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Orbital Interaction Scenarios for different measurements of M31's Tangential Velocity.

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ABSTRACT

This paper explores the different orbital interaction scenarios of the Milky Way-Andromeda (hereafter, MW-M31) system depending on the inferred tangential velocities of M31. The choice of the tangential velocity measurement not only determines the timing of the first interaction but also determines whether the MW-M31 can be a gravitationally-bound system. Thus, using appropriate values of velocity measurements are important to studying the predicted merger of this system. This paper explores the effect of M31's tangential velocity on the future interaction of MW-M31 system. Since MW and M31 are the two dominant galaxies in the Local Group, their encounter will affect the evolution of two galaxies in terms of the star formation rate, satellite galaxy dynamics, tidal stream formation and formation of warps in gas disks.

Using a variety of tangential velocity measurements to simulate the orbital interaction scenario, this paper reports two findings. Adding tangential velocity to the equation unequivocally delays the timing of the first interaction of the MW-M31 system. Also, the system tends to go towards an gravitationally-unbound state with the increase in M31's tangential velocity, resulting only in fly-by interactions.

Keywords: Galaxy — Local Group — Satellite galaxy — Gravitationally bound — Galaxy evolution

1. INTRODUCTION

Bodies under the influence of Newton's law of gravitation constitute a gravitationally bound system and a system of gravitationally bound galaxies constitutes the Local Group (hereafter, LG). The MW is a member of an LG and is predicted to be on a collision course with its neighbor, M31. However, the uncertainty in the measurements of M31's tangential velocity has been a point of disagreement and the value of the tangential velocity can affect the future interaction of the MW-M31 system. This project concentrates on different orbital interaction scenarios of the MW-M31 system, based on the different measurements of M31's tangential velocity.

A galaxy is a gravitationally bound set of stars whose properties cannot be solely explained by a combination of baryons (stars and gas) and Newton's law of gravity. The main constituent of a galaxy is dark matter. The LG is dominated by the three spiral galaxies: MW, M31 and the Triangulum galaxy (M33). The mass and dynamics of these galaxies have been the subject of research in studies like Cox & Loeb (2008) and van der Marel & Guhathakurta (2008). The analysis of these topics are important for the study of galaxy evolution, which consists of stellar evolution within a galaxy, future interactions within the local group (collisions, fly-bys) and active galactic nuclei (AGN) feedback that has an affect on the gas content (and hence the star formation rate) within the galaxy. Thus, the study of galaxy evolution gives us the potential knowledge about the structures inside the LG, satellite galaxies (small systems around massive galaxies) interactions and tidal streams (van der Marel et al. 2012b).

Studies in near-field cosmology have taken huge strides in explaining the local universe and have placed the LG in a proper cosmological context. In 2012, the first proper-motion measurements of M31 stars were reported with the Hubble Space Telescope (Sohn et al. 2012). Extracting the results from Sohn et al. (2012),van der Marel et al. (2012a) studied the future dynamical evolution of the MW+M31+M33 system using N-body simulations and semi-analytic orbit integration. However, all the work had been done without the accurate knowledge of the 3D velocity vectors of the members of the LG. As a result, the future interaction of the MW-M31 system has been a matter of debate. For instance, van der Marel & Guhathakurta (2008) presented several different statistical methods to estimate the tangential velocity vector of M31. This paper found $V_{tan} = 42$ km/s with a 1σ confidence interval of $V_{tan} \leq 56$ km/s. Recently, van der Marel et al. (2019) reported the tangential velocity inferred from the DR2 and HST data $V_{HST+DR2} = 57^{35}_{-31}$ km/s; while the tangential velocity inferred by van der Marel et al. (2012b) was $v_{tan} = 17.0$ km/s with a 1σ confidence region $v_{tan} \leq 34.3$ km/s; on the other hand, the value inferred by Salomon et al. (2016) gives a value of $v_{tan} = 162 \pm 62$ km/s.

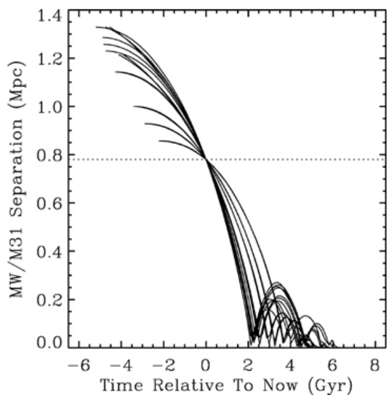

Figure 1. This figure was adapted from Cox & Loeb (2008). This paper used N-body hydrodynamic simulation to predict the future encounter of MW and M31, according to models with different initial conditions of relative distance, relative velocity and masses. Though in each scenario the merger is inevitable, the time of the first approach is different in each model.

In light of these developments, there are a lot of open-ended questions. Some of them are:

1. How will the uncertainties in the velocity measurements of M31 affect the future interaction of satellite galaxies, like M33, with other galactic bodies?

2. How do the uncertainties in speed impact how we place the LG in the context of cosmological simulations?

3. What are the consequences (of these uncertainties in measurement) on the history of LG's evolution? Loeb et al. (2005) and McConnachie et al. (2009) have studied this issue through N-body simulations of the past interaction of M31 and M33.

2. PROJECT

The collision timing of Milky Way and Andromeda is heavily dependent on the initial conditions. Nevertheless, it is generally predicted by all models that the first close approach is expected to be in the next 3-5 Gyr and the collision is expected to occur in 10 Gyr (Schiavi et al. 2019). However, the velocity constraints on M31 (the tangential velocity) has a lot of uncertainty. Different instruments and methods of measurement yield different results with varying degrees of precision (see §1). Depending on what velocity one uses, the timing of the collision changes and affects the future evolution of the LG. This project is interested in varying the tangential velocity measurements of M31 with respect to MW and studying the various scenarios of the merger. The galactocentric velocity values, (34 ± 36, -123 ± 25, -19 ± 37) km/s, are drawn from van der Marel et al. (2019). The calculation of tangential and radial velocity vectors is outlined in §3.

V_{radial}	V_{tan}
(54.513,-77.688,38.186)	(-22.513,-49.312,-68.186)
(72.414,-103.200,50.725)	(-20.414,-36.800,-45.725)
(56.254,-80.169,39.405)	(-2.254,-27.831,-53.405)
(48.001,-68.407,33.624)	(-37.001,-65.592,-80.624)

Table 1. Table showing the velocity vectors of the radial velocity (V_{radial}) and tangential velocity (V_{tan}) used in this project. The values in each list represent the x, y and z components of the velocity vectors in km/s.

This paper will concentrate on the following questions:

- What are the alternative orbital interaction scenarios of the MW+M31 system, given the uncertainties in the tangential velocity of M31?

- Will the timing of the merger be earlier or later than predicted by the simulation data?

Note that uncertainties in position and mass can also vary the orbital interaction scenarios of the MW-M31 system but that will not be the focus of this project.

Since MW and M31 are the two dominant spiral galaxies in our LG, their interaction is central to understanding not only the past trajectory M33 about M31 but also the future evolution of the LG. Studying the orbital past is critical to understanding the satellite galaxy dynamics, tidal streams (van der Marel et al. 2019), star formation history of these galaxies and formation of warps in gas disks (Patel et al. 2017). Also, if M31's velocity vector with respect to the MW changes, the future interaction scenario of the M31-MW system changes. Thus, depending on the initial conditions that this system is subjected to, the future interactions are affected significantly.

3. METHODOLOGY

This project draws the simulation data from van der Marel et al. (2012a). This paper used collisionless N-body simulations to study the orbital evolution and merger of MW-M31-M33 system. N-body simulations are used to study a dynamical system of particles. Since the gas content in these galaxies comprise only a small fraction of their total masses, this study only included stars and dark matter in its simulations. Although this was a great tool to study the overall dynamics of the interaction, it was not possible to study the formation of tidal streams, and star formation.

In order to generate the desired plots, this project's approach is going to be similar to that adopted by Cox & Loeb (2008). First, the actual simulation data will be used to generate separation and velocity plots over time. Then, using the tangential velocity measurements of M31, alternative orbital interaction scenarios will be generated (similar to Fig.1).

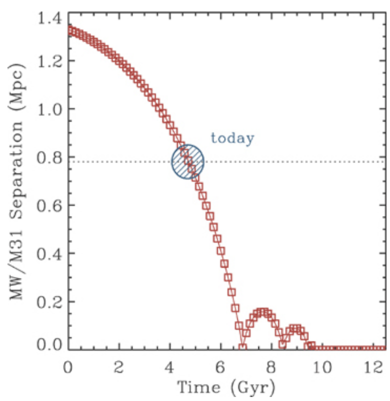

Figure 2. This figure is adopted from Cox & Loeb (2008).Separation of MW and M31 is shown during their collision course. The current separation, at 780 kpc, is marked with a dotted horizontal line.

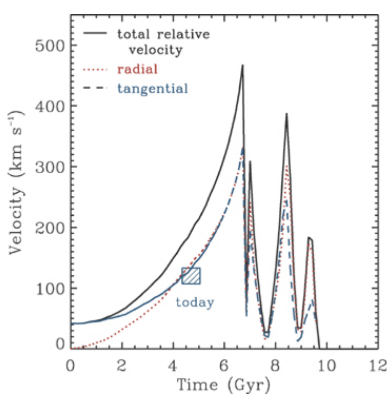

Figure 3. This figure is adopted from Cox & Loeb (2008).The relative velocities between the centers of MW and M31 is shown. The current velocities are marked at $\approx 4.7Gyr$.

The code used to generate the results first calculates the center of mass position of M31 relative to that of MW. Originally, the code did not incorporate tangential velocity values. For this project, the code is modified to first find the radial velocity components of M31. The galactocentric velocity vectors ($\vec{v}$) are projected onto the center of mass position vector ($\vec{r}$).

$$proj_{\vec{r}}\vec{v} = V_{radial} = (\vec{v} \cdot \vec{r})\frac{\vec{r}}{r^2}. \qquad (1)$$

Once the radial velocity values are obtained, one just needs to subtract the radial velocity values from $\vec{v}$ to get the tangential velocity values of M31. Next, the code calculates the acceleration due to gravity (due to MW) of M31. The halo and the bulge of spiral galaxies like M31 follow a Hernquist potential profile ($\Phi_{Hernquist}$) and thus the acceleration due to gravity ($\vec{a}$) will be induced by the Hernquist profile (Hernquist 1990).

$$\vec{a_H} = -\nabla\Phi_{Hernquist} = -\frac{GM}{r(r+r_a)^2}\vec{r}. \qquad (2)$$

Here G is the universal gravitational constant, M is the halo and the bulge mass of M31, r is the relative separation of the center of masses of MW and M31 and r_a is the Hernquist scale length.

However, the disk particles of M31 follow the Miyamoto-Nagai acceleration profile. At large distances from the disk, the Miyamoto-Nagai potential (Φ_{MN}) can be estimated as a decaying exponential profile (Miyamoto & Nagai 1975).

$$\Phi_{MN} = -\frac{GM_d}{\sqrt{R^2+B^2}}. \qquad (3)$$

The interaction of M31 with the halo of MW will introduce friction into the equation. This friction will take away energy from the system and will prevent M31 from escaping or being in a stable orbit around MW. Thus this friction, called dynamical friction, will decelerate M31 and aid in the merger of the two galaxies. The dynamical friction assumes an isothermal sphere profile for the dark matter halo of M31.

$$a_f = -0.428\frac{GM\ln(\Lambda)}{r^2}\frac{\vec{v}}{v}, \qquad (4)$$

where a_f is the acceleration produced due to dynamical friction, M is the mass of the host galaxy (in this case MW), G is the universal gravitational constant, $\ln(\Lambda)$ is the Coulomb logarithm. The Λ parameter is defined as:

$$\Lambda = \frac{b_{max}}{b_{min}}, \qquad (5)$$

where b_{max} is the current separation between MW and M31 and $b_{min} = GM/v_c^2$ (v_c is the circular speed at large radii of M31). In the code, we treated the dynamical friction as a free parameter by introducing a fudge factor. This fudge factor is dimensionless quantity between 0 and 1 that is responsible for regulating the strength of dynamical friction. A fudge factor of 1 implies maximum dynamical friction (equation 4) while the factor's value of 0 indicates no dynamical friction.

Thus the total acceleration of M31 will be the sum of the accelerations induced by dynamical friction, the Hernquist profile and the Miyamoto-Nagai profile.

The next step in the process was to use the LeapFrog function to predict the position and velocity of M31 at succeeding time-steps. The LeapFrog function uses the kinematic equations to predict the future position and velocity. Firstly, it uses current position and velocity of M31 to predict the position of M31 at next half time-step. Then it uses the current velocity and acceleration to predict the velocity at the next time step. Finally, using the position calculated at the half time-step and the velocity at the full time-step, the LeapFrog function calculates the position at the full time-step. Integrating over the LeapFrog function will provide the separation and relative velocity of the MW-M31 system over time.

This project will first use the simulation data from van der Marel et al. (2012a) to reproduce the actual separation and relative velocity of M31 with respect to MW (similar to Figures 2 & 3). Then it will proceed to use the tangential velocity vectors as tabulated in §2 to plot the different orbital interaction scenarios of the M31-MW system. This paper will not concern itself with the entire merger process but will focus its attention on the first interaction. The prediction is that the tangential velocity vector of M31 will delay the time of the first interaction of M31-MW. That is, these spiral galaxies will first interact later than predicted by the actual simulation data. Moreover, greater values of tangential velocities (≥ 100 km/s) do not result in mergers. Instead the system is more likely to encounter a fly-by interaction. At some point (tangential velocities exceeding 120 km/s), the system will become unbound.

4. RESULTS

This project first tested the code at $V_{tan} = 0$ km/s. This was primarily done to set the value of the fudge factor so that the analytical orbit at $V_{tan} = 0$ km/s matches the simulated orbit (during the first close approach). The appropriate fudge factor was found to be anywhere between $0.0 - 0.3$. Then, the code was instructed to randomly choose numbers for the components of the galactocentric velocity vector within the allowed error space. Plotting the results confirmed the hypothesis that the addition of tangential velocity vector delays the timing of the first interaction. The two galaxies encounter each other roughly between $4.5 - 5$ Gyr. Moreover, as the tangential velocity exceeds the magnitude of 100 km/s, a fly-by interaction seems more probable.

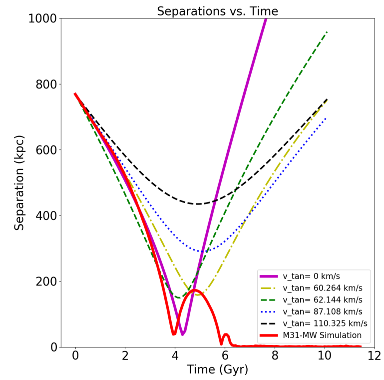

Figure 4. This figure plots the relative separation between MW and M31 for different values of the tangential velocity. The values used are tabulated in the legend. The x-axis represents the time (in Gyr) and the y-axis denotes the separation (in kpc). With the increase in tangential velocity, a fly-by interaction scenario seems more probable. It is evident that tangential velocity slows down the process of the first encounter and the galaxies are expected to first encounter anywhere between $4.5 - 5$ Gyr from today.

The code developed for this project also plotted the total relative velocity ($V_{tan} + V_{radial}$) of M31-MW system and found that the velocity values (with non-zero V_{tan}) peak between $4.5 - 5$ Gyr.

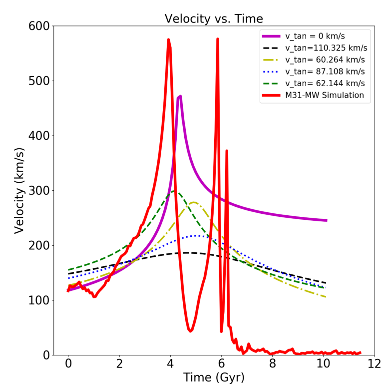

Figure 5. This figure plots the relative velocity of M31-MW system for different values of the tangential velocity of M31. The values of the velocities used are tabulated in the legend. The x-axis represents the time (in Gyr) and the y-axis denotes the velocities (in km/s). Higher tangential velocity values peak later (at around $4.5 - 5$ Gyr) than the velocity value plotted from the simulation data.

5. DISCUSSIONS

The results declared in the previous section do agree with this project's hypothesis. The MW-M31 system's first interaction is predicted to occur later than the simulation data suggests. The tangential velocity measurement of M31 is still a subject of debate and different methods have given different and varied results (discussed in §1). The timing and the type of interaction (merger or fly-by) will affect the different aspects of galaxy evolution like the star formation rate (due to mass loss or mass transfer) and tidal stream formation (due to the interaction of spiral galaxies with the satellite galaxies).

6. CONCLUSIONS

This paper explored the different orbital interaction scenarios of the MW-M31 system from the the inferred tangential velocities of M31. Depending on the measurements of the tangential velocity used, the interaction of MW-M31 system can differ significantly. Thus, using the appropriate values of velocity measurements is important to studying the predicted merger of the this system. This paper explored the question of the timing and the type interaction.

It was found that indeed the first orbital interaction occurred later than expected by the simulation data. Moreover, the chances of complete merger become very unlikely beyond 100 km/s of tangential velocity.

Of course, there are certain aspects this study ignored. For instance, M33's affect on the orbital path was not considered for this project. The full and ideal treatment of the case would be to solve it as a three-body problem. Since there are no theoretical solutions to the three-body problem, it would require an analytical solution and the orbital interaction scenario would definitely change due to the gravitational effects of M33 on the two spiral galaxies.

7. ACKNOWLEDGEMENTS

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