Study of the Magellanic Clouds and Hypervelocity Stars Using Monte Carlo Simulations

ICTP PWF Summer Internship

This report is submitted to the ICTP Physics Without Frontiers: Bangladesh Summer Internship Program, in partial fulfillment of the requirements for completion of the internship.

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Abstract

The orbital evolution of Large and Small Magellanic Clouds were studied under the influence of the gravitational field of Milky Way (MW) Galaxy. Two distinct potentials were used to study the effect of potential variations. Their orbits were integrated backwards in time to study historical trajectory of the galaxies. The interactions were studied probabilistically, using Monte Carlo simulation, to estimate nearest approach both temporally and spatially. The investigation yielded that their event of closest interaction likely occurred near the present epoch. Furthermore, Hypervelocity Stars (HVS) were investigated to determine their possible origins through 3D orbital simulation with respect to combined potential of LMC, SMC and MW. This revealed that the HVS did not originated from a single source. This study confirms that utilizing accurate Galactic potentials with stochastic modeling, dynamical history of satellite galaxies and stellar populations can be investigated.

1 Introduction

Large and Small Magellanic clouds are small galaxies orbiting Milky Way (MW) galaxy. They are the closest galaxies to our own, and are therefore much easier to study. Yet, their motion around MW is complex enough to be interesting, as their orbit is influenced by the gravitational field of the MW and each other. Therefore, study of these galaxies reveals how MW influences their trajectory and their orbital evolution.

The principal goal of this investigation is to study the motion of LMC and SMC. For this, their orbital trajectories need to be integrated. Galpy is a python package specifically created for this purpose (Bovy 2015). Galpy can use different types of potentials. In this investigation, we used Galpy and Astropy to integrate the orbital trajectories of the galaxies using "MWPotential2014" (hereafter MWP) and "MWPotJ23" (hereafter MWJ) potentials (Jiao et al. 2023). The initialization parameters for SMC orbits were taken from Gaia Collaboration et al. (2021). Use of different potential allowed us to observe their subtle effects on the motion of the galaxies and how the results affect the orbit in 3D.

Monte Carlo (MC) simulation was used for probabilistic estimation of interaction between LMC and SMC. This enables study of the distance of closest approach between LMC and SMC and their distance of closest approach to the MW, both temporally and spatially. Analysis of 3D orbital clouds due to the distribution generated from MC simulation provides a picture of how the trajectories diverge in the past.

In addition to studying the motion of the Magellanic Clouds, this project also explored stellar dynamics within the MW, focusing on Hypervelocity Stars (HVS). The Galactic halo contains a small number of stars traveling at speeds faster than the local escape velocity on trajectories that will carry them into intergalactic space (Han et al. 2025). These are the Hypervelocity Stars (HVS). In this investigation, such stars were investigated to determine their possible origin using MC simulation of orbital trajectories in 3D. For this, we used Astroquery python package (Ginsburg et al. 2019) to retrieve Gaia DR3 data (Gaia Collaboration et al. 2023). Besides, studying their motion may give clues on the strong gravitational interactions and past history of our galaxy.

2 Findings

2.1 Large Magellanic Cloud Orbital Components

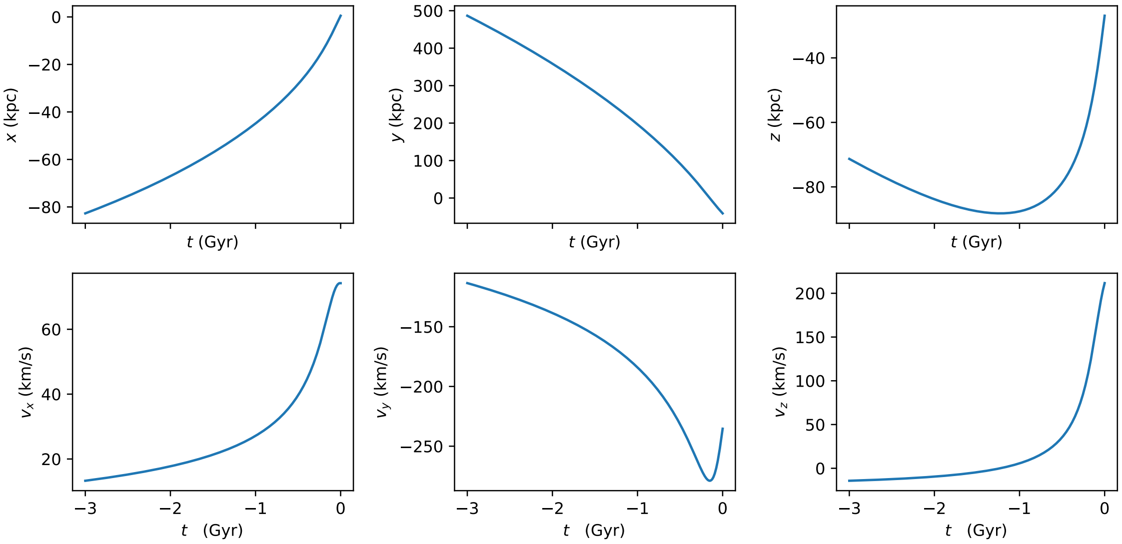


Figure 1: LMC orbital components plotted using MWP. All subplots share identical horizontal scale.

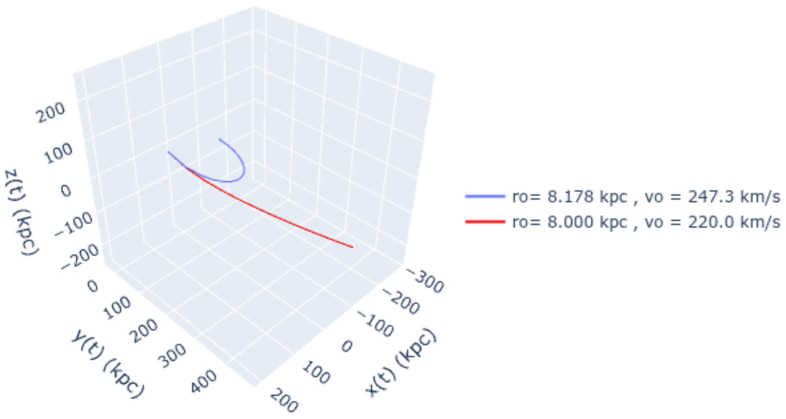


Figure 2: LMC orbit in 3D from -3 to 0 Gyr with different set of ro and vo.

We observe the orbital evolution of LMC, backward in time from -3 Gyr to 0 Gyr. This allows us to examine the past trajectory of LMC within the MW's gravitational field. The orbital integration was based on currently observed parameters of the LMC. Figure 1 shows the variation of the positional components (x, y, z) in kiloparsecs and velocity components (v_x, v_y, v_z) in kilometers per second over time. All subplots share the same time axis, allowing for a easier comparison of each component's evolution. The motion reflects the combined influence of the Galactic potential and LMC's initial kinematic properties. Figure 2 shows the orbit in 3D, where the importance of using the correct ro and vo values is demonstrated, as they set the length and velocity scale of the coordinate system. In fig. 2 different set of ro and vo changed the orbit significantly.

2.2 Effects of Potential Variation

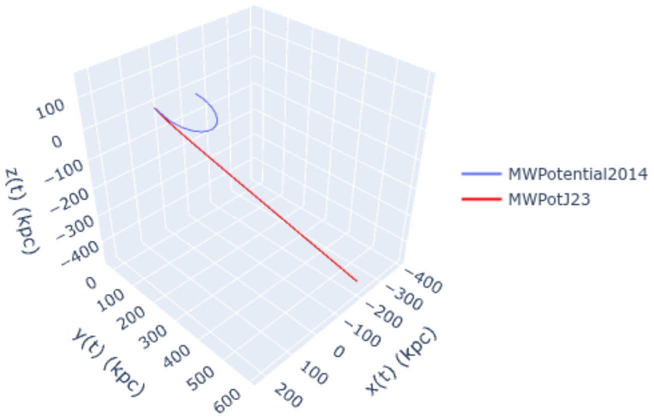


Figure 3: LMC 3D orbit from -3 to 0 Gyr using MWP and MWJ

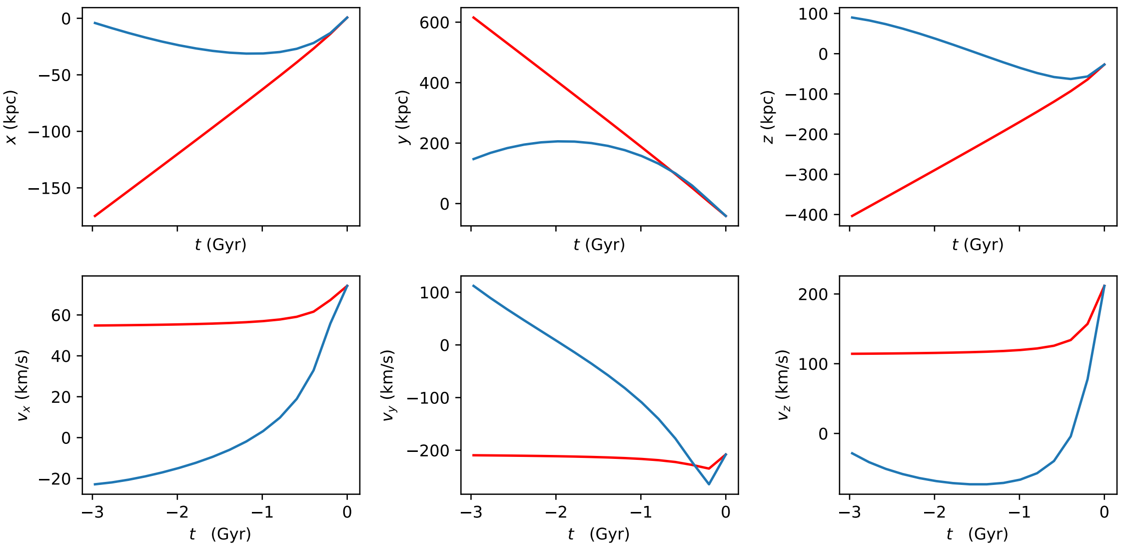
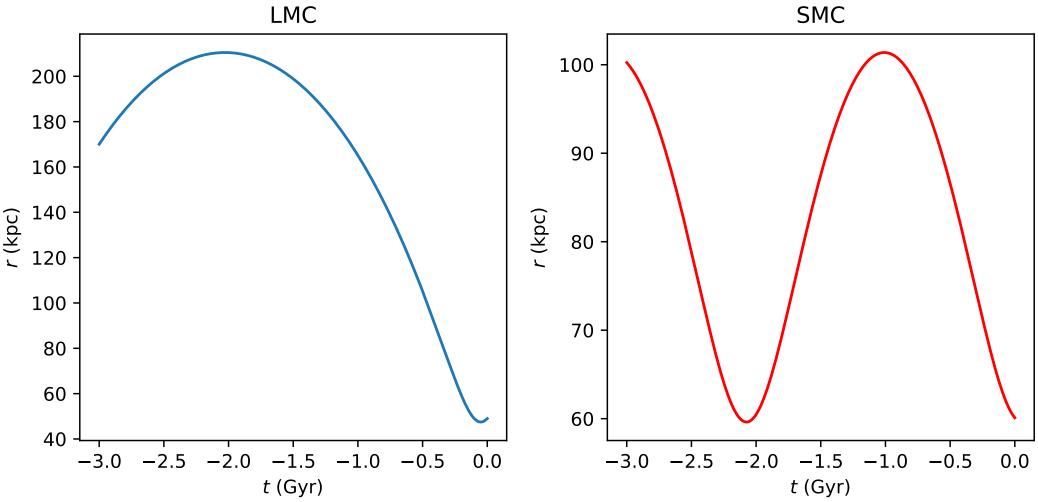


Figure 4: LMC orbital components plotted using MWP (blue) and MWJ (red). All subplots share identical horizontal scale.

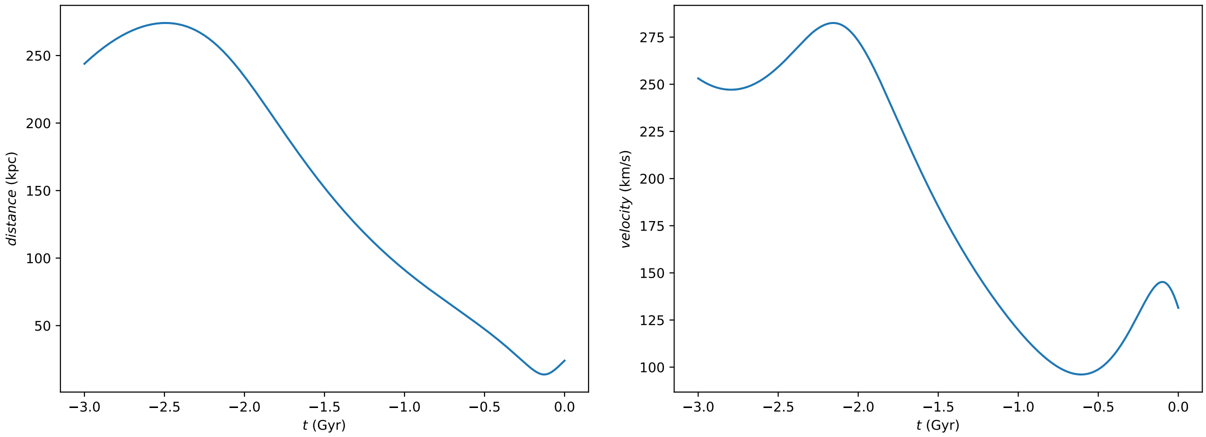
Here, we integrated LMC orbit using two different potentials (MWP and MWJ). Figure 4 shows the orbital components due to the two potentials. We can see that the orbital components due to each potential look quite different and the resulting 3D orbit for each potential is also distinct, as shown in fig. 3. This is due to the different dynamical mass of MW in each potential, as the mass of MW in MWP ($\sim 7.3 \times 10^{11}\ M_\odot$) is almost 4 times that of MWJ ($\sim 1.99 \times 10^{11}\ M_\odot$) (Bovy 2015; Jiao et al. 2023).

2.3 Large and Small Magellanic Clouds

In fig. 5a we can see that the distance from galactic center (GC) for SMC and LMC have a periodic nature. SMC have a much smaller period than that of LMC. Although, such periodic nature can not be observed for figs. 5b and 5c, we can see that the highest peak



(a) Position from galactic center



(b) Relative Distance

(c) Relative Velocity

Figure 5: (a): Position from galactic center over time for LMC and SMC orbit. Relative distance (a) and velocity (b) between LMC and SMC over time, plotted using MWP.

in relative distance graph correspond to the fact that at that time LMC had the largest distance from GC whereas SMC had the least distance. The same time corresponds to the highest peak observed in the relative velocity curve. We can also see in fig. 6 that SMC orbits LMC.

2.4 Monte Carlo Simulation of LMC and SMC Orbits

Here, we simulate the LMC and SMC orbits using MC simulation, generating representative curves corresponding to normal distribution of their orbital parameters under MWP potential. From fig. 7 we can see that, LMC and SMC have highest probability of coinciding near 0 Gyr. From fig. 8a we see that, between -0.5 to 0 Gyr, LMC and SMC have the lowest distance with highest probability. Also, within this time frame, all the different curves closely agree. As we go towards -3.0 Gyr, the curves diverge. In fig. 8b, orbits of both LMC and SMC diverge as they go away from each other. Which matches

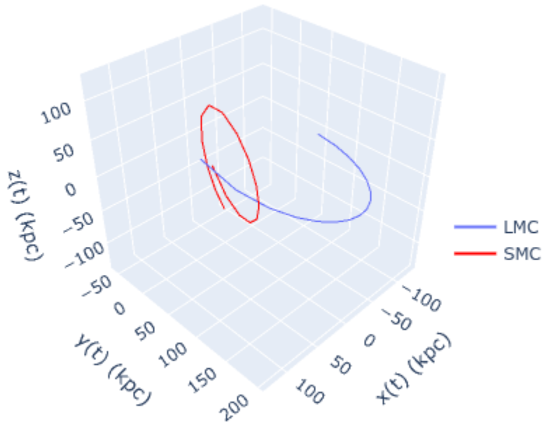


Figure 6: LMC and SMC 3D orbit plotted using MWP.

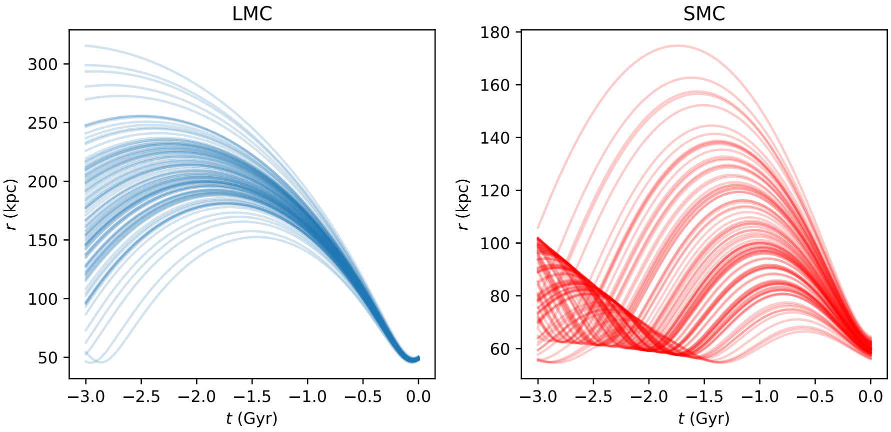


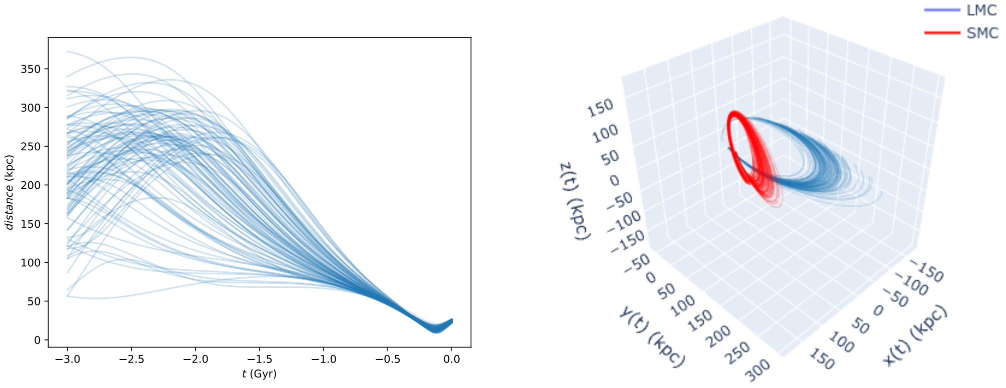
Figure 7: Position of LMC and SMC orbits from galactic center over time plotted using MWP.

our earlier observation of figs. 7 and 8a.

In fig. 8b, MC simulation was used to simulate ensembles of the three-dimensional trajectories of the LMC and SMC. Each curve represents a single realization from the distribution functions of the orbital parameters. This provides a probabilistic illustration of evolution of each system.

The overlapping regions between the LMC and SMC orbits indicates past interactions between the two galaxies, which is consistent with the analyses earlier inferred from the analysis of closest-approach distance. It can be observed that the trajectories of the LMC and SMC converge as time nears 0 Gyr. This indicates narrowing uncertainty as their orbits near the present.

Figure 10 emphasize that small variations in initial conditions can lead to significantly different orbital trajectory over long time limit.



(a) (b)

Figure 8: (a): Relative distance between LMC and SMC over time.
(b): 3D visualization of LMC and SMC Orbital Uncertainty.
All plots used MWP potential.

2.5 Distance of Closest Approach: Monte Carlo Simulation

$$P(r_{\text{min}} \leq R_e) = 0.0 \quad (1)$$
$$P(r_{\text{min}} \leq 2R_e) = 0.02 \quad (2)$$
$$P(r_{\text{min}} \leq 3R_e) = 0.34 \quad (3)$$

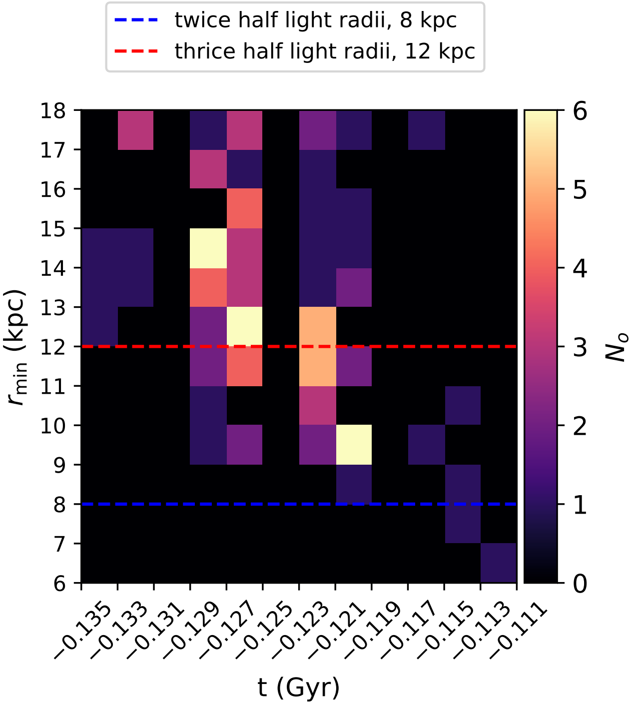
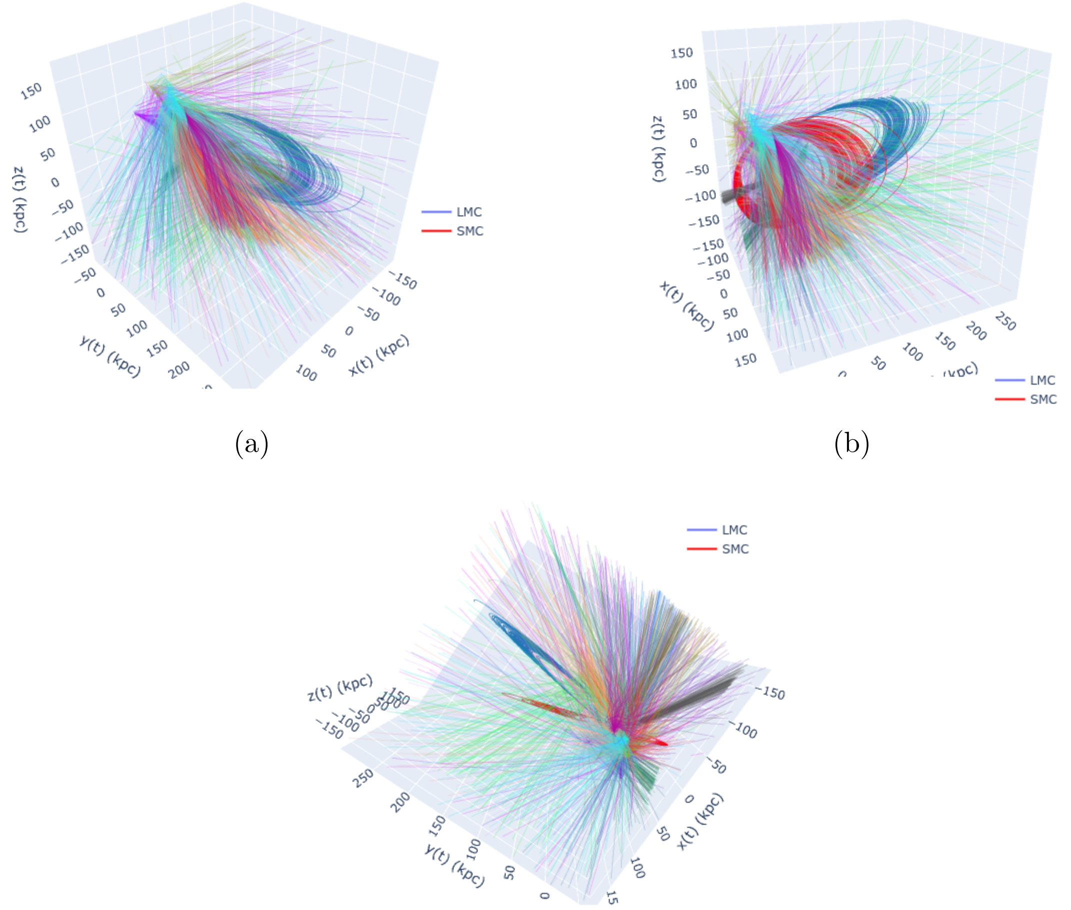


Figure 9: Heatmap showing the distance of closest approach, r_{min} between LMC and SMC, obtained from MC simulation using MWP potential. Here, N_o is the Orbit Counts, i.e. number of orbits that fall within the given distance within the given time frame.

Here, $r_{\min}$ is the distance of closest approach and R_e is the half-light radii. Figure 9 shows that there are few cases for closest distance less than two times that of half light radii exist. But within thrice half light radii, considerable number of cases are available. This is confirmed by our calculation in eqs. (1) to (3). However, fig. 9 provides additional insight into the *timing* of these close-approach events, highlighting *when* they are most likely to occur.

Since the two galaxies (LMC and SMC) came significantly close, their orbital histories have been affected due to their interaction. As a result, tracing their orbit backward in galpy may not reproduce true pre-interaction trajectory, instead requiring more careful Hydrodynamical N–body simulations, as in Wang et al. (2019).

2.6 Hypervelocity Stars



(a)

(b)

(c)

Figure 10: (a), (b), (c) shows MC simulation of HVS orbital trajectories with respect to LMC and SMC orbital trajectories.

Figure 10a shows 3D visualization of the orbits of Hypervelocity Stars (HVS) relative to the LMC and SMC. The stars are affected by the combined gravitational field of the MW, LMC and SMC. But, LMC and SMC are moving with respect to the Galactocentric Coordinates (GCC). Therefore, in this investigation for HVS, we used moving potentials for LMC and SMC. The effective potential combined the effects of both LMC and SMC along with MW. In fig. 10a, each colored line shows a simulated trajectory in GCC, illustrating the spatial distribution and possible origin directions of the HVS population. Then, fig. 10b shows 3D visualization of HVS orbits relative to LMC and SMC from alternative perspective. Finally, fig. 10c shows 3D visualization of HVS orbits relative to LMC and SMC, shown from a different viewing angle. This perspective highlights the spatial distribution and convergence of HVS trajectories with respect to both galaxies. As time reaches 0, the curves of HVS converge. Which again indicates the growing uncertainty in the historical orbit. Figure 11 shows this uncertainty at a larger spatial scale.

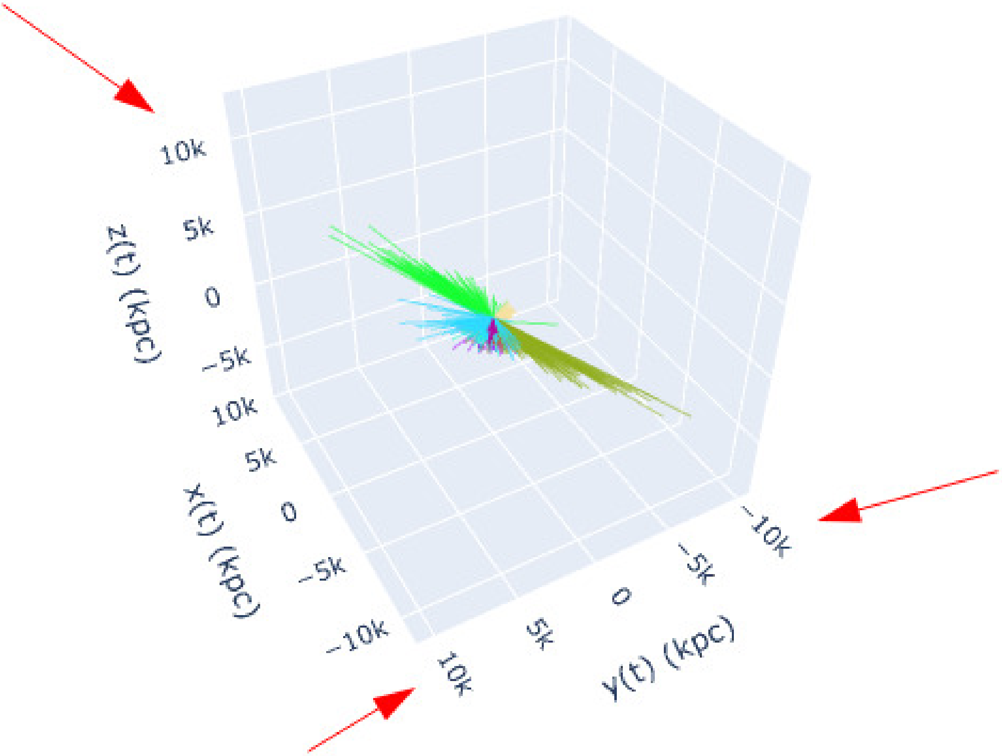


Figure 11: 3D visualization of HVS orbits relative to LMC and SMC, displayed on a larger spatial scale. Shows that the HVS trajectories converge towards LMC or SMC.

2.7 Analysis of HVS Orbits Near the Galactic Center

Here, we select only the stars that pass close to the center (within 5–10 kpc) of either the MW, the LMC, or the SMC. For this, we used modified potential as described in section 2.6. This should allow the HVS trajectories to better reflect physical system. We applied MC sampling to the observed parameters (distance, proper motion, and radial velocity) to produce an ensemble of possible orbits for each HVS, representing uncertainty in their trajectory. This helps us to assess how confidently a star's orbit pass near a galactic center. We generated X–Y and X–Z plots for each HVS to view orbital geometry from different planes. The MC-based 2D visualizations enable a probabilistic understanding of HVS origins rather than a single deterministic orbit.

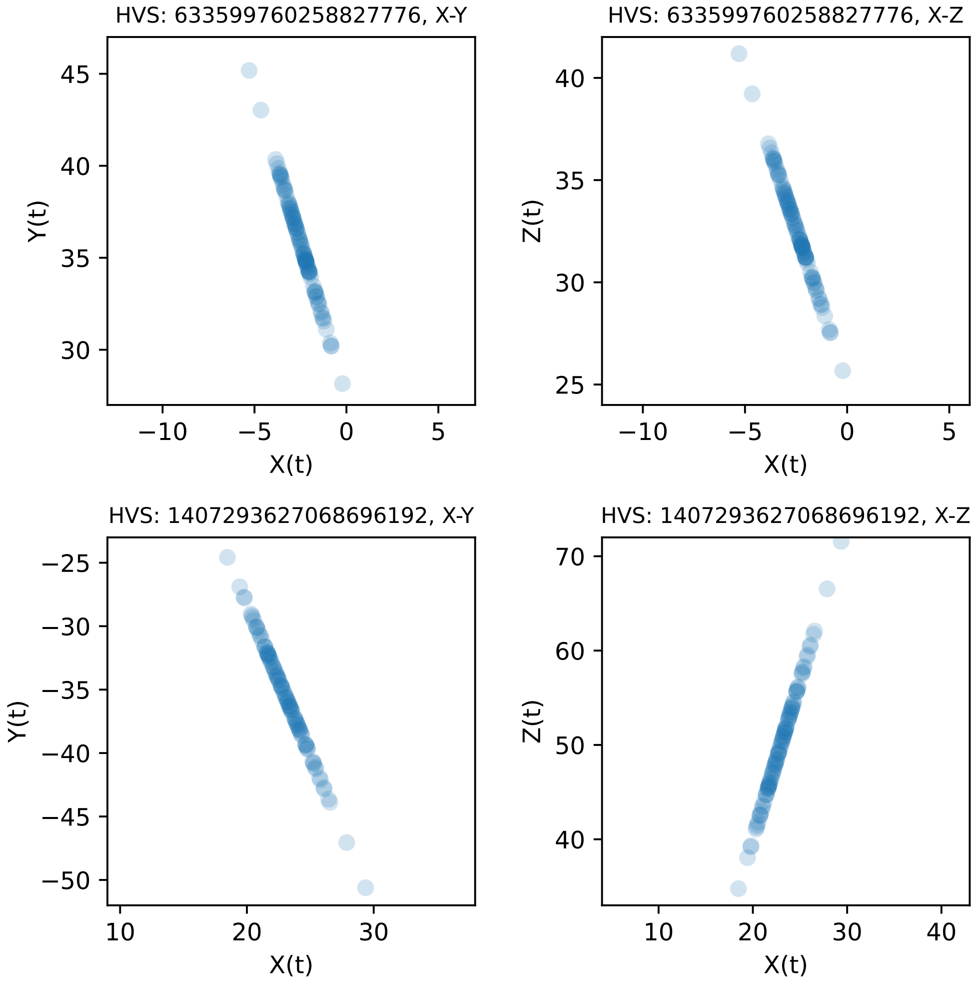


Figure 12: MC simulated X–Y and X–Z orbital projections of HVS's near the MW, LMC, and SMC (within 5–10 kpc).

3 Conclusion

- In this project, orbital evolution of LMC and SMC was observed under the gravitational field of MW galaxy using *Galpy* library.
- Application of different potentials shows distinct trajectory in 2D which also provides vastly different trajectory in 3D, confirming sensitivity of orbital motion to potential variation.
- The analysis of LMC–SMC interaction revealed periodic variations in galactocentric distance and relative velocity. It also shows that LMC and SMC came close near the present epoch and may have been gravitationally bound to each other in the past.
- MC simulations indicates that the two galaxies likely came closest near the present epoch. The probability distribution of the minimum distance demonstrates that a considerable fraction of close interaction events happen within three half-light radii region.

- The study of HVS reveals that many of their orbits converge near the LMC and SMC, implying that these stars may not have originated from a single source.

  MC-based orbital ensembles captured the uncertainty in HVS trajectories and illustrated possible ejection origins.

4 Data Availability

All codes and scripts used in this study are available at the following GitHub repository: https://github.com/amitavdas/ICTP_Summer_Internship_2025

5 Acknowledgement

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Approval

The internship report titled “Study of the Magellanic Clouds and Hypervelocity Stars Using Monte Carlo Simulations” submitted by Amitav Das, a participant of the ICTP PWF: Physics for Bangladesh Online Summer Internship, has been found satisfactory in partial fulfillment of the requirements of the internship program. The internship was conducted under the supervision of **Istiak Hossain Akib** during the period **15 July 2025** to **15 October 2025**.

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