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An AMUSE Based Research Project

# THE MILKY WAY AND ITS EXOTIC MILLISECOND PULSAR POPULATION: A STATISTICAL ANALYSIS

*Is there the possibility that millisecond pulsars living in the Milky Way migrated from the Large Magellanic Cloud?*

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## Abstract

Millisecond pulsars are objects with a large variety of use in the field of physics, from testing the theory of general relativity to finding the first extra-solar planetary system. This paper investigates the discrepancy of the theorised population of non-binary millisecond pulsars with that of the one observed today. More explicitly, it looks to investigate whether millisecond pulsars found in the Milky Way may have originated from another galactic system, namely the LMC. To do so, AMUSE, a programming framework which most notably enables the bridging of multiple systems as well as resolving issues with a multi-scale nature is incorporated. By bridging the galactic neighbourhood with one another, millisecond pulsars are systematically shot from a globular cluster modelled after NGC 1783 for a time period of 1Gyr. Although results show that millisecond pulsars currently orbiting the Milky Way may have originated from another system, they also show that only a minute fraction of them would have come from the LMC.

# Contents

# 1 Introduction

From being used to detect the first extra-solar planetary system (Wolszczan and Frail, 1992) to being the centre of discussion in Nobel Prize-winning papers testing the theory of general relativity (Taylor and Weisberg, 1982), millisecond pulsars have become a popular research topic in the field of physics since their discovery in 1967 (Hewish et al., 1968).

Pulsars are rapidly rotating neutron stars formed after a supernova explosion which periodically emits electromagnetic radiation as charged particles accelerate along their magnetic field lines. This periodic and stable emission of signals is the source behind their broad use within the field. To date, there are upwards of 2800 detected pulsars (Manchester et al., 2005) and figure 1-1 shows the distribution of their population within the Milky Way.

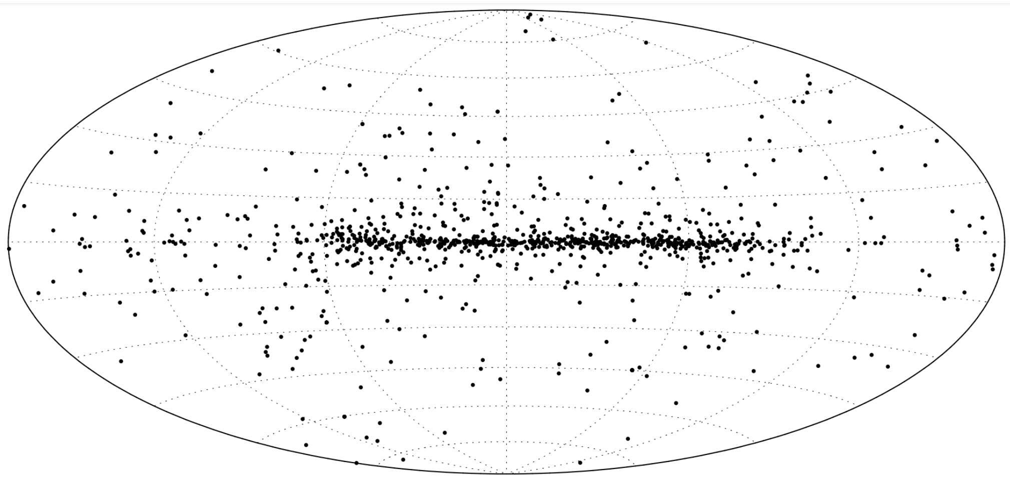

**Figure 1-1:** The population map of pulsars within the Milky Way. The plane of the galaxy can be denoted with the horizontal line of the pulsar population. (image courtesy of Lorimer (2001))

Although there has been a vast amount of research conducted regarding pulsars, there is still an abundance of questions left unanswered. One such mystery is the significant fraction of millisecond pulsars within the Milky Way having no companions. Although it's proposed that these millisecond pulsars may have gotten rid of their companions via ablation, which seems to be the case for PSR 1957 +20 (Fruchter et al., 1988), the timescales of such a process make this explanation inconclusive. One possible reason for this observed fraction of solitary pulsars that have yet to be touched upon by research may be the capturing of millisecond pulsars from nearby galactic systems such as the Large Magellanic Cloud (hereafter LMC) or Small Magellanic Cloud (hereafter SMC). This paper takes a statistical approach with the help of AMUSE[1] (Portegies Zwart and McMillan, 2018) in investigating the possibility of millisecond pulsars migrating from the LMC to the Milky Way.

[1] Code available at: https://amusecode.github.io/

The paper is composed of six main sections. Section two gives a brief introduction of millisecond pulsars providing the reader with justification as to why such a topic is interesting to investigate. Section three dissects the mathematical theory implemented within our code, giving for a better understanding of the eventual results. An overall discussion on AMUSE and the code is found in section four in which we also justify some further assumptions made. Section five and six describes the general procedure and discusses the results of the paper respectively. Section seven will summarise the report with a general conclusion as well as suggesting possible research that can be built from our paper.

## 2 Millisecond Pulsars: What are they?

The millisecond pulsar birthrate in the Milky Way is $2\times10^{-5}$ yr$^{-1}$ (Lorimer, 1999) and forms once a massive star loses its fuel, causing it to no longer sustain hydrostatic equilibrium and collapse onto itself. If the star is massive enough, it will cause a supernova explosion in which the remaining object, the neutron star, ends up weighing around $1.4M_{\odot}$ with a significant portion of the original mass ejected from the system. Since the star is now only a fraction of its original size (a few kilometres in radius), for it to conserve angular momentum, it's spin drastically increases. The periodic signal received from these celestial objects stems from the fact that charged particles accelerate along the magnetic field lines and as the pulsar rotates along its axis if the beam passes our line of sight a signal is detected. It is noteworthy to mention, however, that it is still unclear how their magnetic field arises (Cruces et al., 2019) but this is out of the scope of the paper.

This report focuses on a particular class of pulsars called millisecond pulsars. These pulsars have a period $T$ of $1.4 \leq T$ ms $\leq 30$ (Lorimer, 2008), meaning they can spin just shy of a thousand times per second along their axis. The report investigates this class of pulsar specifically as a quicker spin induces a weaker magnetic field, in turn, allowing them to live longer (Phinney and Kulkarni, 1994). A 'normal' pulsar tends to live around 100 Myr (Toscano et al., 1999a), whereas, millisecond pulsars have a lifetime comparable to the age of the Universe (Lorimer, 2008), allowing the opportunity to be captured within the Milky Way without us even realising they may have originated from another system.

However, a typical supernova explosion will not yield the rapid spin millisecond pulsars exhibit. To obtain its rotational speed millisecond pulsars need to originate from a binary system. In this binary system, the massive star dies first and goes through a supernova explosion following the same procedure described earlier. If the binary system remains bounded, the resulting neutron star may start to accrete mass from its companion causing its angular momentum (and therefore spin) to increase (Saxton, 2020). Due to the globular cluster being the densest region of the galaxy, they are somewhat of a nursery for millisecond pulsars since there is a larger probability for a neutron star to interact with another celestial object to increase their spin in these regions.

As the millisecond pulsar accretes mass, the orbit of the system starts to contract emitting gravitational potential energy and giving rise to the possibility for the system to become unbound (Kul). Another possible scenario for the system to be disrupted is one in which a second supernova explosion, this time of the companion star, occurs, causing the millisecond pulsar to get ejected. Nevertheless, these two scenarios are not the norm with 80% of detected millisecond pulsars being found in binary systems (Lorimer, 2008).

# 3 Distribution of our Millisecond Pulsars

## 3.1 The Velocity Distribution

As alluded to in the previous section, millisecond pulsars tend to live in binary systems. Pulsars in a binary system have low velocities and therefore will never get unbound from the LMC. For this reason, one assumption we make is that all millisecond pulsars in our simulation get ejected via a secondary supernova explosion initiated by their companions. We apply this assumption by changing the time interval in which millisecond pulsars are born at (further discussed in section 5).

Although a supernova explosion can be symmetric in the dying stars frame, this is not the case in the centre-of-mass frame. The millisecond pulsar will feel a rebound effect after its partner's supernova explosion and in turn, get a boost in its velocity. If half the systems mass gets ejected during the supernova event the binary system is destroyed (Hills, 1983) and the millisecond pulsar may obtain a velocity high enough to become unbound from the LMC.

There have been many papers investigating the velocity distribution of pulsars over the past few decades (Lorimer et al. (1997) ; Hansen and Phinney (1997) ; Toscano et al. (1999b) ; Hobbs et al. (2005)) each providing differences in their results. This paper uses Hansen and Phinney (1997) as a reference point simply due to it calculating the ejection velocities for pulsars after a supernova ejection which is the scenario that allows the pulsars to become unbound from the LMC. Furthermore, this velocity distribution is used since it takes into account the fainter, quicker pulsars as well as the slower, brighter ones that some of the other studies overlooked. Using Monte Carlo simulations, they found that pulsars ejected from a supernova tend towards the following velocity distribution:

$$P(v_k) = \sqrt{\frac{2}{\pi}} \frac{\bar{v}^2}{\sigma_v^3} e^{-v_k^2/2\sigma_v^2} \tag{1}$$

Where $\bar{v}$ is the mean velocity of the population, $\sigma_v$ the standard deviation of the distribution and $v_k$ the kick velocity. Upon simulation, they found that the mean velocity is given as $\bar{v}_k = 250 - 300$ km s$^{-1}$ with a standard deviation of $\sigma_v = 190$ km s$^{-1}$. The mean velocity for this paper was chosen at $\bar{v_k} = 250$ km s$^{-1}$ while keeping the standard deviation at $\sigma_v = 190$

km s$^{-1}$. The distribution function of equation 1 with the chosen values for this paper is shown in figure 3-1.

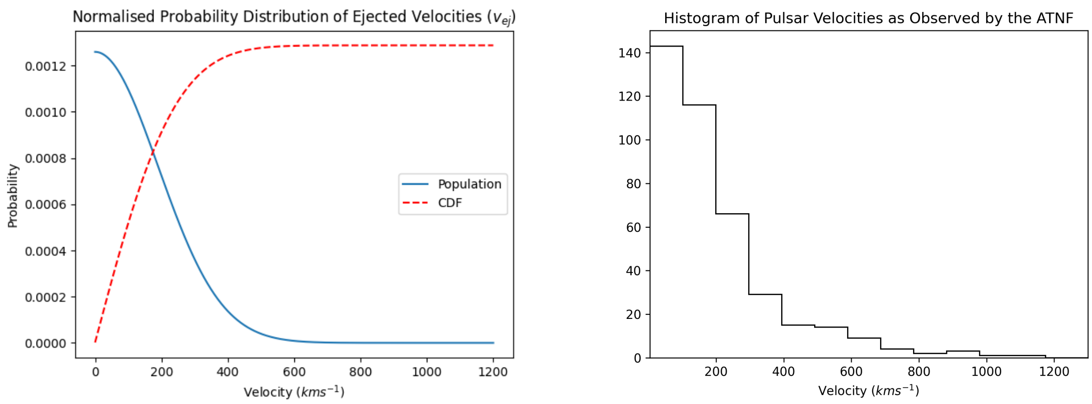


**Figure 3-1:** Left: Normalised distribution function and cumulative distribution function (CDF) of the velocities in our simulation. Right: Histogram of pulsar velocities in km s$^{-1}$ using the ATNF catalogue (Manchester et al., 2005)

As can be seen in the figure above, most millisecond pulsars will have their velocities in the lower end of the spectrum. This trend fits that of the observed data with the histogram shown on the right-hand side, further showing the strength of the chosen velocity distribution of the report. To improve the ejection mechanism the code randomly multiplies the $v_x, v_y, v_z$ values by $-1$ or 1 such that the direction of ejection is random.

## 3.2 The Mass Distribution

Another aspect to keep in mind with the simulated millisecond pulsars is the mass attributed to them. Although this will not play a role in the orbit and evolution of the system, it is defined as it allows calculation on the energy of the system. Calculating the energy of the system provides information on the reliability and stability of the simulation.

Although pulsars tend to have a mass of $1.4M_\odot$ following the Chandrasekhar limit, millisecond pulsars accrete mass after their supernova explosion meaning they can attain a mass exceeding this. The mass distribution for the sampled population adopted in this report uses a Gaussian distribution utilising the values found by Antoniadis et al. (2016) as this is one of the more recent works investigating the issue. The Gaussian distribution is taken simply due to the lack of papers providing a mass distribution towards the population. Furthermore, the Central Limit Theorem states that distributions tend to a normal distribution at a large enough sample size limit. Antoniadis et al. (2016) found that at least 3% of all millisecond pulsars have a mass above $2.1M_\odot$ which allowed the calculation of the standard deviation when working backwards. Furthermore, the paper constrains the maximum mass as $2.15M_\odot$ while stating that the average mass of the millisecond pulsar population being between $1.3 \leq \bar{M}_\odot \leq 1.5$.

# 4 The Code

The code is separated into several different scripts. This section dissects the individual scripts and describes their role in the simulation.

## 4.1 Gravitational Potentials

The simulation incorporates four gravitational potentials, one for the SMC, one for the LMC, one for the globular cluster the millisecond pulsar is shot out from and finally, one for the Milky Way. The potentials are based on code imported from the AMUSE community `galactic_potentials`.

The potential of the LMC and SMC incorporates both a Plummer and Navarro–Frenk–White (NFW) potential (Navarro et al., 1997). Although this gives for an idealised version of the potential for these two irregular galaxies, numerous papers have approximated their potentials as such with great success (Bes; Yoshizawa and Noguchi (2003); Bekki and Chiba (2005)). The SMC, being the smallest galactic system, will have minimal effect on the trajectory of the pulsar and a general model of its potential suffices for the report. Furthermore, although the pulsar originates from the LMC, given that it has to be ejected from the system to be captured by the Milky Way the pulsar's trajectory will be minimally affected by the LMC potential meaning that it is right to ignore some of the finer details. Lastly, the paper isn't interested in the intricate details of the evolution of the pulsar within these systems instead it aims to find which parameters are needed for the pulsar to be bound to the Milky Way and so such generalisation of potentials are deemed suffiecient for the report.

The Milky Way potential is taken from the one developed by Bovy (2015), namely `MWpotentialBovy2015`. This code also provides an idealised version of the potential however it incorporates a bulge model with a power-law density profile along with a Miyamoto-Nagai potential describing the disk and an NFW potential for the dark matter halo. His paper provides extensive details if one wishes to know further. However, it is noteworthy to realise that both the spiral arms and bar of the Milky Way are ignored in this profile, nevertheless, it provides an accurate representation of the general galactic potential.

The globular cluster will have the weakest potential within the simulation. However, since the millisecond pulsar originates at this location, it is essential to represent such a system. The globular cluster mimics the cluster NGC 1783 which inhabits the LMC. The potential used will be that of a Plummer potential as this profile was first introduced to imitate globular cluster environments (Plummer, 1911).

One final comment on the potentials is that they are rigid potentials, this means that neither the LMC, SMC, globular cluster or Milky Way are evolving throughout the simulation and therefore will have no interaction with one another including tidal effects. Although this is a large assumption, as mentioned earlier, the report doesn't look to analyse in intricate detail the trajectory of the millisecond pulsar, instead, it looks at whether the millisecond pulsar ends up being bound to the Milky Way and therefore potentials which interact would only add unnecessary complication to the code and yield it inefficient.

## 4.2 The Code's Methodology

The simulation begins by running the two scripts `galpot_init.py` and `particle_init.py`. `galpot_init` set's up and initialises the analytical potentials for the LMC, SMC and a globular cluster as calculated based on the models described in the previous section. The script `coordinates.py` plays an essential role in doing so as it converts coordinates from the International Celestial Reference System (ICRS) system, in which the original data is provided in, into cartesian coordinates while simultaneously converting it into the galactocentric frame with the help of `astropy`. Furthermore, `coordinates.py` contains the coordinates and velocities associated with the galactic systems at the initial time-step - that means the conditions 1Gyr in the past which is the time the simulation starts generating the millisecond pulsar population.

`particle_init.py` initialises the millisecond pulsar to be emitted based on the parameters given in section 3 and for every time-step generates a set of particles that represent and traces the LMC, SMC, globular cluster and millisecond pulsars centre of mass. The object classes governing the potentials and millisecond pulsar are systematically updated as the simulation evolves.

The representation of the galactic centre of mass done in `particle_init.py` allows the simulation to keep track of the location of the potentials. Furthermore, during each time-step the millisecond pulsar generator generates a new star to be emitted from the LMC based on a probability dependent on the calculated millisecond pulsar birth rate in the LMC (more on this later).

The backbone of the program is in `evol.py`. This script is what evolves the particle sets over time. The LMC and SMC centre of mass particles interact with each other through a Hermite integrator and are both bridged with the Milky Way potential with the help of AMUSE's bridge functionality. The globular cluster's centre of the mass particle, on the other hand, uses a `drift_without_gravity` solver which is in turn bridged with the potentials of the LMC, SMC and Milky Way respectively. The orientation of the globular cluster's initial velocity is chosen such that it will remain bound to the LMC.

The neutron stars are generated throughout the simulation, potentially adding a new millisecond pulsar each time-step based on a probability dependent on the birthrate of such a celestial object for every time-step within the LMC. The millisecond pulsars may then interact with one other through a Hermite integrator while simultaneously still being bridged with the LMC, SMC, Milky Way and globular cluster potentials. The bridging between the different systems allows the simulation to incorporate all possible effects from the potential onto one another's orbit, which in turn would affect the overall trajectory of the millisecond pulsar.

At the end of the simulation, a check is carried out to filter the data into only showing the millisecond pulsars which are close to the Milky Way. The `evol.py` script outputs three different files: `neut_stars_positions.pkl`, `check.txt` and `gal_lines.pickle`. `neut_stars_positions.pkl` contains a data frame that keeps track of each millisecond pulsars trajectory in the simulation. The rows represent neutron stars while the columns represent a given time in the simulation. `check.txt` contains the indices in this data frame which represent the neutron stars deemed to be caught by the Milky Way's potential. The `gal_lines.pickle` file contains the coordinates of the LMC, SMC and globular cluster's centre of mass particles.

The whole program is run from `interface.py`. This script gives multiple prompts, providing the user with some flexibility in what they want to obtain. First, it asks whether one wants to generate a new set of neutron stars or not, it proceeds by asking if one wants to obtain plots of the trajectories and whether one wants to print in a text file the final positions of the bounded millisecond pulsars.

If one wants to generate a new set of millisecond pulsars, the code `evol.py` is called and a simulation is carried out. If one wants to plot, the three output files mentioned earlier are called by another script, `plotters.py`. This script contains all the functions that plot the data. It also contains a function called `pplot`, which is not used in the final simulation but was used to make the GIF files showcasing the time behaviour of our program.

If one wants to calculate distances, the final coordinates of the stars that came close are used to calculate the distance modulus to the galactic centre. The output file is called `distances.txt`. These can then, for example, be compared against known neutron stars to see how the simulated results vary with observations.

The complete program, including results, can be obtained at: https://zenodo.org/record/4166276#.X51s0XVKgrg

The program may also be found on GitHub at: https://github.com/ErwanH29/Team-B-Millisecond-Pulsars

## 5 The Simulation

The simulation begins by initialising the LMC, SMC and Milky Way system. The SMC and LMC's position and velocity parameters are provided by SIMBAD (Wenger et al., 2000) and can be referenced in table 1 and table 3. The heliocentric frame which the data is based on gets converted into the galactocentric frame with the help of `astropy`. This conversion enables the Milky Way to become the frame of reference. After evolving the system backwards 1Gyr in time, the globular cluster, modelled after the LMC's NGC 1783, is added to the system whose initial values are also shown in table 3. The code traces the system backwards by reversing the velocity's sign in the gravitational code. The research then initialises the system at this time and takes the values found as the new initial conditions. By doing so we do not take into account the stellar formation rate history nor the evolution of the different potentials and so our initial values may differ to what the actual scenario was 1Gyr back in time.

| Object | R.A (ICRS system) | Dec. (ICRS system) | Distance (kpc) |
|---|---|---|---|
| LMC | 05h 23m 34.6s | $-69°45'22''$ | 49.97 |
| SMC | 00h 52m 38.0s | $-72°48'01''$ | 61.7 |
| Globular Cluster | 04h 59m 08.6s | $-65°59'15''$ | 50.1 |

**Table 1:** Initial (heliocentric) positional values of the LMC, SMC and NGC 1783 used for the simulation. Data was taken from Wenger et al. (2000), except for the distance of NGC 1783, taken from

| Object | $v_x$ (km s$^{-1}$) | $v_y$ (km s$^{-1}$) | $v_z$ (km s$^{-1}$) |
|---|---|---|---|
| LMC | 47.0 | 242 | 225 |
| SMC | 5.35 | 164 | 136 |

**Table 2:** Initial (heliocentric) velocity values of the LMC and SMC. Data was taken from Wenger et al. (2000). The velocity of the globular cluster is calculated from the circular velocity formula at a given radius due to the minimal amount of measurements regarding the velocity of NGC 1783.

The globular cluster is assumed to be a collisionless system such that the millisecond pulsar doesn't have it's trajectory drastically alter at the beginning of each ejection. A collisionless cluster was chosen for the paper as it reduces the dependency on arbitrary parameters such as the number of particles within the globular cluster or the proximity they have with one another. Furthermore, for large velocities, neighbouring stars will have a negligible effect on an unbound pulsar.

The simulation proceeds by evolving the system forwards in time for 1Gyr with the help of the bridge code mentioned in section **??**, allowing for the multi-scale system to be represented at the current time with the emitted millisecond pulsars having their final positions being their positions now. By moving forwards in time, once again we neglect the stellar formation rate of all three galactic systems which may play a role in the overall mass and therefore the potential of the system. Nevertheless, we assume that the LMC emits an isolated millisecond pulsar from a supernova every 1.80 Myr.

This emission rate of one millisecond pulsar every 1.80 Myr is determined based on the average star formation rate (SFR) of both the Milky Way and LMC in the last 2Gyr, found to be $0.68 - 1.45\ M_\odot\ \mathrm{yr}^{-1}$ (Robitaille and Whitney, 2010) and $0.2 M_\odot\ \mathrm{yr}^{-1}$ (Harris and Zaritsky, 2009) respectively. Using the fact that millisecond pulsars are born every $5 \times 10^4$ years in the Milky Way (Lorimer, 2008), the ratio of the SFR between both systems was taken to obtain the final birth rate of millisecond pulsars within the LMC. Using this information a millisecond pulsar is born every 0.36 Myr in the LMC when using an SFR of $1.45 M_\odot$ for the Milky Way. Given the fact that 20% of all millisecond pulsars are in non-binary systems Lorimer (2008) and the report only looks at non-binary millisecond pulsars, this gives for a final value of a millisecond pulsar birth occurring every 1.80 Myr in the LMC.

It is clear from this that many assumptions are made - for instance taking a 1 : 1 relation between the birth rate of millisecond pulsars in the LMC and Milky Way as well as the arbitrary value used for the SFR of the Milky Way. However, given the information currently provided this can be deemed as a sufficiently accurate representation of the non-binary millisecond pulsar population of the LMC.

In the end, a total of 555 millisecond pulsars get simulated, and so given the velocity distribution, it is expected that only a minute fraction of these gets captured by the Milky Way. To further simplify data processing, the code filters through the data by only extracting the bound pulsars, defined as millisecond pulsars within $\pm$20kpc from the galactic centre in all three spatial coordinates $(x, y, z)$.

## 6 Results

### 6.1 A Qualitative Analysis

*The following sections are not going to be emphasised in the referee report as the simulation continuously gets refined and for every new trial new results are obtained. Nevertheless a brief description of the results are given to show the reader what has been obtained up to now and give a brief idea of what the final report will have.*

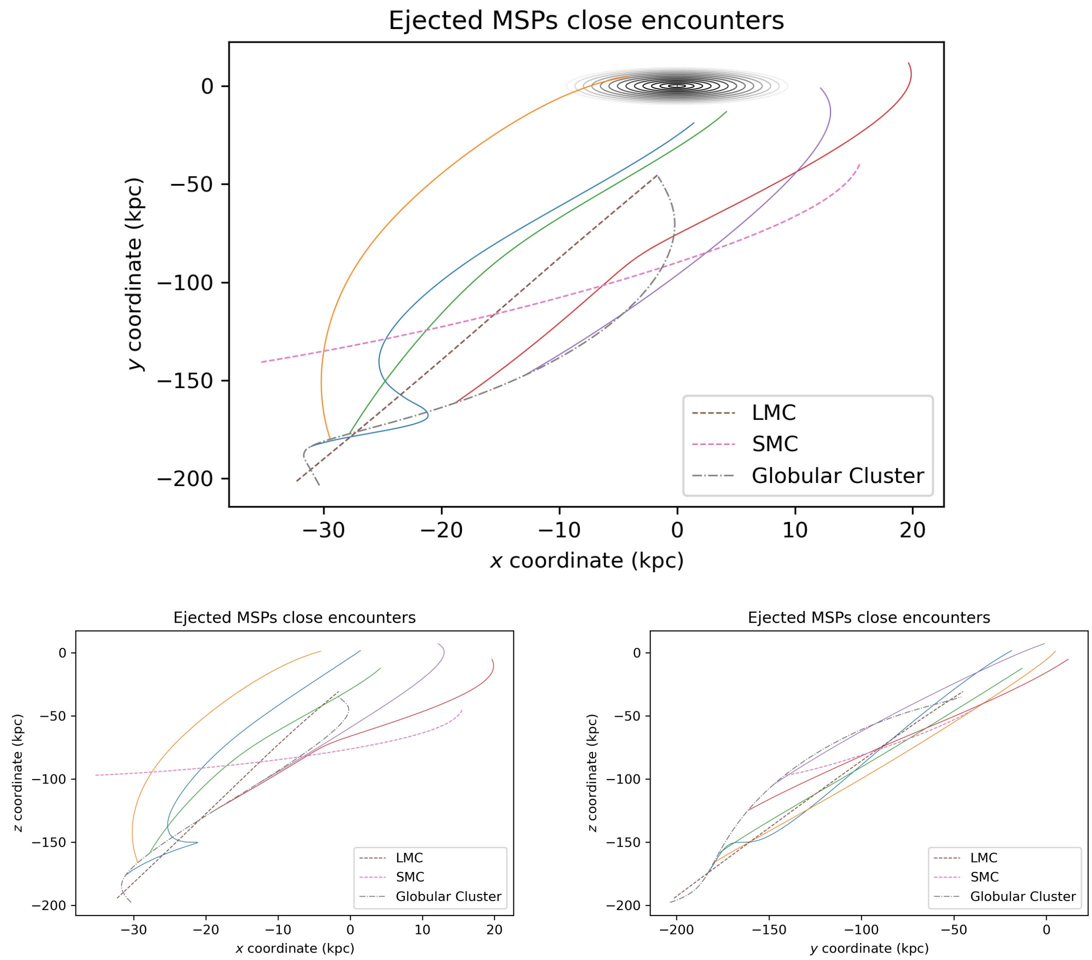


**Figure 6-1:** Top: Captured millisecond pulsar trajectories in the $xy$ plane. The Milky Way is shown with the contour lines of its potential. Bottom Left: Captured millisecond pulsar trajectories in the $xz$ plane. Bottom right: Captured millisecond pulsar trajectories in the $yz$ plane.

The three plots above show the trajectories of the bound millisecond pulsars, defined to be pulsars with a final position within 34 kpc of the Milky Way, in three different planes. The simulation emitted a total of 555 pulsars meaning that 0.90% of them got captured.

This represents only a minute fraction of the total population being captured, however it illustrates the possibility of millisecond pulsars migrating between different galactic systems.

Observed in the $xy$ plot are pulsars curving towards the Milky Way's galactic center. This curving inwards implies that due to the short integration time our simulation uses, their respective distance modulus from the galactic center will be skewed towards larger distances in our final results as the pulsar hasn't had time to be embedded within the galaxy. Furthermore, since the potential well is much larger at the center of the Milky Way, once the millisecond pulsar approaches it, there is the possibility that it gets bounded to it affecting it's orbital properties and making it indistinguishable with pulsars born within the Milky Way further implying that results obtained will be skewed towards higher distances.

A keen eye would notice that both the red and blue solid lines have each a significant bump in their trajectory. These bumps may be induced via the interaction of newly generated millisecond pulsars with these two objects as they both seem to occur while still following the globular cluster's trajectory. If this is the case, this notion would give rise to further unaccounted for uncertainty as newly generated pulsars seem to affect each other's orbit. This stems from our assumption that all millisecond pulsars within the LMC is born in one globular cluster with a definite location, while in reality they would be born all over the LMC, having little effect on one another. The plots of the other simulations shown in Appendix 7 do not seem to suggest this is a common occurrence and so it wouldn't pollute the final results as much as this particular simulation suggests it to.

It would be interesting to increase the total time simulated of the system since it would allow the captured millisecond pulsar system starts to stabilise and be fully embedded within the Milky Way. However given that the age of the LMC is roughly 1 Gyr Age, integrating forwards 2 Gyr in time would make no sense for the system established in this paper. Instead one could direct their attention to the closest established galactic system, M31, who is $2.43 \times 10^6$ (Vilardell et al., 2010) light years away. A millisecond pulsar emitted with the mean velocity used in this paper of 250 km $s^{-1}$ would take roughly 3 Gyr to arrive to the Milky Way assuming that the Universe is static. This means that any pulsar emitted in the first 7 Gyr of the M31 system could have migrated to the Milky Way without us ever knowing and they would have the time to be fully embedded within the Milky Way. Of course the velocity needed would have to be perfectly lined to our galactic system and so only a few could be captured, however it is a possibility that could be investigated further given the much larger time frame of the simulation, and the larger millisecond pulsar population formed in M31.

### 6.2 A Quantitative Analysis

The table below shows the distance modulus of bound pulsars from the center of the Milky Way in kpc. One can immediately observe in the large variation of not only the amount of bound pulsars, but also their respective distances to the galactic center.

| | Pulsar 1 | Pulsar 2 | Pulsar 3 | Pulsar 4 | Pulsar 5 | Pulsar 6 | Pulsar 7 | Pulsar 8 |
|---|---|---|---|---|---|---|---|---|
| Trial 1 | 18.9 | 6.53 | 18.4 | 23.5 | 14.2 | - | - | - |
| Trial 2 | 20.9 | 24.2 | 15.1 | 20.4 | 5.58 | 26.4 | 30.6 | 16.3 |
| Trial 3 | 24.1 | 23.5 | 17.1 | 21.4 | 9.30 | 19.3 | - | - |
| Trial 4 | 15.2 | 23.0 | 33.1 | - | - | - | - | - |
| Trial 5 | 25.1 | 15.9 | 17.5 | - | - | - | - | - |

**Table 3:** Data table of bound simulated millisecond pulsars with values given in kpc with respect to the center of the Milky Way.

The range of the distances vary drastically from being anywhere between 5.58 kpc all the way to 33.1 kpc, although most seem to revolve around 20 kpc. If we compare these results with the histogram provided in figure 6-2 we can see that there aren't many observed pulsars roaming the Milky Way at the distances most of these simulated pulsars have as their final position. Nonetheless it gives rise to the idea that the observed pulsars far from the galactic center may have originated from the LMC, although it may also have been simply kicked from the Milky Way itself.

It was to be expected that the distances found are values skewed towards the larger distances since the simulation doesn't evolve at large enough times. The results highlight the possibility of millisecond pulsars near the galactic center originating from other galactic systems and these are the ones of interest as their orbital properties would have been greatly affected by the potential observing such objects would simply suggest they were born here and is why investigating the same idea but using a much older galactic system such as M31 would be very interesting to look at.

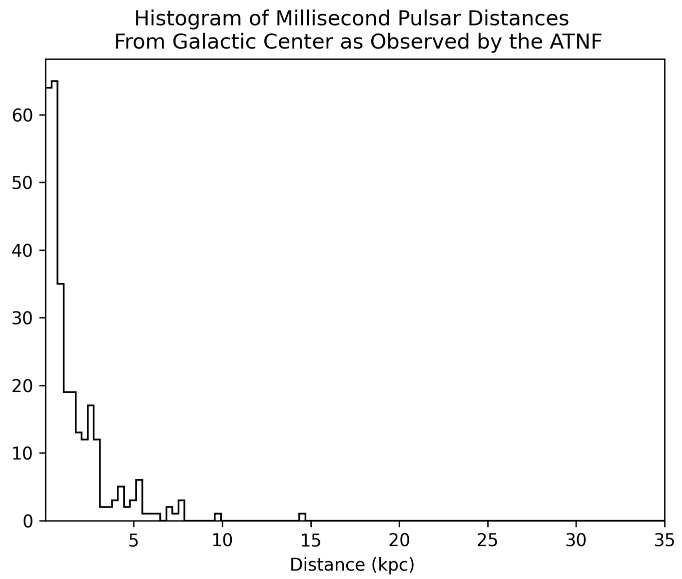


**Figure 6-2:** Histogram of the distance modulus of the observed millisecond pulsar population with respect to the center of the Milky Way. Sample size of 291 using data from Manchester et al. (2005).

### 6.3 Noise and Error

*We have yet to delve into this are further but the plan is to do many more simulations and compare the fraction of pulsars caught by the Milky Way to give a general feel as to the percentage captured for each simulation. We also aim to look at the distribution of the caught millisecond pulsars to see the overall results.*

#### 6.3.1 Energy Stability

*We aim to add a discussion on the total energy evolution of the system but with recent updates in our simulation we have not yet implemented the tracking of the energy in the new code.*

## 7 Conclusion

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# Appendix A: Graphs of the other simulations used

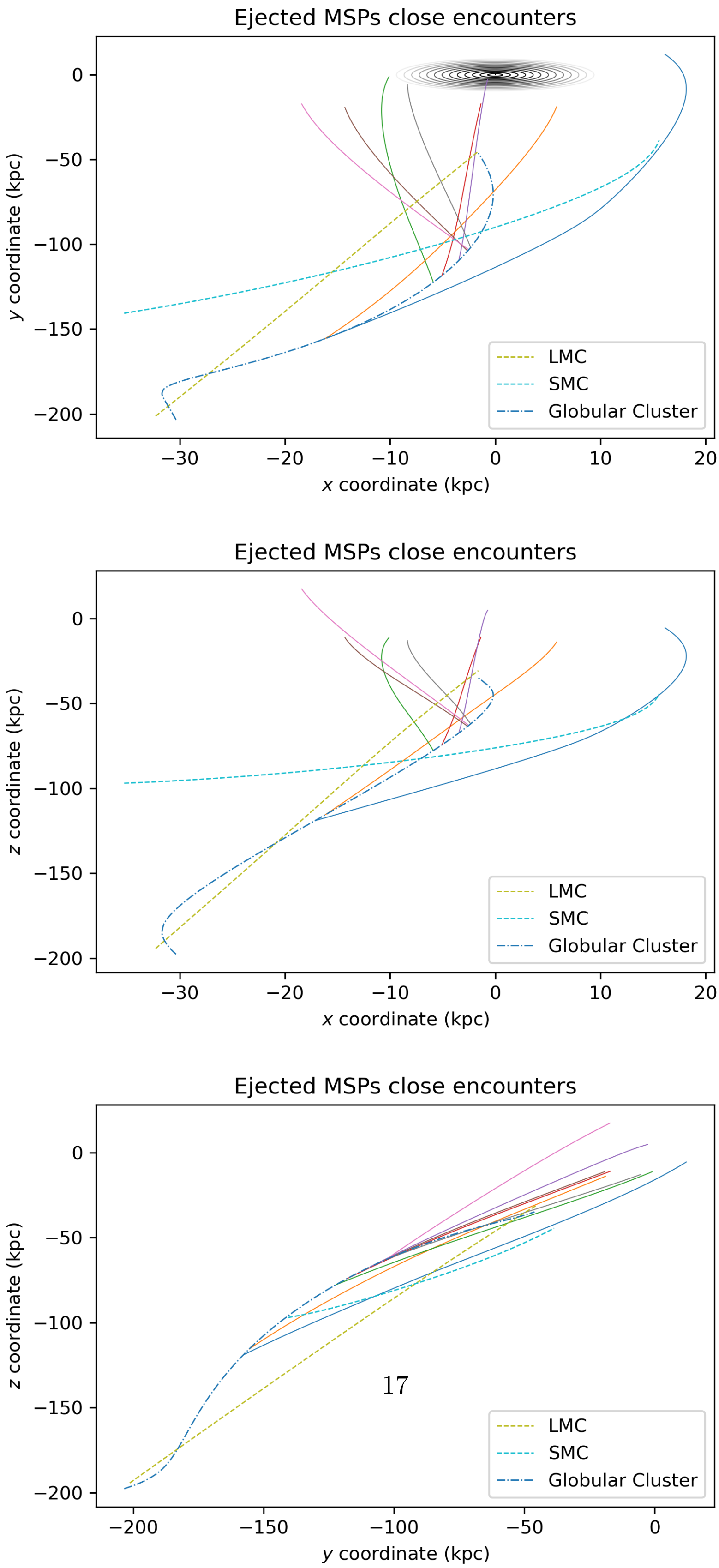


**Figure A.1:** Top: Captured millisecond pulsar trajectories in the $xy$ plane. The Milky Way is shown with the contour lines of its potential. Middle: Captured millisecond pulsar trajectories in the $xz$ plane. Bottom: Captured millisecond pulsar trajectories in the $yz$ plane.

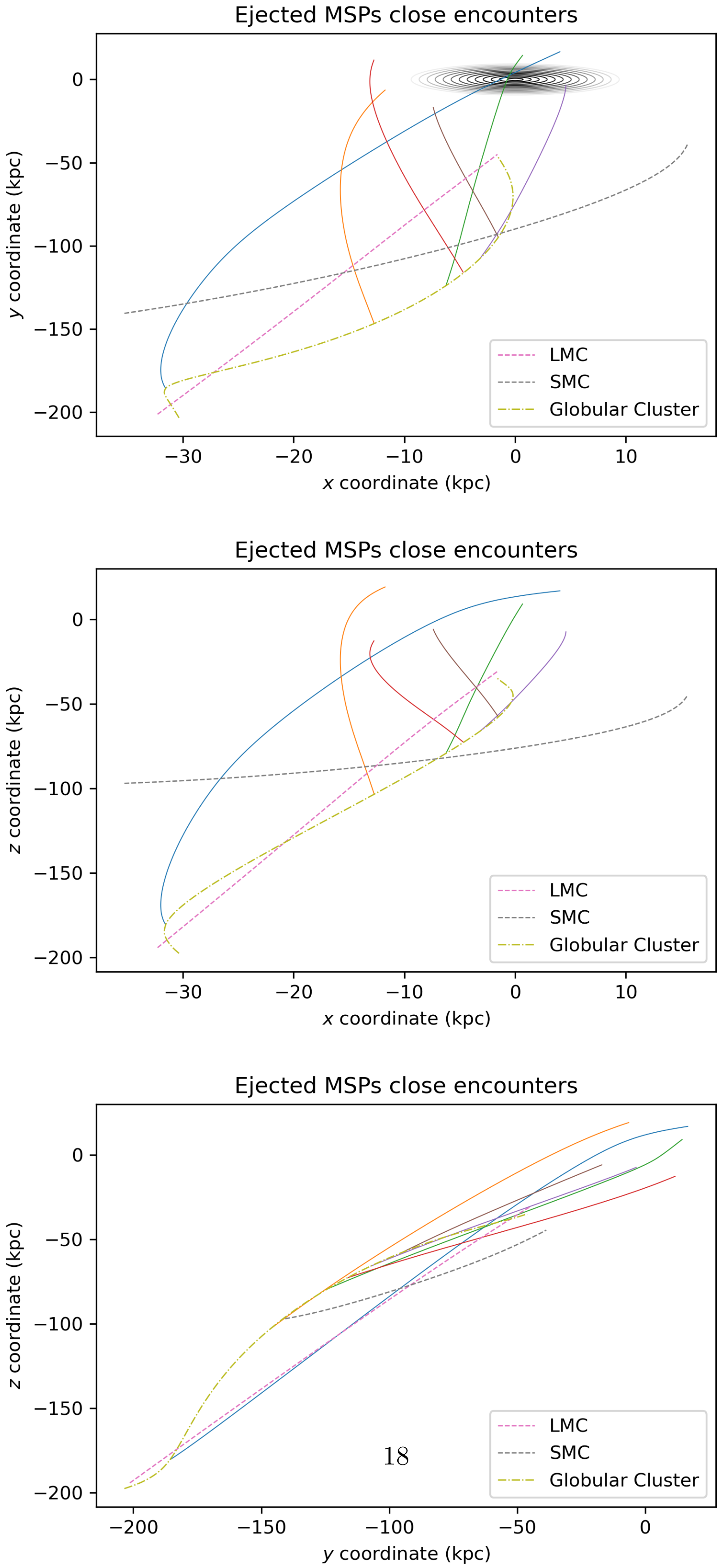




**Figure A.2:** Top: Captured millisecond pulsar trajectories in the $xy$ plane. The Milky Way is shown with the contour lines of its potential. Middle: Captured millisecond pulsar trajectories in the $xz$ plane. Bottom: Captured millisecond pulsar trajectories in the $yz$ plane.

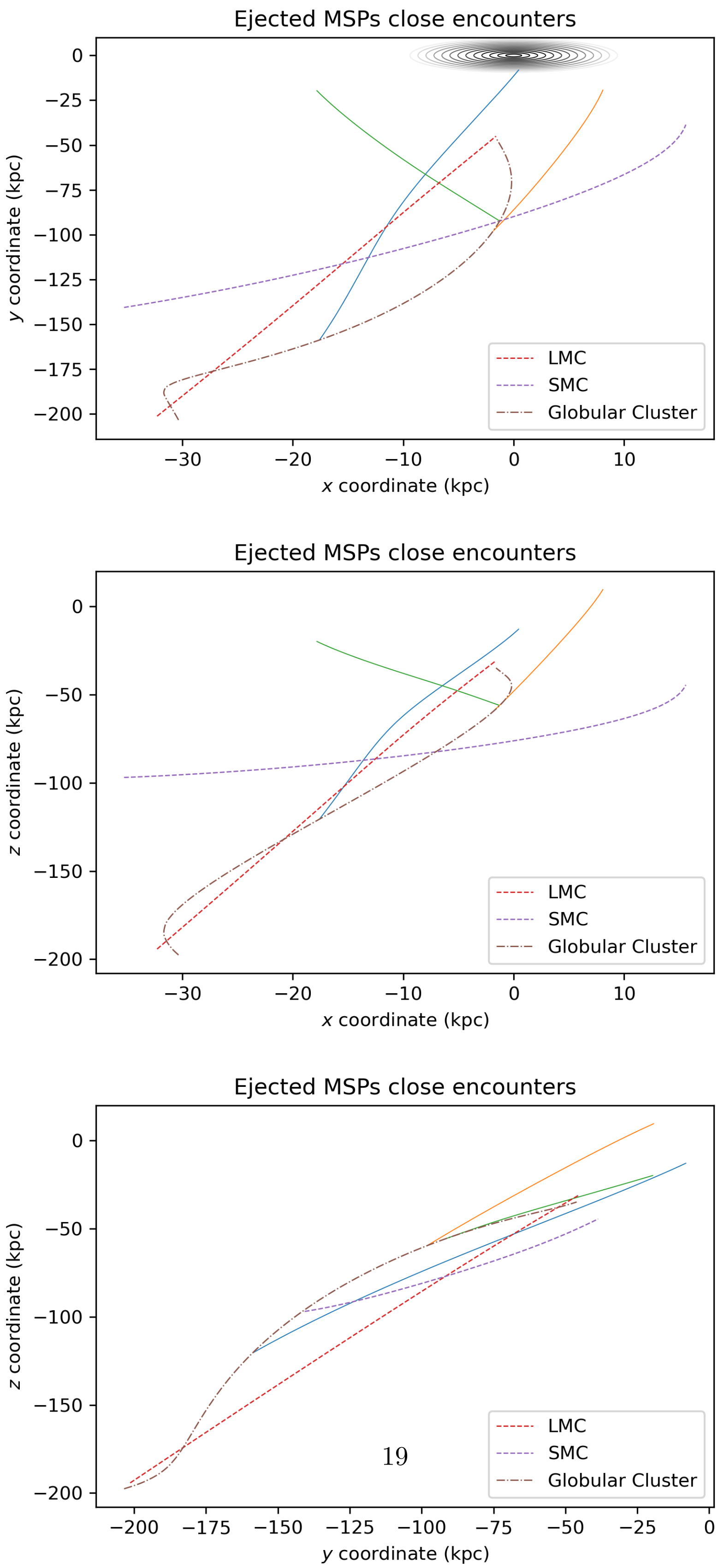


**Figure A.3:** Top: Captured millisecond pulsar trajectories in the $xy$ plane. The Milky Way is shown with the contour lines of its potential. Middle: Captured millisecond pulsar trajectories in the $xz$ plane. Bottom: Captured millisecond pulsar trajectories in the $yz$ plane.

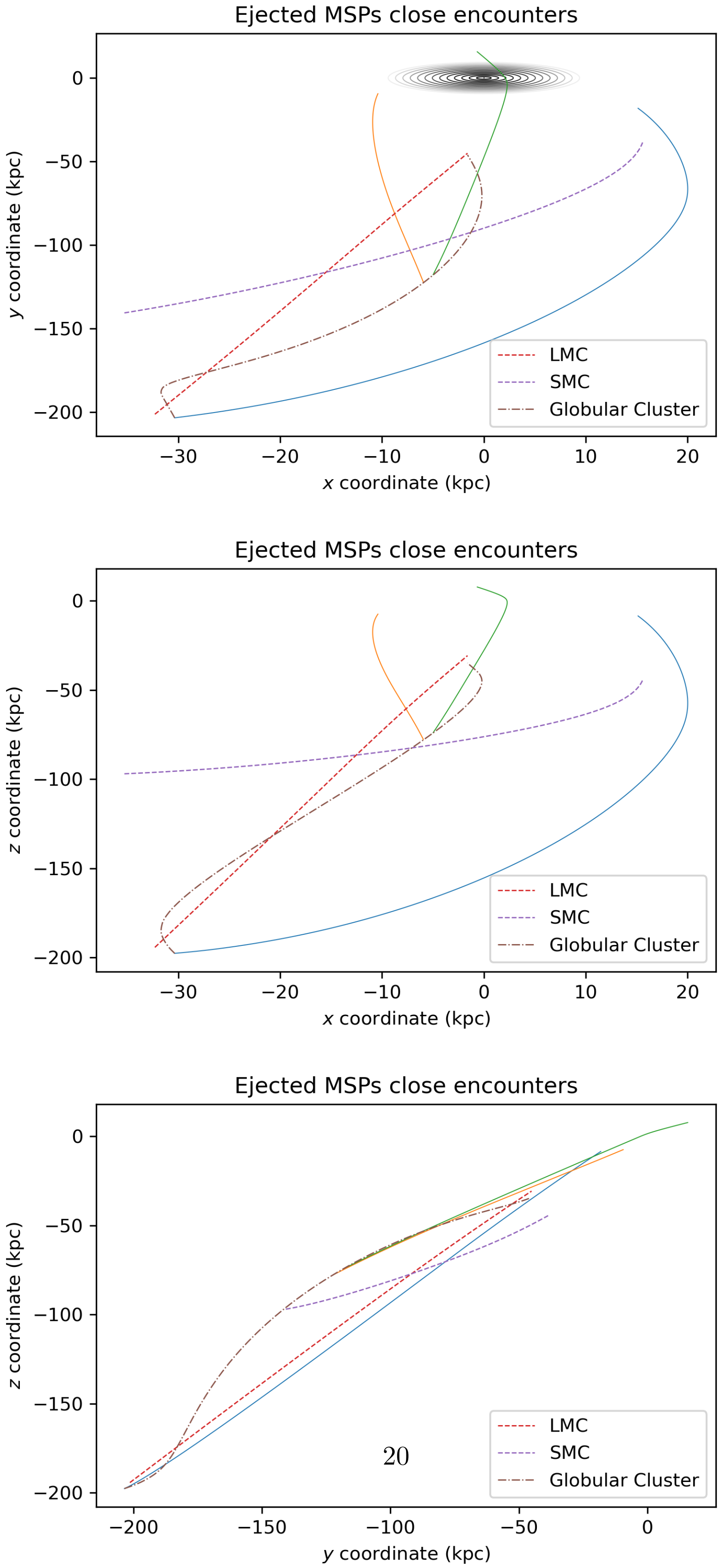


**Figure A.4:** Top: Captured millisecond pulsar trajectories in the $xy$ plane. The Milky Way is shown with the contour lines of its potential. Middle: Captured millisecond pulsar trajectories in the $xz$ plane. Bottom: Captured millisecond pulsar trajectories in the $yz$ plane.

# Appendix B: Graph showing all the millisecond pulsar trajectories

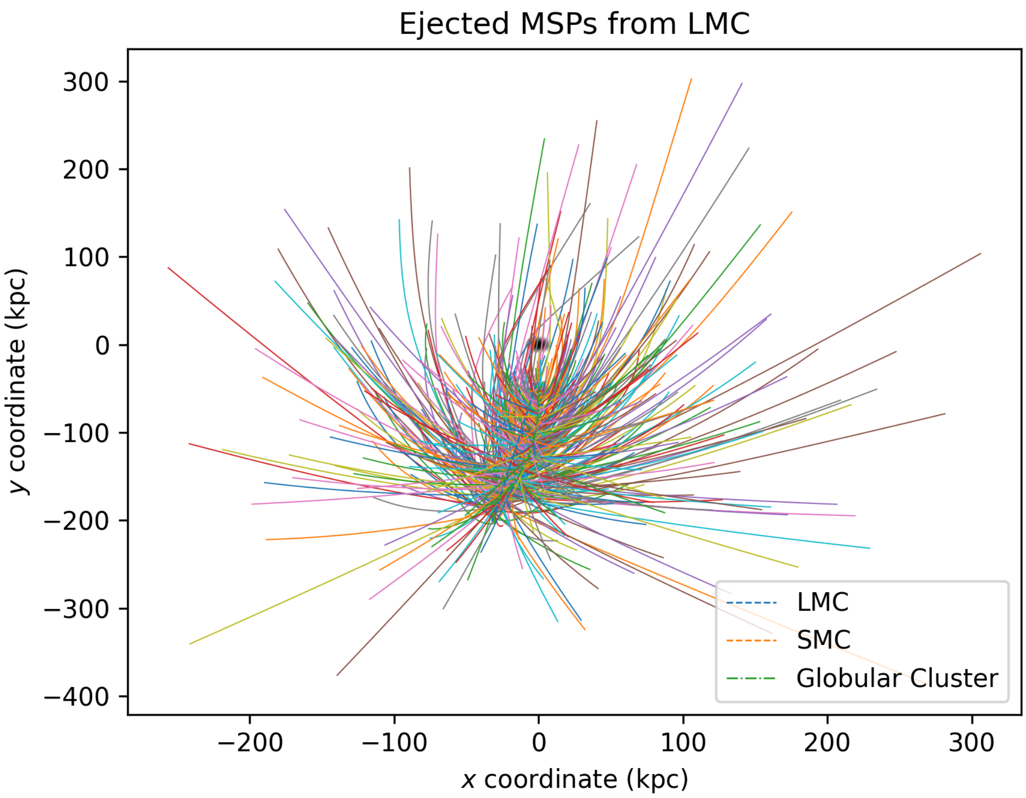


**Figure B.1:** Graph showing all the emitted millisecond pulsars during one run of a simulation.

The plot above shows the trajectories of all the emitted millisecond pulsars of a given simulation. When compared to the other plots showing the $xy$ plane it is interesting to note that although a large portion of the simulated pulsars are ejected from the LMC, they do not get captured into the Milky Way (as was reflected in the results). This could be due to a combination of having too high a velocity to be captured into the Milky Way as well as the evolution of the system being too small since over time, the pulsars can curve back inwards towards the Milky Way as it feels it's potential.

Nevertheless it is interesting to see that a large portion of the population of isolated millisecond pulsars could be roaming in deep space unaffected by galactic systems and motivates the idea of investigating emitted millisecond pulsars from M31.