Tracing Stellar Close Encounters with Our Sun from GAIA DR2, LAMOST DR4, and RAVE DR5 Catalogues

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Abstract. Our Sun is surrounded by the Oort Cloud (in radius 0.5 pc) which can be perturbed by various external factors. One of those is the stellar close encounter with our Sun. This kind of perturbation can induce the cometary showers in our Solar System. In this work, we attempt to make numerical simulations to trace the orbit of stars which close encounter with our Sun in the cases of Milky Way’s axisymmetric only and with non-axisymmetric potentials. We have selected solar neighborhood stars from GAIA DR2, LAMOST DR4, and RAVE DR5 which have highly precise kinematics.

In this work, we find a few stars that have counter parameter \(d_m\) less than or equal to 2 pc in both of past and future close encounters with the Sun. We also find a few stars (ID 283, 290, 297, 298) even with \(d_m \leq 0.5\) pc within their errors, for past close encounters at time \(t_m \geq 0.5\) Myr ago. These stars should have perturbed the Oort Cloud’s stability long time ago. Furthermore, we find a few stars (ID 293, 299, 300) with \(d_m \leq 1\) pc within their errors, at \(t_m > 0.6\) Myr for future close encounters. Besides that, adding non-axisymmetric component of Milky Way does not change the results. This suggests that the non-axisymmetric component of Milky Way potential has small effect in perturbing the orbital motion of stars for short timescale. That’s why the values of \(d_m\) are relatively similar within their errors, for both cases of the Milky Way potential.

1. Introduction

Our Solar System is surrounded by the Oort Cloud [1]. It is highly likely presumed that this cloud has spherical shape with radius of 0.5 pc and the total number of comets is supposed to be \(10^{11}\) [2]. At such distance, this cloud is weakly gravitationally bound with our Sun and can be perturbed by various external factors. One of those factors is the stellar close encounter with our Sun. This perturbation can trigger the moving of cometary showers into the region of giant planets, see [3,4,5]. The impact of such showers is believed by several researchers to associate with comet bombardments of the Earth and its Moon because of some craters were produced from impacts of long-period comets (LPCs) which are originated from the Oort Cloud, see [6,7].

The search for stellar close encounter with our Sun was considered by several researchers [2,7,8,9,10,11,12,13,14,15,16,17,18]. The frequency of stellar close encounter at distance less than 1 pc is 12 stars/Myr, it means that there is possibility to find past and future stellar close encounters with our Sun from new up to date data. In this work, we combine GAIA DR2,
Table 1. The sample of our selected solar neighborhood stars from GAIA DR2, LAMOST DR4, and RAVE DR5 catalogues. Here ID, $\alpha$, and $\delta$ are the identification number from GAIA DR2 catalogue, right ascension, and declination of the stars, respectively.

| ID  | $\alpha$ ($^{\circ}$) | $\delta$ ($^{\circ}$) | $\mu_{\alpha}\cos\delta$ $\pm$ $\sigma$ (mas/yr) | $\mu_{\delta}$ $\pm$ $\sigma$ (mas/yr) | $\rho$ $\pm$ $\sigma$ (mas) | $V_r$ $\pm$ $\sigma$ (km/s) |
|-----|----------------|----------------|--------------------------------|--------------------------------|----------------|----------------|
| 284 | 95.059        | 37.048        | 0.105 $\pm$ 0.917                          | 0.815 $\pm$ 0.790                          | 34.505 $\pm$ 0.615                          | 38.53 $\pm$ 2.12 |
| 291 | 98.309        | 2.821         | 3.252 $\pm$ 1.433                          | -2.338 $\pm$ 1.254                         | 38.368 $\pm$ 0.899                          | 42.14 $\pm$ 6.94 |
| 293 | 164.241       | 24.404        | 2.414 $\pm$ 1.960                          | -10.227 $\pm$ 2.086                        | 39.680 $\pm$ 1.070                          | -38.44 $\pm$ 2.31 |
| 298 | 60.836        | 21.112        | 0.041 $\pm$ 1.500                          | -4.601 $\pm$ 1.484                         | 47.865 $\pm$ 1.816                          | 37.77 $\pm$ 3.35 |
| 299 | 91.526        | 48.861        | 8.929 $\pm$ 1.945                          | 9.205 $\pm$ 1.800                          | 50.747 $\pm$ 1.301                          | 40.86 $\pm$ 4.43 |
| 300 | 6.907         | 34.717        | -10.056 $\pm$ 1.969                        | 12.406 $\pm$ 2.003                         | 56.291 $\pm$ 1.961                          | -28.62 $\pm$ 5.25 |

LAMOST DR4, and RAVE DR5 catalogues to cover all over the sky for tracing stellar close encounters with our Sun, explained in section 2. In section 3, we make simulations of stars’ orbit in our Galaxy’s potential in order to trace stellar close encounters with our Sun. We summarize our results and conclusion in section 4.

2. Data
We use stars from GAIA DR2, LAMOST DR4, and RAVE DR5 catalogues which have highly precise kinematics. These catalogues have the most recent observational data of stars that cover all over sky. From these catalogues, we have 306 selected solar neighborhood stars which have parallax ($\rho$) greater than or equal to 33.33 mas with relative error ($\sigma_{\rho}/\rho$) less than or equal to 10%. These stars also have highly precise kinematics such as proper motion ($\mu_{\alpha}\cos\delta$, $\mu_{\delta}$) and radial velocity ($V_r$) with their 1$\sigma$ confidence. From these kinematics data, we attempt to integrate the orbit of the stars to find the stellar close encounter with our Sun. A few of our selected solar neighborhood stars can be seen in Table 1.

3. Model and Simulation
To make orbit integration of the stars, we use galpy package in Python, see [19]. Galpy contains various kind of gravitational potentials that we can use to model our Galaxy’s potential. In this work, we model the potential of Milky Way in two cases, i.e. axisymmetric only and with non-axisymmetric components. In the case of Milky Way potential with axisymmetric only, we use MWPotential2014 from galpy package which provides the best fit to Milky Way’s rotational curve, see [19].

The MWPotential2014 consists of the bulge, disk, and halo dark matter. Power spherical potential cut off, as seen in equation (1) is used to model the bulge and potential of [20], as seen in equation (2), is used to model the disk. While potential of [21] is used to model the halo dark matter, see equation (3). The equation (1) and (3) can be transformed into potential equation using Poisson equation, i.e. $\nabla^2\Phi = 4\pi G\rho$, see [22]. The detail values of parameters for MWPotential2014 and descriptions can be seen in [19].

$$\rho(r) = A \left(\frac{r_1}{r}\right)^{\alpha} e^{-\left(\frac{r}{r_2}\right)^2}$$  \hspace{1cm} (1)

$$\Phi(R, z) = -\frac{A}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}$$  \hspace{1cm} (2)

$$\rho(r) = \frac{A}{4\pi a^3} \left(\frac{1}{r}\right)^{\alpha} \left(1 + \frac{1}{a}\right)^{\alpha}$$  \hspace{1cm} (3)
In the case of Milky Way potential with non axisymmetric component, we add 4 spiral arms potential from [23], as seen in equation (4), into MWPotential2014. Here $B_n = K_n H(1 + 0.4 K_n H)$, $C_n = \left[\frac{8}{3\pi^2}, \frac{1}{2}, \frac{8}{15\pi}\right]$, $D_n = \frac{1 + K_n H + 0.3 (K_n H)^2}{1 + 0.3 K_n H}$, $K_n = \frac{n N}{R \sin(\alpha)}$, and $\gamma = N \left[\phi - \phi_{ref} - \ln(R/r_{ref})\right]$. The detail value of parameters and its descriptions of spiral arms potential can be seen in [19] and [23].

The Sun’s position in the Galaxy is adopted from [24], i.e. $(x_\odot, y_\odot, z_\odot) = (8.5, 0.0, 0.025)$ kpc. While the sun’s velocity is adopted from [25], i.e. $(u_\odot, v_\odot, w_\odot) = (-11.1, 12.4, 7.25)$ km/s with $V_{lsr} = 220$ km/s, as computed by [19]. We integrate the orbit of stars from $-5$ Myr to $+5$ Myr with timestep 50 yr. Our monte carlo simulations were done with 1000 iterations for each star using fourth order runge kutta integrator. In these simulations, we calculate the distance of every star to our Sun at any given time as $d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$. The star’s minimum distance to our Sun is then called as the counter parameter ($d_m$) and its minimum epoch at $d_m$ is denoted as $t_m$. Following [2], we search the stellar close encounter with our Sun at $d_m < 2$ pc.

4. Results

We present the past and future stellar close encounters with our Sun in Figure 1 in the cases of axisymmetric only and with non-axisymmetric components. The given errors of $d_m$ and $t_m$ are 1σ confidence. We find a few stars that have $d_m \leq 2$ pc from our Sun in both of past and future close encounters (see Table 2). There are 4 stars (ID 283, 290, 297, 298) that close encountered with our Sun with $d_m < 0.5$ pc within their errors, at $t_m \geq 0.5$ Myr ago. The nearest star that close encountered with our Sun is ID 283, i.e. $d_m = (0.13 \pm 0.07)$ pc at $t_m = (0.74 \pm 0.07)$ Myr ago.
Table 2. The stellar close encounters with our Sun with \( d_m \leq 2 \) pc in the cases of Milky Way’s axisymmetric only and with non-axisymmetric components. Here ID is the identification number of stars from GAIA DR2 catalogue.

| ID | Axisymmetric | | | Non Axisymmetric | | | |
|---|---|---|---|---|---|---|
|   | \( d_m \pm \sigma \) (pc) | \( t_m \pm \sigma \) (Myr) |   | \( d_m \pm \sigma \) (pc) | \( t_m \pm \sigma \) (Myr) |   |
| 283 | 0.13 \( \pm \) 0.07 | \(-0.74 \pm 0.04\) | 0.13 \( \pm \) 0.07 | \(-0.74 \pm 0.04\) |   |   |
| 288 | 1.90 \( \pm \) 0.23 | \(-0.91 \pm 0.06\) | 1.91 \( \pm \) 0.23 | \(-0.91 \pm 0.07\) |   |   |
| 290 | 0.41 \( \pm \) 0.14 | \(-0.62 \pm 0.11\) | 0.41 \( \pm \) 0.14 | \(-0.62 \pm 0.11\) |   |   |
| 291 | 1.56 \( \pm \) 0.21 | 0.49 \( \pm \) 0.05 | 1.55 \( \pm \) 0.21 | 0.49 \( \pm \) 0.05 |   |   |
| 292 | 0.93 \( \pm \) 0.18 | 0.64 \( \pm \) 0.04 | 0.92 \( \pm \) 0.18 | 0.64 \( \pm \) 0.04 |   |   |
| 293 | 1.76 \( \pm \) 0.24 | 0.62 \( \pm \) 0.06 | 1.74 \( \pm \) 0.23 | 0.61 \( \pm \) 0.06 |   |   |
| 297 | 0.34 \( \pm \) 0.09 | \(-0.55 \pm 0.05\) | 0.34 \( \pm \) 0.09 | \(-0.55 \pm 0.05\) |   |   |
| 298 | 0.58 \( \pm \) 0.11 | \(-0.48 \pm 0.05\) | 0.58 \( \pm \) 0.11 | \(-0.48 \pm 0.05\) |   |   |
| 299 | 0.83 \( \pm \) 0.22 | 0.63 \( \pm \) 0.14 | 0.81 \( \pm \) 0.21 | 0.62 \( \pm \) 0.12 |   |   |
| 300 | 1.72 \( \pm \) 0.99 | 1.70 \( \pm \) 0.95 | 1.72 \( \pm \) 1.02 | 1.69 \( \pm \) 0.97 |   |   |
| 301 | 1.96 \( \pm \) 2.45 | \(-2.38 \pm 1.02\) | 1.91 \( \pm \) 2.16 | \(-2.51 \pm 1.07\) |   |   |

0.04) Myr ago in both of axisymmetric only and with non-axisymmetric components. This star should have perturbed the Oort Cloud with such value of \( d_m \). We compare our results with [2,12,13,18,26] and it is still in a good agreement with them, although they obtained smaller values of \( d_m \) for a few stars due to the difference in the potential model and its parameters used in the simulations.

Besides that, there are 3 stars (ID 293, 299, 300) that will close encounter with our Sun with \( d_m < 1 \) pc within their errors at \( t_m > 0.6 \) Myr. The nearest star that will close encounter with our Sun is ID 299 with \( d_m = (0.83 \pm 0.22) \) pc at \( t_m = (0.63 \pm 0.14) \) Myr in the case of axisymmetric only and \( d_m = (0.81 \pm 0.21) \) pc at \( t_m = (0.62 \pm 0.12) \) Myr in the case of with non-axisymmetric component. Although this star is outside of the Oort Cloud’s radius, there is still possibility that it perturbs the Oort Cloud’s stability in the future. If we compare the results in the case of axisymmetric only and with non-axisymmetric component, we find there is a small difference in the value of \( d_m \) and \( t_m \), see Table 2. It suggests that the non-axisymmetric component of the Milky Way has small effect in perturbing the orbital motion of stars in short timescale.

Several of our selected solar neighborhood stars still have large error of their kinematics data. It causes the calculation errors of \( d_m \) and \( t_m \) of several stars become larger. Our criteria in combining the kinematics data from GAIA DR2, LAMOST DR4, and RAVE DR5 catalogues needs to be specified more strictly, not only from parallax, but also from other kinematics data.

In this work, we confirm and suggest that there is possibility of past and future stellar close encounters with our Sun which can perturb the Oort Cloud’s stability and triggering cometary showers in the vicinity of giant planets. Besides that, we can also learn the condition of our Solar System when the stellar close encounters occur in the future. However, it is also interesting to learn in the future work, how the four stars that had close encountered with our Sun at \( d_m < 0.5 \) pc can perturb the Oort Cloud’s stability.

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