxy was more massive and smaller. When Bett et al. (2010) included the effects of baryons, they find that the formation of a central galaxy increases the angular momentum of the halo significantly.

1.3. *Importance of Halo Spin in Galaxy Evolution*

In the context of Milky Way and M31 – two galaxies bound to merge – examining the ASAM becomes important due to three reasons: (i) first, the ASAM of individual galaxies can help us in testing the correlation between the halo spin and the size of the embedded galaxy (see e.g., Jiang et al. 2019) and the spin vs. morphology correlation, (ii) it gives us a way to assess how the merger remnant halo spin relates to the spin of the initial galaxies, and lastly, (iii) it can be used to examine how the DM spin evolves through a merger. Initially, the formation of an elliptical galaxy was thought to be the result of repeated galaxy mergers (Tinsley & Larson 1977). Later studies point out that the formation of elliptical galaxies is more complicated and depends on several other factors (like morphology of initial galaxies, orbital parameters, etc.) (see e.g., Barnes 1992). In addition to this, Rodriguez-Gomez et al. (2017) analyzed the effects of halo spin on galaxy morphology and found that for less massive halo mergers ($\lesssim 10^{10} M_{\odot}$), the halo spin plays a crucial role in determining the morphology of the galaxy while for halo masses comparable to that of the MW, the spin has weak effects on the morphology of the remnant. Thus, analyzing the evolution of halo spins through mergers is important to understand the evolution of galaxies.

1.4. *Open Questions*

The halo spin parameter can be used to determine the angular momentum of the embedded galaxies and therefore galaxy sizes (Fall & Efstathiou 1980). Moreover, the halo spin parameter can be roughly approximated by a log-normal distribution (Bullock et al. 2001). However, an important question remains unanswered – what is the underlying mechanism behind the characteristic spin distribution, besides the random processes? Moreover, current studies (e.g., Drakos et al. 2019) ignore the individual spin of the initial haloes before the merger, probably due to computational constraints. Another open question is how individual halo spins evolve through a major merger event. Even in the simplest models (like that in Abadi et al. 2010), the inclusion of cold baryons (in the absence of star formation and feedback mechanisms) resulted in significantly high mass central galaxy formations. Thus, the real effects of the inclusion of proper star formation and feedback mechanisms on the halo merger remnant is another unanswered question.

2. THE PROPOSAL

2.1. *Specific Question to be Studied*

In this paper, we want to compare how the spin of individual galaxy haloes (MW and M31) evolve through a merger by quantifying them at different points in time. We will begin by estimating the individual ASAM for the haloes surrounding Milky Way and M31 galaxies. After this, we estimate the time of the galaxy merger and analyze the final halo merger spin. Additionally, we will also try to calculate the ASAM for both galaxies throughout their merger – from beginning to end.

2.2. *Methodology*

The general approach used to analyze the halo spin(s) is given below:

- We first analyze the initial (t = 0 snapshot) data files for MW and M31 and quantify the initial spins (Angular Momentum) for both these galaxies.
- For each of these files, we select only the halo particles to be the representative of the whole galaxy (as we are interested in the halo spins).
- We use the simulation data files for each galaxy and calculate the ASAM at each point of time during their evolution (again, we only use halo particles). This will give tell us how the spin (of each galaxy) evolves during the merger of MW and M31.
- Using the OrbitCOM code, we plot the relative distance and velocities of M31 and MW. We then identify the points of the closest approach as well as the time of the final merger. At these times, we retrieve the individual galaxy halo spins from the plot created in the above point.
- We can now calculate the total merger remnant spin by adding both individual galaxies' spins at the time of the merger. Thus we now have the spin of the merger remnant and we also know how the spin evolves through a merger from initial galaxies.
- An important point to note here is that after both galaxies merge, their relative velocities are close to zero, i.e., the center of mass frame of one galaxy can be roughly assumed to be the same as that of the other one. Thus, with this assumption, the ASAM can be calculated easily.

Let us now discuss how to quantify the angular momentum correctly. Recall that the specific angular momentum is a vector. Therefore, we have to develop a new code that can calculate the net angular momentum vector, and therefore, the ASAM. The idea to do this is simple: for each halo particle, we have 3 velocities (x, y, and z) and three position vectors (x, y, and z). The cross product of two vectors (say $\vec{r}$ and $\vec{v}$) in terms of their components can be written as: $\vec{r} \times \vec{v} = (r_2 v_3 - r_3 v_2)\hat{i} - (r_1 v_3 - r_3 v_1)\hat{j} + (r_1 v_2 - r_2 v_1)\hat{k}$ (see Figure 2). Thus, for each of the halo particles, we calculate its angular momentum using the above expression and store the individual $\hat{i}, \hat{j}$, and $\hat{k}$ components separately in arrays. At last, we sum all individual components over all the halo particles to estimate the total average angular momentum. Dividing this quantity by the total mass of the halo would yield the ASAM for the body.

2.3. *First Guess at the Results*

As the halo spin correlates with the disk spin, we believe that the angle of ASAM for individual galaxies should be close to the angle of ASAM of galaxies' disks. Estimating the magnitudes of spins of M31 and MW is an area of active research. Thus our simple estimates should be consistent with current literature. For the halo merger remnant, however, multiple factors, such as the angle of collision, the relative orientation of the halo spins right before the collision, etc., will play an important role. Nonetheless, as the number of halo particles increases post-merger, and the relative velocity plot (for MW and M31) shows zero velocity (but individual velocities decrease in magnitude) after galaxies have merged, we can guess that the halo remnant should have less spin than the sum of individual galaxy spins before the merger.

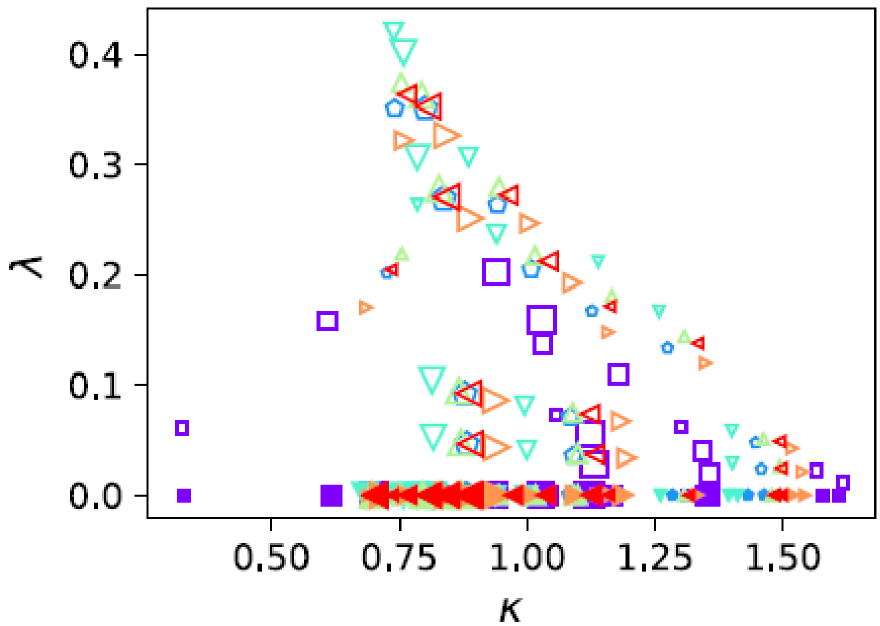

Figure 1. This figure has been taken from Drakos et al. (2019). The x-axis shows the dimensionless energy parameter while the y-axis shows the dimensionless spin parameter. For a more detailed explanation, we refer the readers to Drakos et al. (2019). Open points indicate tangential initial velocities, and filled points denote radial initial velocities. Colors tell the six different density profiles analyzed in the original paper.

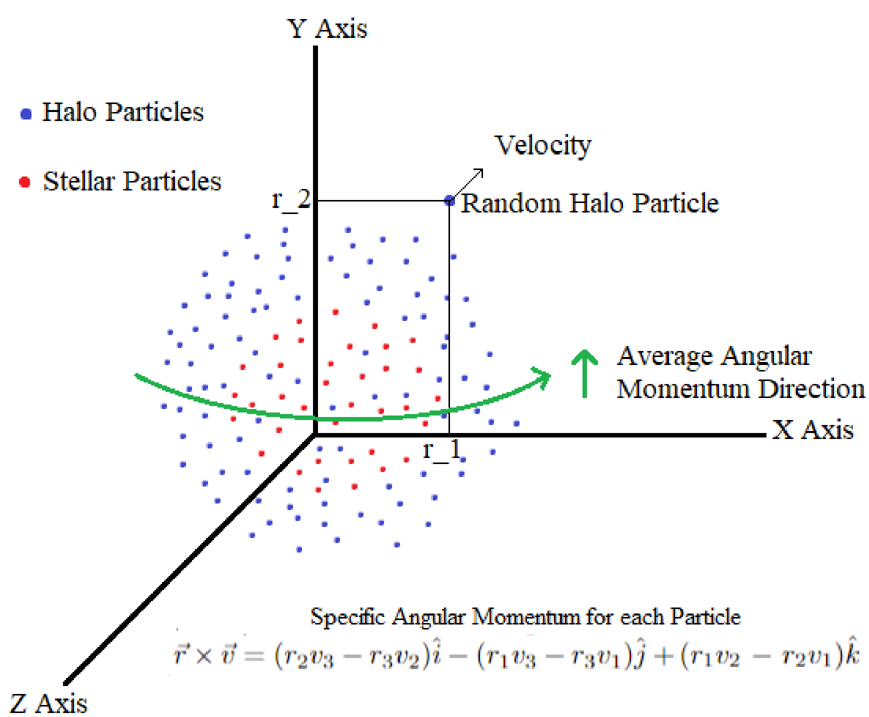

Figure 2. This figure shows a general galaxy halo and stellar particle distribution. We also show a random halo particle's velocity and x, y, and z coordinates (Note: z coordinate for the selected particle is 0 in this case). We also plot an example of the direction of the angular momentum of the whole body.

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