Approaches of stars to the Sun

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Abstract. Close approaches of stars to the Solar System perturb comets from the Oort cloud so that they pass into the planetary system – the gravitational impulse changes the distribution of observable comets. This paper presents the results of calculations of the motion of stars in the solar neighbourhood in the past and future. The main results for each star are: the time of the encounter and the minimum distance between the Sun and the star. They are calculated using three different methods: a straight line motion model, a model with a Sun – star Keplerian interaction, and the numerical integration of the equations of motion with galactic perturbations included. In the last case, two models of the Galactic potential are used: a simplified potential of the Galactic disk and the more complex potential of the Galaxy by Dauphole and Colin. Coordinates and velocities of nearby stars are taken from several different catalogues: the Gliese catalogue, the Hipparcos catalogue, and the Barbier-Brossat catalogue of Radial Velocities.

Key words: Galactic potential models – origin of comets – solar neighbourhood – Hipparcos observational data

1. Introduction

Encounters of nearby stars with the Sun are an interesting aspect of the dynamics of the Solar neighbourhood. Stellar perturbations of the comet cloud can produce observable comets. This hypothesis for the source of the long-period comets was first proposed by Oort (1950). Another effect of perturbations on the Oort cloud is the possibility of dynamical evolution of cometary trajectories into planet-crossing orbits.

Other possible sources of such perturbations are GMC (Giant Molecular Clouds) and the Galactic potential. In this article we are interested mainly in the problem of the motions of nearby stars in the past and future, using various methods of calculations, models of stellar motion, and kinematical data sources. Although the problem was already studied by several authors (Matthews, 1994; Mülläri and Orlov, 1996; Garcia-Sanchez *et al.*, 1997) we take into account the most recent Galactic potential models and the observational data for nearby stars.

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Table 1. The closest star approaches – parameters of encounters determined by straight-line motion model and hyberbolic trajectory model (stars from the Gliese catalogue)

N	Name	T $\times 10^3$ y	$\Delta T(\pm)$ $\times 10^3$ y	D $\times 10^4$ AU	$\Delta D(\pm)$ $\times 10^4$ AU	T_h $\times 10^3$ y	q $\times 10^4$ AU
83	GJ 2005	+33.144	4.123	15.419	177.316	+33.144	15.419
306	NN	+1790.325	2220.709	31.729	2193.310	+1790.250	31.717
457	NN	+1636.002	2947.057	7.461	32645.566	+1635.994	7.460
529	Gl 120.1A	-432.973	113.897	28.040	1771.691	-432.973	28.040
945	Gl 208	-532.289	143.519	34.075	354.201	-532.289	34.074
1162	Gl 271 A	+988.634	489.085	37.482	1071.531	+988.631	37.481
1721	Gl 411	+19.983	1.063	29.106	2.741	+19.983	29.106
1847	Gl 445	+43.859	3.465	19.681	36.367	+43.859	19.681
1851	Gl 447	+70.540	9.275	38.529	7.607	+70.540	38.529
1930	Gl 459.2	+419.503	331.234	29.774	5607.787	+419.503	29.774
1974	Gl 473 A	+7.570	0.242	5.958	37.705	+7.570	5.958
1976	Gl 474	+428.585	188.237	5.351	11041.800	+428.584	5.351
2080	NN	+1060.540	1255.850	34.157	5457.935	+1060.533	34.155
2293	Gl 551	+25.969	3.503	21.789	1.329	+25.969	21.789
2320	Gl 559 A	+27.348	3.421	18.629	2.262	+27.348	18.629
2781	Gl 682	+64.596	8.377	39.011	23.020	+64.596	39.011
2851	Gl 699	+9.802	0.289	23.790	0.816	+9.802	23.790
2856	Gl 700.1A	+428.784	115.487	36.210	860.022	+428.783	36.210
2894	Gl 710	+1038.644	432.204	25.935	1022.814	+1038.642	25.935
2962	Gl 729	+134.805	43.855	39.321	14.845	+134.806	39.321
3170	Gl 783 A	+38.329	5.885	37.241	47.310	+38.329	37.241
3539	Gl 860 A	+89.307	12.282	38.848	14.155	+89.307	38.848
3709	NN	-517.122	178.230	9.140	2679.965	-517.121	9.140
3738	GJ 2157	+428.822	132.351	28.608	1387.536	+428.822	28.608
3745	Gl 905	+36.492	2.311	19.525	9.168	+36.492	19.525

2. Observational data

The main source of data for our calculations are stellar catalogues containing stars in the solar neighbourhood. First we used the Catalogue of Nearby Stars – CNS (Gliese and Jahrheiss, 1991) wherein we found complete information about coordinates and velocities of 1946 stars. Second, we used the results of the Hipparcos mission, published in June 1997. The Hipparcos catalogue (ESA, Hipparcos, 1997) contains the most accurate positions and proper motions of nearby stars. Unfortunately, it does not contain any information about their radial velocities. We combined the ground-based observational data on radial velocities with Hipparcos results. Radial velocities were taken from CNS and the Catalogue of Radial Velocities (Barbier-Brossat, 1994). We selected from the Hipparcos catalogue 1665 stars closer to the Sun than 25 pc. Coordinates and proper motions of these stars were combined with radial velocities from the Gliese catalogue (904 stars) and Barbier-Brossat catalogue (1979 positions in the catalogue containing ground-based measurements in several years for 660 stars). Generally, we found more stars with exisiting radial velocity measurements in the Gliese catalogue (the Barbier-Brossat catalogue in many cases contains older observational data).

Table 2. The closest star approaches – parameters of encounters determined by straight-line motion model and hyberbolic trajectory model (stars from the Hipparcos catalogue)

Name	T $\times 10^3$ y	$\Delta T(\pm)$ $\times 10^3$ y	D $\times 10^4$ AU	$\Delta D(\pm)$ $\times 10^4$ AU	T_h $\times 10^3$ y	q $\times 10^4$ AU
Gl 208	-513.6737	118.3418	34.0543	249.1814	-513.6732	34.0539
Gl 411	+20.0591	0.9732	29.8004	2.2189	+20.0591	29.8004
Gl 559 A	+27.6618	2.9851	18.6438	1.8070	+27.6619	18.6438
Gl 710	+1418.5400	519.1518	7.3842	5524.2814	+1418.5304	7.3833
Gl 699	+9.7292	0.2803	23.5721	0.9823	+9.7292	23.5721
Gl 358	-62.8195	3.1160	38.6732	38.6991	-62.8195	38.6732

3. Methods of calculations

3.1. Methods available

The parameters of encounters can be calculated by several different methods. The most simple "straight line motion model" is the fastest method, but all gravitational forces are neglected. We may also account for the Keplerian Sun-star interaction (hyperbolic orbits). More significant are Galactic perturbations. We used two Galactic potential models and numerically integrated the motion of the Sun and each Star: a Galactic disk potential model and a complete Galactic potential (Dauphole and Colin, 1996). To compare our results with other authors (Mülläri and Orlov, 1996) we added a galactic potential model published by Kutuzov and Ossipkov (1989).

3.2. Galactic potential models

We present a short overview of the Galactic potential models. Their detailed descriptions are available in the quoted papers (in particular description of constants for each potential model).

A tidal potential model of the Galactic disk was used, for example, by Heisler and Tremaine (1986). This model is simple and very useful in case of numerical integration. In the heliocentric Galactic reference frame the equations of the stellar motions are:

$$\ddot{x} = -\frac{\mu}{r^3}x$$
$$\ddot{y} = -\frac{\mu}{r^3}y$$
$$\ddot{z} = -\frac{\mu}{r^3}z - 4\pi G\rho z$$

(where $\mu = G(M_\star + M_\odot)$, ρ is the local density of mass)

Table 3. The closest star approaches – parameters of encounters determined by numerical integration using potential of Galaxy (stars from the Gliese catalogue)

Star		Used potential model			
		Tidal potential of disk		Dauphole and Colin model	
N	Name	T_d $\times 10^3$ y	R_d $\times 10^4$ AU	T_{min} $\times 10^3$ y	R_{min} $\times 10^4$ AU
83	GJ 2005	+33.144	15.419	+33.144	15.419
306	NN	+1790.344	31.701	+1790.270	31.501
457	NN	+1631.164	8.929	+1633.163	8.598
529	Gl 120.1A	-432.765	27.933	-432.835	27.973
945	Gl 208	-532.259	34.096	-532.295	34.098
1162	Gl 271 A	+988.256	37.712	+988.545	37.663
1721	Gl 411	+19.983	29.106	+19.983	29.106
1847	Gl 445	+43.859	19.681	+43.859	19.681
1851	Gl 447	+70.539	38.528	+70.540	38.528
1930	Gl 459.2	+419.282	29.675	+419.357	29.710
1974	Gl 473 A	+7.570	5.958	+7.570	5.959
1976	Gl 474	+428.316	5.326	+428.406	5.335
2080	NN	+1057.746	33.375	+1058.630	33.656
2293	Gl 551	+25.969	21.789	+25.969	21.789
2320	Gl 559 A	+27.348	18.629	+27.348	18.629
2781	Gl 682	+64.596	39.011	+64.596	39.011
2851	Gl 699	+9.802	23.790	+9.802	23.790
2856	Gl 700.1A	+428.778	36.225	+428.793	36.227
2894	Gl 710	+1038.628	25.890	+1038.753	25.964
2962	Gl 729	+134.818	39.319	+134.815	39.320
3170	Gl 783 A	+38.329	37.240	+38.329	37.241
3539	Gl 860 A	+89.307	38.848	+89.307	38.848
3709	NN	-516.919	9.239	-516.980	9.213
3738	GJ 2157	+428.821	28.612	+428.807	28.619
3745	Gl 905	+36.492	19.525	+36.492	19.525

In contrary, the Kutuzov and Ossipkov (1989) potential model formulas are more complicated and include forces from all Galactic components. Integration of the Sun and star motions are referenced to the Galactic center. Basic form of two-component potential in the cylindrical Galacticial coordinates (related to the Galaxy Center) is described by

$$\Phi(R, z) = \Phi_0 \left(a\phi_a + b\phi_b\right)$$

More detailed formula (with constants included in model, see Mülläri *et al.* (1996)):

$$\Phi(R,z) = \Phi_0 \left(\frac{a\alpha}{\alpha - 1 + \sqrt{1 + \kappa((\frac{1}{r_0})^2 (R^2+z^2) + 2(1-\epsilon)(\sqrt{\epsilon^2 + \frac{z^2}{r_0^2}} - \epsilon))}} + \frac{b}{1 + \frac{\lambda}{r_0}\sqrt{R^2+z^2}} \right).$$

The Dauphole and Colin Galactic potential model (1996) is based on newer observational data and includes the gravitational forces from the bulge, disk and halo. It is expressed in the cylindrical galactocentric coordinates. Basic potential formula is

$$\Phi(R,z) = \Phi_b(r) + \Phi_d(R,z) + \Phi_h(r)$$

where the components of the form are:

$$\Phi_{b,h}(r) = -\frac{GM_{b,h}}{\sqrt{r^2 + b_{b,h}^2}}$$

$$\Phi_d(R,z) = -\frac{GM_d}{\sqrt{R^2 + \left(a_d + \sqrt{z^2 + b_d^2}\right)^2}}$$

($M_{b,h}, b_{b,h}, M_d, a_d, b_d$ are constants of the model, see Dauphole and Colin (1996)).

3.3. Searching for "parameters of encounters"

The main results of our calculations are the time and the distance of encounter. For 1946 stars from the Gliese catalogue and 904 stars from the Hipparcos catalogue (data combined with radial velocities from the Gliese catalogue) we determined T_{min} and r_{min} using the straight line motion model, the "hyperbolic trajectory" model, and numerical integration with the three different Galactic potentials. We integrated the equations of the star's motion with the RA15 integrator (Everhart, 1985). We estimated the errors in our results for the straight-line model using the stated catalogue errors.

4. Results

We present the closest stellar passages. The selection criteria were: minimum distance of encounter less than 4×10^5 AU (about 2 pc) and time interval ± 2 Myrs. The selected stars are presented in the tables. Tab. 1 presents the parameters of encounters calculated by the straight-line motion model and the "hyperbolic trajectory" model for stars from the Gliese catalogue. In the header of table N there is the line number in the catalogue, "name" is the catalogue name of the star (NN – "no-name" for object without name), T, D are the time and distance of the encounter calculated by the straight-line model, $\Delta T, \Delta D$ are the estimated errors in these values. T_h and q are the time of passage and distance of perihelion for calculations using the hyperbolic orbit of the close passing star. Similar results for stars from the Hipparcos catalogue are collected in Tab. 2. These stars were selected using the same criteria as in the previous group. The names of the stars were taken from the Gliese catalogue. The results for encounters determined by numerical interation for the same sample of stars are collected in Tabs. 3 and 4. The values of time and distance are shown in the tables as T_d, R_d (for integration using the simplified tidal potential of the disk) and T_{min}, R_{min} (for integration using the Dauphole and Colin potential model).

Table 4. The closest star approaches – parameters of encounters determined by numerical integration using Galactic potential models (stars from the Hipparcos catalogue)

Star	Used potential model			
	Tidal potential of disk		Dauphole and Colin model	
Name	T_d $\times 10^3$ y	R_d $\times 10^4$ AU	T_{min} $\times 10^3$ y	R_{min} $\times 10^4$ AU
Gl 208	-513.6499	34.0697	-513.6901	34.0921
Gl 411	+20.0591	29.8004	20.0591	29.8004
Gl 559 A	+27.6619	18.6438	27.6619	18.6438
Gl 710	+1418.4289	7.4439	1419.2555	7.1608
Gl 699	+9.7292	23.5721	9.7292	23.5721
Gl 358	-62.8195	38.6731	-62.8193	38.6730

5. Discussion

Considering the results obtained we can state that very close stellar approaches are not present in our calculations for the past and future. No passages closer than 50,000 AU were found. We encountered in our studies significant problems with data sources and data errors. The velocities of objects in the solar neigbourhood are still determined with low precision. The published radial velocities for the same star often have very different values and poor agreement with each other. In many cases, the uncertainties of our results are very large. Additional difficulties may arise from resolving barycentric to individual motions in binary systems (and long-term velocity changes) (Garcia-Sanchez *et al.*, 1997). However, we compared several methods of calculatons to better verify our results. Generally, most trajectories of nearby stars can be approximated by straight lines. Accounting for the Sun-star interaction is required only in the case of a very close encounter with a massive, low-velocity star (not found in our results, but always possible on the basis of future, more complete and accurate data). The results of calculations with several Galactic potentials demonstrate the influence of the Galaxy over long intervals of time. Use of several potentials was advantageous to verify the application of the Galaxy models. We compared our results with similar studies of Müllári and Orlov (1996). We have selected the same sample of close stellar approaches using similar rules and the same catalogue data. Our results are in good agreement for the straight-line motion model. When using the Kutuzov and Ossipkov potential some of our results are different, in particular those for the encounter of the star NN 457 (marked in referred paper as NN 456 with minimum range of 32,000 AU – our result is greater than 85,000 AU for both potential models used).

As for the results based on Hipparcos data, in the closest passage population we found only 6 stars. The closest passing star in this sample is Gliese 710, recently studied by Garcia-Sanchez *et al.* (1997). Our results for this star are similar, although we used a different value of the radial velocity. We plan to apply our studies and results in problems of stellar perturbation in the Oort cloud.

6. Note added at proof

More detailed analysis of close stellar encounters was performed lately by Garcia-Sanchez *et al.* (1999). The Hipparcos results were mixed with the large amount of ground-based radial velocity measurements (both published and unpublished). Dynamical effect on the Oort Cloud was discussed in brief.

Detailed comparison with our results is possible only in case of usage the same values of radial velocity components. For the star Gliese 710, we chose the value $V_r = -13.3$ km s^{-1} published in CNS (Gliese and Jahrheiss, 1991). The problem of the historical and new V_r measurements of this star was exposed by Garcia-Sanchez *et al.* (1999). Finally, the value of $V_r = -13.9 \pm 0.2$ km s^{-1} (based on new measurements with the CfA Digital Speedometers) was adopted in this article. The authors used a straight-line motion model and numerical integration in the Galactic potential using IAU Oort constants and some last published Galactic parameters (applying the fourth-order Runge-Kutta integrator). We used in integrations three self-consistent Galactic potential models. The main conclusions of the quoted paper are similar to ours: the results have a large uncertainties (because of large errors in the observational data), the influence of the Galactic potential is more significant on large time-scale. Disagreement between some results arises mainly from usage of different values of the radial velocity.

In contrary to the paper by Garcia-Sanchez *et al.* (1999), besides the results based on the Hipparcos data, we decided also to include the results based on older data (CNS, Gliese, 1991). We also compare the results of numerical integration with different potential models.

Additionaly, we want to state that according to Weissman (1999), the close approach of Gl 473 is an error (the catalogue value in excess of -500 km s^{-1} is a typographical error). The radial velocity of this star is actually very poorly determined, but is only a few $\mathrm{km\,s^{-1}}$.

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