On the accuracy of close stellar approaches determination

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ABSTRACT

The aim of this paper is to demonstrate the accuracy of our knowledge of close stellar passage distances in the pre-GAIA era. We used the most precise astrometric and kinematic data available at the moment and prepared a list of 40 stars nominally passing (in the past or future) closer than 2 pc from the Sun. We used a full gravitational potential of the Galaxy to calculate the motion of the Sun and a star from their current positions to the proximity epoch. For this calculations we used a numerical integration in rectangular, Galactocentric coordinates. We showed that in many cases the numerical integration of the star motion gives significantly different results than popular rectilinear approximation. We found several new stellar candidates for close visitors in past or in future.

We used a covariance matrices of the astrometric data for each star to estimate the accuracy of the obtained proximity distance and epoch. To this aim we used a Monte Carlo method, replaced each star with 10 000 of its clones and studied the distribution of their individual close passages near the Sun. We showed that for contemporary close neighbours the precision is quite good but for more distant stars it strongly depends on the quality of astrometric and kinematic data. Several examples are discussed in detail, among them the case of HIP 14473. However there exist strong need for more precise astrometry of this star since the proximity point uncertainty is unacceptably large.

Key words: Oort Cloud, solar neighbourhood, stars: kinematics and dynamics.

1 INTRODUCTION

Soon after the Oort (1950) published a paper on the existence of the comet cloud surrounding the Sun, many authors started to investigate the influence of real nearby stars on cometary orbits. One of the earliest complete (at that moment) search for stellar passages near the Sun was published by Makover (1964). He listed all past stellar proximity epochs and distances based on the first edition of the Gliese Catalogue (1957) and obtained with a rectilinear approximation. In recent twenty five years several papers were published in this field, among others Matthews 1994; Mullan & Orlov 1994; Dybczyński & Kankiewicz 1995; García-Sánchez et al. 1999, 2001; Dybczyński 2006; Bohylev 2010b, Jiménez-Torres et al. 2011. The main reason for a continuous interest in determining close star passages is the progress in obtaining stellar data, especially proper motions, parallaxes and radial velocities. Additionally, investigations of long period comets past and future dynamics are more and more detailed (see for example Królikowska & Dybczyński 2014, 2013; Dybczyński & Królikowska 2014, 2015; Królikowska et al.; Królikowska 2014). As a result best possible knowledge on potential stellar perturbers of such motion is of great interest (Fouchard et al. 2011).

With the publication of the first Hipparcos catalogue (1997, hereafter HIP1) the number of stars with known parallaxes has increased significantly. Hipparcos mission (ESA 1997) was a milestone in our last decades advance in gathering data on the spatial distribution of stars in the solar neighbourhood. This mission gave us precise positions, parallaxes and proper motions for ~120 thousands of stars from carefully and in advance selected list, forming the Hipparcos Input Catalogue (Turon et al. 1992). Hipparcos catalogue is complete up to ∼25 pc for all stars brighter than $M_V = 9$ mag (Jahreiß & Wielen 1997) and for the massive stars in this population the completeness reaches a much larger distance. There are two main reasons for which it is difficult to obtain precise information on the spatial velocity for all Hipparcos stars. First - the Hipparcos proper motions, while of great formal precision, are based on relatively short time interval, therefore for a large number of stars they differ from the mean, secular proper motions (Wielen et al. 1999). Several attempts were made to combine Hipparcos proper motions with those from a ground based observations, see for example (Wielen et al. 1999; Hoogerwerf & Blaauw 2000; Wielen et al. 2001). The most fruit-full attempt was the construction of Tycho-2 catalogue (Høg et al. 2000a,b) however combining Tycho-2 proper motions with parallaxes from HIP-1 introduces some inconsistency in treating astrometric data. Recently a
new reduction of Hipparcos raw data were performed and a second, significantly improved version of the Hipparcos catalogue (HIP2, van Leeuwen [2007a, 2011]) have been published. It improves significantly precision of both proper motions and parallaxes.

As it concerns radial velocity, several large projects (see for example Grenier et al. [1999b], Nidever et al. [2003], Nordström et al. [2004]) increased the number available measurements and a large Pulkovo compilation of radial velocities of 35 495 Hipparcos stars was published by Gontcharov (2004). Using HIP2 catalogue, Pulkovo compilation of radial velocities and several other sources of astrophysical parameters (Anderson & Francis [2012]) published an extended Hipparcos compilation of stellar data, known as the XHIP catalogue.

The second reason for investigating stellar passages is our increasing ability to calculate the stellar path relative to the Sun with increasing accuracy, taking into account the Galactic gravity field. Using such advanced methods we should additionally ask about the accuracy of the results and their dependency on the used data. Authors of several previous papers also estimated the accuracy of their results in more or less approximate manner. For example García-Sánchez et al. [2001] simply used the root of a sum of squared error contributions from two components of proper motions, parallaxes and radial velocities. The Monte Carlo method of estimating the accuracy of the distance of a stellar close passage near the Sun was first used by Mülläri & Orlov (1996) but in a simplified manner (for example with assumed 3 km s\(^{-1}\)) error for all radial velocities). Similar attempt was performed by Bobylev (2010E) and recently by Jiménez-Torres et al. [2011] but in all cases only formal errors were taken into account, ignoring mutual correlations between astrometric parameters.

In the present work we used astrometric parameters taken directly from the HIP2 catalogue instead of XHIP mainly because HIP2 presents also a covariance matrix which is necessary to apply the advanced method for the accuracy assessment. We used radial velocities from the XHIP catalogue. For several selected stars we presented comparison of the results based on astrometry and radial velocities from some other sources.

This paper provides the most up to date information on the closely stellar approaches to the Sun, obtained from latest astrometric data and radial velocities augmented with the more elaborated Monte Carlo assessment of the accuracy of the obtained minimal distances and their epochs, based on full covariance matrices included in the HIP2 catalogue. Of course we expect significant improvements from the Gaia mission therefore our computer codes are fully prepared to include new data.

In the next section we describe methods of our calculations. Section 3 consists of the results obtained for selected stars. In section 4 we present a discussion with a very recent paper in section 5 we present a discussion with a very recent paper. In the last section some conclusions and prospects are drawn.

## 2 METHODS OF CALCULATIONS

### 2.1 Units, definitions, reference frames

To achieve the aim of this work we have to study stars (including the Sun) motion under the gravitational influence of the Galaxy. This can be performed only for stars with the full 6D data available, typically expressed in the equatorial frame, i.e. right ascension \(\alpha\), declination \(\delta\), parallax \(\pi\), proper motions \(\mu_\alpha^*\), \(\mu_\delta\) (a star subscript denotes the multiplication by \(\cos\delta\)) and radial velocity \(v_r\). The starting data for a numerical integration, namely position and velocity components in the Galactocentric frame are to be obtained as follows. We first calculate the heliocentric distance of a star from the formula:

\[
r_h = \frac{1000}{\pi}
\]

where the parallax \(\pi\) is expressed in milliarcseconds [mas] what gives \(r_h\) in parsecs. According to comments expressed by van Leeuwen (2007a, chapter 3, page 86) we resisted here to add the so called Lutz-Kelker bias correction, proposed by Anderson & Francis (2012).

Next, heliocentric, equatorial rectangular coordinates of a star (in parsecs) are given by:

\[
\begin{align*}
x_h &= r_h \cos\alpha \cos\delta \\
y_h &= r_h \sin\alpha \cos\delta \\
z_h &= r_h \sin\delta
\end{align*}
\]

If proper motions are given in mas/yr and radial velocity is expressed in \(\text{km s}^{-1}\) than the heliocentric, equatorial rectangular velocity components (in pc/Myr) might be calculated as follows:

\[
\begin{align*}
v_1 &= s \cdot r_h \cdot \mu_\alpha^* / \cos\delta \\
v_2 &= s \cdot r_h \cdot \mu_\delta \\
v_3 &= k \cdot v_r \\
\dot{x}_h &= -\cos\delta \sin\alpha \cdot v_1 - \sin\delta \cos\alpha \cdot v_2 + \cos\delta \cos\alpha \cdot v_3 \\
\dot{y}_h &= \cos\delta \cos\alpha \cdot v_1 - \sin\delta \sin\alpha \cdot v_2 + \cos\delta \sin\alpha \cdot v_3 \\
\dot{z}_h &= \cos\delta \cdot v_2 + \sin\delta \cdot v_3
\end{align*}
\]

where \(s = 0.0048481368\) is a coefficient for angular units conversion and \(k = 1.022689369\) is a coefficient for velocity units conversion. Throughout this paper we use the following units: parsec [pc] as the distance unit, solar mass [\(M_\odot\)] as the mass unit and million of years [Myr] as the time unit. The constant of gravity expressed in these units is: \(G = 4.498297316 \times 10^{-3}\).

Reorientation of the equatorial frame into Galactic one (still heliocentric) involves three rotations:

\[
\mathbf{r}_{h,\text{gal}} = R_z(90^\circ - \theta) R_x(90^\circ - \delta_\odot) R_z(\theta_0 + \alpha_0) \mathbf{r}_{h,\text{equ}}
\]

where \(\theta = 122^\circ 93191857\), \(\alpha_0 = 12^h 51^m 26.27549\) and \(\delta_0 = 27^\circ 07' 42.7043\) are the positional angle and north Galactic pole equatorial coordinates defining the Galactic frame orientation while \(R_z\) and \(R_x\) denote the rotation with respect to \(OX\) and \(OZ\) axes respectively. See Liu et al. [2011] for a recent discussion on the Galactic frame orientation.

To move the origin from the Sun to the Galactic centre it is necessary to add the Galactic position and velocity of the Sun:

\[
\mathbf{R} = \mathbf{r}_{h,\text{gal}} + \mathbf{R}_\odot, \quad \dot{\mathbf{R}} = \dot{\mathbf{r}}_{h,\text{gal}} + \dot{\mathbf{R}}_\odot,
\]

The values for the solar position \(\mathbf{R}_\odot = (x_\odot, y_\odot, z_\odot)\) and velocity \(\dot{\mathbf{R}}_\odot = (u, v, w)\) components should be chosen in accordance with the adopted Galactic potential model. In our calculation we use \(\mathbf{R}_\odot = (x_\odot, y_\odot, z_\odot) = (-8400.0, 17)\) in pc. Since the vertical position of the Sun with respect to the Galactic disk plane is still uncertain we decided to follow arguments of Joshi (2007) and adopt
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2.2 Drawing a stellar clone

In order to estimate the uncertainty of the close stellar passage parameters we replace each considered star with a large number (typically 10000) of its clones, drawn from a multivariate normal distribution. This is possible because in HIP2 catalogue (van Leeuwen, 2007b; 2011) included full information on the covariance matrix of astrometric parameters. Such a procedure possesses an evident superiority over the individual, independent random drawing of each stellar parameter. 

To do this we repeated our calculation of fit' calculation (van Leeuwen, 2013, personal communication) by multiplying corresponding diagonal elements from the covariance matrix by the reference variance \( \sigma_0 \).

According to equation (5) we have:

\[
\Sigma = (U^T U)^{-1} = U^{-1} (U^T)^{-1} = U^{-1} (U^{-1})^T = G G^T
\]

which shows, that \( G = U^{-1} \) is suitable for our purpose of drawing a star clone according to the recipe presented at the beginning of this section.

We tested how different methods of drawing clones affect the dispersion of the proximity position. To do this we repeated our calculation for all selected stars by drawing all parameters of stellar clone independently. In most cases distribution was only slightly different in shape, but in few cases, for example HIP 25240 (see Fig. 7) dispersion was significantly higher than when we used covariance matrix. This shows that the use of the covariance matrix, apart from being closer to the data, in some cases can significantly improve the accuracy of the close stellar approach determination.

2.3 Galactic motion of stars

To study the Galactocentric motion of a star we use a numerical integration of its equations of motion expressed in rectangular coordinates, utilising the well known, fast and accurate RA15 routine by Everhart (1985). To describe the Galactic gravitational potential we use Model I from Irrgang et al. (2013). Since we are interested in motion of nearby stars from their current positions backward or forward to the moment of their closest heliocentric position we deal with rather small time intervals of order of 10 Myr and small heliocentric distances, not exceeding 200 pc, with the only one exception of the star HIP 33369 with the current heliocentric distance of 424 pc (such a large distance makes our results for this star completely unreliable as it is shown in Section 3). For such a small solar vicinity a more sophisticated Galactic potential model, accounting for non-spherical central bulge or for spiral arms is not necessary, as
was checked for example by García-Sánchez et al. (2001) or more recently by Jiménez-Torres et al. (2011).

Gravitational potential $\Phi(r,z)$ considered here is the sum of a central bulge component $\Phi_b(r,z)$ and a massive spherical Galactic halo $\Phi_h(R)$ (dark matter included):

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

where $(r, \theta, z)$ are Galactocentric cylindrical coordinates and $R = \sqrt{r^2 + z^2}$ is a Galactocentric spherical radius. For the Galactic bulge and disk components we use formulae:

$\Phi_b(r,z) = \frac{M_b}{\sqrt{R^2 + b_0^2}} = \Phi_b(r,z) = \frac{M_b}{\sqrt{r^2 + (a_d + \sqrt{z^2 + b_d^2})^2}}$

$\Phi_d(r,z) = \frac{M_d}{\sqrt{r^2 + (a_d + \sqrt{z^2 + b_d^2})^2}}$

and for the Galactic halo we have:

$$\Phi_h(R) = \begin{cases} \frac{M_h}{\sqrt{R}} \left( \frac{1}{1 + \left( \frac{a_h}{R} \right)^{\gamma}} \right) - \frac{M_h}{R} \left( \frac{a_h}{R} \right)^{-\gamma} & \text{if } R < \Lambda \\ \frac{M_h}{R} \left( \frac{a_h}{R} \right)^{-\gamma} & \text{elsewhere.} \end{cases}$$

what, after adopting $\gamma = 2$ and choosing the first equation (we certainly do not go as far as $R = \Lambda = 200$ kpc!) reduces to:

$$\Phi_h(x,y,z) = \frac{M_h}{a_h} \left( \ln \left( \frac{a_h + \sqrt{x^2 + y^2 + z^2}}{a_h + \Lambda} \right) - \frac{\Lambda}{a_h + \Lambda} \right)$$

The equation of motion of a single point mass (a star) under the potential described above, expressed in a rectangular Galactic (and Galactocentric) frame are:

$$\ddot{x} = -\frac{\partial}{\partial x} \Phi_b(x,y,z) - \frac{\partial}{\partial y} \Phi_d(x,y,z) - \frac{\partial}{\partial z} \Phi_h(x,y,z)$$

$$\ddot{y} = -\frac{\partial}{\partial y} \Phi_b(x,y,z) - \frac{\partial}{\partial x} \Phi_d(x,y,z) - \frac{\partial}{\partial z} \Phi_h(x,y,z)$$

$$\ddot{z} = -\frac{\partial}{\partial z} \Phi_b(x,y,z) - \frac{\partial}{\partial x} \Phi_d(x,y,z) - \frac{\partial}{\partial y} \Phi_h(x,y,z)$$

where

$$\frac{\partial}{\partial x} \Phi_b(x,y,z) = \frac{x M_b}{(x^2 + y^2 + z^2 + b_h^2)^{\frac{3}{2}}} = \frac{x M_b}{(R^2 + b_h^2)^{\frac{3}{2}}}$$

$$\frac{\partial}{\partial y} \Phi_b(x,y,z) = \frac{y M_b}{(x^2 + y^2 + z^2 + b_h^2)^{\frac{3}{2}}} = \frac{y M_b}{(R^2 + b_h^2)^{\frac{3}{2}}}$$

$$\frac{\partial}{\partial z} \Phi_b(x,y,z) = \frac{z M_b}{(x^2 + y^2 + z^2 + b_h^2)^{\frac{3}{2}}} = \frac{z M_b}{(R^2 + b_h^2)^{\frac{3}{2}}}$$

$$\frac{\partial}{\partial x} \Phi_d(x,y,z) = \frac{x M_d}{\left( x^2 + y^2 + (a_d + \sqrt{z^2 + b_d^2})^2 \right)^{\frac{3}{2}}}$$

$$\frac{\partial}{\partial y} \Phi_d(x,y,z) = \frac{y M_d}{\left( x^2 + y^2 + (a_d + \sqrt{z^2 + b_d^2})^2 \right)^{\frac{3}{2}}}$$

$$\frac{\partial}{\partial z} \Phi_d(x,y,z) = \frac{z M_d}{\left( x^2 + y^2 + (a_d + \sqrt{z^2 + b_d^2})^2 \right)^{\frac{3}{2}}}$$

Table 1. Model I parameters from Irrgang et al. (2013)

| Parameter                           | Value   |
|-------------------------------------|---------|
| the distance of the Sun from the Galactic centre $R_\odot$ | 8400 pc |
| Galactic bulge mass $M_b$            | $9.51 \times 10^9 M_\odot$ |
| Galactic disk mass $M_d$             | $6.64 \times 10^9 M_\odot$ |
| Galactic halo mass $M_h$             | $2.37 \times 10^9 M_\odot$ |
| bulge characteristic distance $b_b$  | 230 pc  |
| disk characteristic distance $a_d$   | 4220 pc |
| disk characteristic distance $b_d$   | 292 pc  |
| halo characteristic distance $a_h$   | 2562 pc |
| Galactic halo cut-off parameter $\Lambda$ | 200000 pc |
| Galactic halo exponent parameter $\gamma$ | 2 (fixed) |
| Galactic disk matter density near the Sun $\rho_d$ | $0.102 M_\odot/pc^2$ |
| Galactic rotational velocity of the LSR $v_\odot$ | 242 km s$^{-1}$ |
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Figure 2. Distribution of clones of star HIP 19946 in the original Galactic heliocentric frame. In this and all next similar plots black points are the position of clones in the moment of the closest approach obtained from numerical integration. Green points are the position of clones calculated with a straight line motion model. Blue circle is the boundary of the Oort cloud at 0.5 pc.

The result of our calculation is always in the form of a swarm of 10 000 clones stopped at the closest proximity from the Sun. We have inspected all these swarms of clones in 3D and found, that they are typically very flat and can be conveniently presented in 2D plots after applying necessary rotations. To this aim we determine the plane of the maximum scatter using principal components analysis (PCA). As can be read in [Jolliffe 2002] principal component analysis is one of the oldest techniques of multivariate analysis. Using this technique, we can find the largest scatter plane for our clones which is what we would like to present in our plots. Raw results of our calculations consists of Galactocentric coordinates of each star and the Sun. First we must go back to heliocentric frame so we need to subtract the calculated position of the Sun from that of the star.

Then we need to construct a covariance matrix:

\[ \Sigma = \begin{pmatrix} \text{cov}(x, x) & \text{cov}(x, y) & \text{cov}(x, z) \\ \text{cov}(y, x) & \text{cov}(y, y) & \text{cov}(y, z) \\ \text{cov}(z, x) & \text{cov}(z, y) & \text{cov}(z, z) \end{pmatrix} \]

(9)

where for example:

\[ \text{cov}(x, y) = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{n-1} = \text{cov}(y, x) \]

and \(x_i, y_i, z_i\) - are coordinates of ith clone; \(\bar{x}, \bar{y}, \bar{z}\) - are respective means of coordinates of all clones; \(n\) - is the number of clones (here typically 10 000).

Next we use Jacobi transformation to find eigenvalues and corresponding eigenvectors. Then we create matrix \(3 \times 3\) where in first column we place eigenvector corresponding to the largest eigenvalue and in next columns eigenvectors corresponding to the remaining eigenvalues. When we have this matrix with eigenvectors \(v_i\) and vector with coordinates \((x, y, z)\) of clone in Galactic heliocentric frame we can calculate new coordinates \((x', y', z')\) for all clones from equation (10)

\[ \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} v_1 & v_2 & v_3 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \]

(10)

When we look at the results in the original Galactic heliocentric frame (Fig. 2) we see a comparable level of scattering in all planes, but if we express our results with respect to the frame obtained with PCA (Fig. 3) we see large difference in scatter level between \(x'y'\) plane and the other two. This clearly reflects the fact that the swarm of clones stopped at the closest proximity with the Sun is almost flat.

The final result from the PCA (for plotting purposes) we obtain when we reduce our data to two dimensions. To reduce dimensions we use only two eigenvectors corresponding to the two largest
We see that the final plot (Fig. 4) strictly correspond to the first projection in Fig. 3. For the star used in the above examples a straight line motion model is a good approximation for calculating distance of closest approach to Sun, but in next section we show examples when this approximation it’s not that good. As mentioned earlier a distance calculated with a rectilinear motion approximation may be significantly different from a distance obtained from a numerical integration.

3 RESULTS FOR SELECTED STARS

3.1 Selection of stars and overall results

In this research we restricted ourselves to the stars from HIP2 catalogue with known radial velocities. We are interested in the closest stellar passages so a very small subset of these stars were chosen for our calculations. The selection procedure was as follows. For each star in the HIP2 catalogue we checked, if its radial velocity is available in the XHIP catalogue Anderson & Francis (2012). If it is present, we calculated the minimal heliocentric distance of this star (in past or in future) using the rectilinear motion approximation \( D_l \). As a short list of candidates (2538 objects) we selected all stars having this minimal distance \( D_l \) smaller than 20 pc. We used such a large threshold value expecting that the exact minimal distance, obtained from a numerical integration \( D_{\text{min}} \), can be substantially different. In our sample we did not find any star which \( D_l > 10 \) and \( D_{\text{min}} < 2 \) pc so the criterion \( D_l < 10 \) would be probably sufficient. Then we integrated numerically equations of motions of every pair, the Sun and each star from the short list, using full Galactic potential as described in previous section. Our final list consists of 40 stars with the nominal proximity distance smaller than 2 pc. In Table 2 we present a complete list of these stars with their common names, nominal proximity distances and epochs and quality of radial velocity value. In the last column we describe whether the star is our new findings or its proximity was noticed and calculated in some earlier papers. In three cases new stars were independently found by us and by B-J.

In columns 5 and 6 of Table 2 we present results (minimal distance \( D_{\text{min}} \) in parsecs and the corresponding moment of time \( T_{\text{min}} \) in Myr from the present epoch) for the nominal astrometric parameters of each star. The aim of this paper is however to estimate the accuracy of these results. To achieve this we replaced each star with 10,000 of its clones, obtained as described in Section 2.2. Next we numerically integrated motion of all clones and estimated the distance of the most probable proximity point and the corresponding epoch with their uncertainties.

The results for all selected stars are presented in Table 3 and here \( D \) (minimal distance) and \( T \) (the epoch of the proximity) are the most probable values obtained from the respective clone distributions. In some cases they significantly differ from nominal results presented in Table 2. In the case of moment of time its calculating procedure was quite simple: \( T \) is the mean value and its uncertainty \( \Delta T \) is the half of the symmetric interval covering 90 per cent of individual clone values. The situation is much more complicated with the proximity distance estimation, since their distributions are frequently significantly asymmetric. To present the most informative result we decided to calculate three mean coordinates of the most probable proximity point in space (calculating simple means in each coordinate, i.e. \( x' \), \( y' \) and \( z' \)) and then to calculate its distance from the Sun:

\[
D = \sqrt{x'^2 + y'^2 + z'^2}
\]
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Table 2. List of stars with nominal proximity distance smaller than 2 pc. Third column shows quality of radial velocity quoted from the XHIP catalogue. Results from numerical integration of nominal data $D_{\text{min}}$ and $T_{\text{min}}$ are presented in fourth and fifth column, in next two columns we show for comparison purpose the results from the rectilinear motion approximation $D_{\ell}$ and $T_{\ell}$.

| HIP2 ID | Name           | q_{RV} | $D_{\text{min}}$ [pc] | $T_{\text{min}}$ [Myr] | $D_{\ell}$ [pc] | $T_{\ell}$ [Myr] | Earlier publications |
|---------|----------------|--------|------------------------|-------------------------|-----------------|-------------------|---------------------|
| 1392    | HD 1317        | A      | 1.70                   | -0.48                   | 1.70            | -0.48            | new                |
| 3829    | Van Maanen Star| D      | 0.95                   | -0.02                   | 0.95            | -0.02            | a, c, f             |
| 12351   | GJ 1049        | C      | 1.93                   | -0.62                   | 1.92            | -0.62            | a, c, e, f          |
| 14473   | HD 19376       | A      | 0.35                   | -3.73                   | 2.37            | -3.78            | new                |
| 14754   | GJ 127.1A      | D      | 1.62                   | -0.29                   | 1.63            | -0.29            | a, b, e, f          |
| 19946   | BD+03 580      | A      | 1.80                   | -0.54                   | 1.81            | -0.54            | new                |
| 21539   | CD-33 1835     | D      | 1.92                   | -0.14                   | 1.92            | -0.14            | new                |
| 23415   | HD 32111       | A      | 1.71                   | 5.20                     | 3.09            | 5.16             | new                |
| 25001   | HD 34790       | D      | 1.93                   | 4.42                     | 1.88            | 4.39             | a, c               |
| 25240   | HD 35317       | A      | 1.66                   | -0.99                   | 1.63            | -0.99            | a, c, f             |
| 26335   | HD 245409      | A      | 1.54                   | -0.49                   | 1.53            | -0.49            | a, b, d, e, f       |
| 26624   | HD 37594       | A      | 1.98                   | -1.87                   | 1.95            | -1.87            | a, c, e, f          |
| 26744   | HD 38678       | A      | 1.31                   | -0.65                   | 1.30            | -0.85            | a, b, c, e, f       |
| 30067   | HD 43947       | A      | 1.78                   | -0.66                   | 1.78            | -0.66            | a, b, c, e, f       |
| 30434   | HD 44821       | A      | 1.10                   | -1.56                   | 1.11            | -1.56            | a, b, e, f          |
| 33369   | V*BG Mon       | B      | 0.85                   | -5.41                   | 3.68            | -5.38            | new                |
| 38228   | HD 63433       | A      | 1.95                   | 1.35                     | 1.93            | 1.35             | a, b, c, e, f       |
| 38965   | HD 66589       | A      | 1.79                   | -1.09                   | 1.80            | -1.09            | new, f              |
| 42525   | BD+41 1865     | A      | 0.82                   | -0.24                   | 0.82            | -0.24            | new, f              |
| 47425   | GJ 358         | C      | 1.87                   | -0.06                   | 1.87            | -0.06            | a, c, f             |
| 54035   | HD 95735       | A      | 1.44                   | 0.02                     | 1.44            | 0.02             | a, b, d, e, f       |
| 57544   | GJ 445         | A      | 1.06                   | 0.05                     | 1.06            | 0.05             | a, b, c, d, e, f    |
| 57548   | GJ 447         | A      | 1.92                   | 0.07                     | 1.92            | 0.07             | a, b, c, d, e, f    |
| 63721   | HD 113447      | A      | 0.12                   | 0.13                     | 0.12            | 0.13             | new, f              |
| 70890   | Proxima Centauri| B      | 0.94                   | 0.03                     | 0.94            | 0.03             | a, b, c, d, e, f    |
| 71681   | α Centauri B   | A      | 0.96                   | 0.03                     | 0.96            | 0.03             | a, b, c, d, e, f    |
| 71683   | α Centauri A   | A      | 0.98                   | 0.03                     | 0.98            | 0.03             | a, b, c, d, e, f    |
| 75311   | BD-02 3986     | A      | 1.62                   | 4.84                     | 3.55            | 4.92             | a, c                |
| 77910   | HD 142500      | A      | 1.82                   | 3.05                     | 1.04            | 3.07             | a, c                |
| 84263   | HD 155117      | A      | 1.11                   | -6.53                    | 2.44            | -6.52            | new                |
| 85661   | HD 158576      | A      | 0.52                   | 1.88                     | 0.39            | 1.88             | a, c, f             |
| 87052   | HD 161959      | A      | 1.91                   | 5.80                     | 6.92            | 5.88             | new                |
| 87937   | Bernard Star   | A      | 1.15                   | 0.01                     | 1.15            | 0.01             | a, b, c, d, e, f    |
| 89825   | GJ 710         | A      | 0.29                   | 1.39                     | 0.30            | 1.39             | a, b, c, d, e, f    |
| 90112   | HD 168769      | A      | 0.89                   | -1.86                    | 0.97            | -1.86            | a, c, f             |
| 92403   | GJ 729         | A      | 1.98                   | 0.15                     | 1.98            | 0.15             | a, b, c, d, e, f    |
| 94512   | HD 179339      | A      | 1.99                   | 3.63                     | 2.04            | 3.63             | a, c, f             |
| 103738  | HD 19951       | A      | 1.18                   | -3.86                    | 2.36            | -3.90            | c, f                |
| 110893  | HD 239660      | A      | 1.92                   | 0.09                     | 1.92            | 0.09             | a, b, c, e, f       |

a - Jiménez-Torres et al. (2011), b - Bobylev (2010a), c - García-Sánchez et al. (2001), d - Dybczynski & Kankiewicz (1999), e - Dybczynski (2006), f - Bailer-Jones (2014).

can be made. First, there are two stars, HIP 33369 and HIP 75311, for which our results are completely unreliable. First star is at the exceptionally large distance at the present epoch (424 pc) and any uncertainties in its position and/or velocity significantly amplifies when numerically integrating its motion back to the solar proximity. While its nominal proximity distance is only 0.85 pc we, basing on the contemporary astrometric data for this star, cannot say anything reliable about its real minimal distance from the Sun 5 Myr ago.

For the second star, HIP 75311, the main source of the unacceptable uncertainty in the proximity distance is the large formal error of its proper motion. Both components of the proper motion of this star have uncertainties on the level of 300 per cent in the HIP2 catalogue. The nominal proximity distance is 1.62 pc, the most probable value equals 5.71 and both should be treated as highly unreliable. Both these stars are marked with '?' in Table 3 as well as five more stars due to their large proximity position errors.

There is also one additional star marked in the same way despite of its small error, namely HIP 63721. The reason for this is that we are aware of its highly unreliable parallax in HIP2. Instead of $\pi = 217$ mas included in HIP2 other sources present parallax value well beyond 5 mas (see for example Fabricius & Makarov (2000)). HIP2 value is also discarded in XHIP catalogue.

There are also 12 stars (marked with '*' just after their HIP numbers in Table 3) in our final list which are now close to the Sun and simultaneously close to their proximity epoch. For these stars a proximity uncertainty is practically equal to their current astrometric position and velocity uncertainties and therefore small or very small. In our calculations we integrated them only over extremely short time intervals and we did not observe any uncertainty...
Table 3. Estimated minimum distance $R$ from the Sun and corresponding moment of time $T$ for 40 stars that nominally can came closer than 2 pc. A dash marks cases where we cannot obtain reasonable values.

| HIP ID | $D$ [pc] | $\Delta D$ [pc] | $T$ [Myr] | $\Delta T$ [Myr] |
|--------|-----------|-----------------|-----------|-----------------|
| 1392   | 1.70      | 0.16            | -0.48     | 0.02            |
| 3829 * | 0.95      | 0.05            | -0.02     | <0.01           |
| 12351  | 2.26      | 1.47            | -0.71     | 0.45            |
| 14473 ?| 0.22      | 7.84            | -3.78     | 0.74            |
| 14754  | 1.64      | 0.27            | -0.29     | 0.04            |
| 19946  | 1.91      | 1.32            | -0.55     | 0.13            |
| 21539 *| 1.97      | 0.49            | -0.14     | 0.03            |
| 23415 ?| 1.65      | 7.82            | 5.35      | 1.43            |
| 25001  | 2.07      | 1.54            | 4.67      | 1.70            |
| 25240  | 1.66      | 0.30            | -0.99     | 0.05            |
| 26335  | 1.54      | 0.09            | -0.49     | 0.01            |
| 26624  | 1.98      | 0.25            | -1.87     | 0.08            |
| 26744 ?| 1.71      | 4.21            | 14.12     | 2.30            |
| 27288  | 1.31      | 0.10            | -0.85     | 0.06            |
| 30067  | 1.78      | 0.11            | -0.66     | 0.01            |
| 30344  | 1.11      | 0.23            | -1.57     | 0.11            |
| 33369 ?| 51.00     | –               | -4.96     | –               |
| 38228  | 1.95      | 0.16            | 1.35      | 0.03            |
| 38965  | 1.87      | 1.16            | -1.10     | 0.23            |
| 42525  | 0.99      | 0.96            | -0.25     | 0.09            |

| HIP ID | $D$ [pc] | $\Delta D$ [pc] | $T$ [Myr] | $\Delta T$ [Myr] |
|--------|-----------|-----------------|-----------|-----------------|
| 47425 *| 1.90      | 0.45            | -0.06     | 0.01            |
| 54035 *| 1.44      | 0.01            | 0.02      | <0.01           |
| 57544 *| 1.06      | 0.03            | 0.05      | <0.01           |
| 57548 *| 1.92      | 0.04            | 0.07      | <0.01           |
| 63721 ?| 0.13      | 0.04            | 0.14      | 0.03            |
| 70890 *| 0.94      | 0.03            | 0.03      | <0.01           |
| 71681 *| 0.96      | 0.09            | 0.03      | <0.01           |
| 71683 *| 0.98      | 0.04            | 0.03      | <0.01           |
| 75311 ?| 5.71      | –               | 5.23      | –               |
| 77910  | 1.94      | 1.59            | 3.15      | 0.90            |
| 82625 ?| 1.20      | 4.64            | -6.59     | 1.07            |
| 85661  | 0.52      | 0.62            | 1.88      | 0.11            |
| 87052 ?| 1.81      | 5.87            | 5.90      | 1.27            |
| 87937 *| 1.15      | 0.01            | 0.01      | <0.01           |
| 89825  | 0.29      | 0.35            | 1.39      | 0.08            |
| 90112  | 0.91      | 1.31            | -1.87     | 0.20            |
| 92403 *| 1.98      | 0.04            | 0.15      | <0.01           |
| 94512  | 2.06      | 2.33            | 3.65      | 0.46            |
| 103738 | 1.18      | 0.69            | -3.87     | 0.30            |
| 110893 *| 1.92     | 0.04            | 0.09      | <0.01           |

Figure 5. HIP 25240 - the example of a compact swarm of clones resulting from a current distance of this star which is relatively close to the minimum value (nominally 1 Myr ago).

amplification. The example of such a result is presented in Fig.5. Any further discussion of the accuracy of our results for these stars seems unnecessary.

3.2 Examples

The remaining 20 stars present a wide variety of proximity distance accuracy estimations. We will discuss several representative examples in following subsections.

3.2.1 HIP 89825 (Gliese 710)

This star is a well known future visitor in the solar neighbourhood, see for example Mülläri & Orlov (1996); Dybczyński & Kankiewicz (1999); García-Sánchez et al. (2001); Dybczyński (2006). According to the latest estimation of its astrometric parameters presented in HIP2 catalogue and using $v_r = -13.8 \, \text{km s}^{-1}$ (Gontcharov (2006), used also in XHIP) we obtained the proximity distance (both nominal and mean) as small as 0.29 pc. As it is clearly depicted in Fig.6 the straight linear motion approximation works very well in this case. The swarm of clones of this star is however significantly dispersed, mainly due to large uncertainties of proper motions of Gliese 710. If one had used an older value of its radial velocity: $-23 \, \text{km s}^{-1}$ (Wilson 1953), later confirmed for example in the Palomar/MSU survey (Reid et al. 1995), the minimal distance would reduce even further, down to 0.17 pc and almost all clones of this star would be situated closer than 0.5 pc from the Sun i.e., the widely accepted radius of the outer Oort cloud.

3.2.2 HIP 14473 (HD 19376)

This star is our new finding and the only one in our list for which an estimated proximity distance in the past (3.78 Myr ago) is significantly smaller than the adopted radius of the Oort cloud. We estimated this minimal distance to be $D = 0.22 \, \text{pc}$ with the proximity position uncertainty $\Delta D = 7.84 \, \text{pc}$ (see Fig.7). The reason of such a large error of our estimation is a large uncertainty of proper motion of this star. If one obtain much more accurate value (for example from Gaia mission) this star should be considered as a serious candidate for the stellar perturber of cometary motion in the past.

3.2.3 HIP 103738 (HD 199951)

Here we have a good example of the significant difference between the exact numerical integration in the Galactic field and the rectilin-
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3.2.4 HIP 87052 (HD 161959)

This star is another one among 10 stars recognised in this paper for the first time as possibly visiting the solar vicinity. The reason for this novelty is that the straight line motion approximation (green points in Fig. 9) gives the proximity distance for this star as large as almost 7 pc! The distance to the most probable proximity point from numerical integration obtained by us is only 1.81 pc but its dispersion is large so we estimated rather large error for this value, namely ±5.87 pc. This is the consequence of a large uncertainty of proper motion for this star. This is also present when we compare nominal proximity points obtained on the basis of different astrometric catalogues, as it is depicted in Fig. 10.

3.2.5 HIP 84263 (HD 155117)

In this case the minimal distance obtained from a numerical integration reduces to 1.20±4.64 pc comparing with 2.44 from a rectilinear model. This star has very small proper motion with rather big relative errors which together with the long numerically integrated time interval (over 6 Myr) gives a widely spread swarm of clones, with significant number located inside the assumed Oort cloud sphere (see Fig. 11).

3.2.6 HIP 77910 (HD 142500)

Using numerical integration with full Galactic potential we almost double the minimal distance of HIP 77910 from the Sun, obtaining $D = 1.94 \pm 1.59$ pc (black points in Fig. 12). This makes its
gravitational influence on Oort cloud comets weaker but since its estimated mass is $2 \, M_\odot$, it should still be considered as a potential stellar perturber.

3.2.7 HIP 57791 (HD 102928)

HIP 57791 is an extra example (outside our star list but for example included by García-Sánchez et al. [1999]) of completely different results from the rectilinear approximation and numerical integration. In this case a full model moves out the proximity point from 1.8 pc to 3.7 pc from the Sun (see Fig. 13) what makes this star rather improbable stellar perturber for the Oort cloud comets.

4 'LAST MINUTE’ DISCUSSION

Just in the moment we had our paper ready for submission we learned about a very recent paper by Bailer-Jones [2014]. He used almost identical data and methods and obtained results similar to ours in many respects. However there are also several differences in our approach and as a consequence his results are in many cases significantly different so it is worth to study in detail each individual star case.

In his Table 3 B-J describes 65 close (closer than 2 pc from the Sun) stellar passages. However, for many stars he included several variants (based on different stellar data) so in fact he presented stellar proximities for 42 individual stars. This is very close to 40 stars in our Tables 2 and 3 but surprisingly we have only 27 stars in common. There are two main reasons for this discrepancy. First, B-J presents his results in significantly different manner. He calculate simple mean of all proximity distances for all clones with 90 per cent confidence intervals and in many cases this method somewhat overestimates the distance we should expect. The heliocentric
distance is obviously positive so its distribution is often significantly asymmetric. Moreover mean value is rather sensitive to outliers and due to the limitation to positive values almost all outliers are placed at one side of the mean. For this reason we decided to present the distance to the most probable proximity position, as it is described in detail in Sec. 3.1. Since B-J selected stars for his published Table 3 using only mean distances several objects were shifted out to his Internet large table. The most spectacular example is the star HIP 14473. As it is shown in Fig. 7 spatial positions of proximity points of individual clones are widely spread. B-J calculated the mean of all this distances and report the result (in his extended, Internet table) to be 6 pc. In our approach we report the proximity distance as 0.22 ± 7.84 pc (of course the second number is the uncertainty in proximity point position, not the formal error in the proximity distance which must be positive).

The second reason for several discrepancies between B-J and our results is his usage of few questionable radial velocities from RAVE catalogue. The great majority of velocities taken by B-J from RAVE catalogue seems to be obviously erroneous, in some cases greater than the escape velocity from our Galaxy. B-J also commented all these cases as uncertain. In our investigation we did not use these velocities.

There are also several other differences in the methods (e.g. the Galaxy potential model) and result presentation, including the main purpose of the work: we aimed at studying and presenting the accuracy of proximity calculations while B-J concentrate on completing the list of closest stellar approaches. He also discuss in detail many problematic cases which helped us to reveal the source of some discrepancies, e.g for HIP 85605.

As it concerns the influence of the Galaxy potential model, B-J used the Dauphole and Colin model (1995; 1996) and states: “While better models may now exist, the results are not very sensitive to the exact choice”. The influence of different Galaxy models for close stellar approaches to the Sun was recently discussed by Jiménez-Torres et al. (2011) and their conclusion is that for more distant stars the results are sensitive to the choice of the model. They present a large table comparing results for different models (their tab.3) but erroneously instead of presenting their own results they copied results from Jiménez-Torres et al. (2011) and Jiménez-Torres et al. (2013). Since we used a very recent model by Irrgang et al. (2013) we are interested in such a comparison.

B-J kindly made available for us his nominal results (Bailer-Jones, 2015, personal communication). Thanks to that we were able to study the difference between stellar results for two models in use (including slightly different initial Sun position and velocity and marginal difference in the Galactic frame orientation). We found moderate differences in the nominal closest stellar approach distances for several objects. In Table 4 we present selected examples of such differences (for the purpose of this comparison we used exactly the same stellar initial data as B-J).

In the following sections we discuss in detail all discrepancies we found in the stellar close approaches lists of B-J and ours.

### 4.1 14 stars present in B-J but omitted here

There are two groups of stars from B-J list missing in our paper. First is the result of using RAVE radial velocities (not used by us) and the second comes from the utilisation of astrometric parameters (mainly proper motions) from the XHIP catalogue, where HIP2 astrometry was replaced by some other, frequently taken from HIP1 or Tycho-2.

From the first group (10 stars), in our opinion, only star HIP 87784 can be treated as having close approach to the Sun (assuming that the RAVE radial velocity of -66.30±3.60 km s⁻¹ found by B-J will be confirmed). Also HIP 75159 might be considered as real (but highly uncertain) solar neighbourhood visitor. The rest (HIP 2311, HIP 41312, HIP 53911, HIP 55606, HIP 91012, HIP 100280, HIP 104256 and HIP 104644) are results of using unacceptable radial velocities.

Coming to the second group:

- HIP 34617 is the double system and proper motions in HIP-2 are not necessarily the best, so probably B-J result, using Tycho-2 values, is better.
- HIP 85605 is also a double system and erroneous parallax for this star exists in Hipparcos, as pointed out by SIMBAD database comment (“Parallax and proper motion are not compatible with CCDM J17296+2439A: the large proper motion and parallax of this star in Hipparcos (π=202mas, μ=362mas/yr) is most likely an artefact”). The similar opinion is expressed in Fabricius & Makarov (2004).
- HIP 86961 and HIP 86963 are members of the triple system and according to Henry et al. (2006) both these stars have significantly erroneous parallaxes in Hipparcos catalogues.

### 4.2 12 stars present in this paper but omitted in B-J

Apart from some differences in Galaxy potential model described above the main reason for some our stars missing in B-J list is presenting the mean value of the closest Sun-star distance. In many cases this results in larger values than presented by us, which includes stars HIP 1392, HIP 14473, HIP 19946, HIP 23415, HIP 25001, HIP 26744, HIP 77910, HIP 84263 and HIP 87052. For all these 9 stars the nominal proximity distance calculated by B-J is below the 2 pc threshold but his mean distance is larger and he excluded them from his published list.

There are three more stars in our list that are omitted by B-J. First is star HIP 21539 for which nominal proximity distance for data taken from XHIP catalogue is 1.92 pc but uncertainty of its radial velocity is undetermined (see Sec. 4.2.1) and probably for that reason B-J removed this star from his sample. Next two stars are HIP 33369, our nominal result equals 0.85, and HIP 75311 - HIP2 astrometry combined with the radial velocity from Pulkovo catalogue gives nominal proximity distance of 1.62 pc. These two stars

| object | D₁min [pc] | D₂min [pc] |
|--------|------------|------------|
| 14473g | 0.072      | 0.375      |
| 14473p | 0.095      | 0.353      |
| 75159r | 0.347      | 0.251      |
| 23415p | 1.486      | 1.715      |
| 84263x | 1.419      | 0.802      |
| 84263p | 0.723      | 1.112      |
| 84263g | 0.731      | 1.117      |
| 87052p | 0.394      | 1.914      |
| 87052x | 1.409      | 2.736      |
| 91012r | 0.446      | 0.350      |
have enormously large uncertainty of the proximity point position so their mean distance values are larger then 10 pc (and therefore omitted by B-J), but their nominal solutions are below the 2 pc limit.

4.3 Other difficult cases
As we have all nominal solutions kindly made available by B-J (also those corresponding to his large, Internet table) we carefully compared his results with ours. Few problematic cases we found for stars with the nominal proximity distance smaller than 2 pc:

- For HIP 1647 B-J found a radial velocity of -86.8 ± 28.8 km s^{-1} in RAVE catalogue and obtained the closest nominal distance of 1.979 pc. While in our model this distance is even smaller, 1.881 pc we think this result should be discarded. The reason is that HIP 1647 have a well established (since 1928) radial velocity of +12 km s^{-1}, i.e. in opposite direction.

- For HIP 10332 B-J have obtained a minimal, nominal distance of 1.793 pc basing on XHIP data. While XHIP authors treat this star astrometry as problematic and incorporate (a little bit inconsistently) its parallax from HIP1 and its proper motion from Tycho-2, the problem seems to be more serious. In Luck et al. [2011] the authors obtained the heliocentric distance for this star to be over 4 kpc. HIP 10332 (V*UX Per) is a classical δ Cepheid type star with the period over one year. There was well known problem in Hipparcos mission with obtaining correct parallaxes of classical cepheides and this star is most probably one of the problematic Hipparcos results.

- B-J used also XHIP data for HIP 24670 obtaining the nominal proximity of 1.729 pc. Proper motions of this star are very small with large uncertainties in all catalogues, which connected with its large current distance (over 160 pc according to HIP2) makes the uncertainty of the proximity distance very large. Mean value from B-J equals 5.3 pc.

- HIP 32475 according to B-J has the close approach nominal distance of 1.725 pc basing on XHIP data, where TYCHO-2 proper motions are included. This star is in fact a close binary (CCDM J06467+0822AB), unresolved in Hipparcos and Tycho catalogues. If we treat TYCHO-2 proper motions as superior to HIP2 this B-J result is fully valid.

- For HIP 75807 B-J found a radial velocity of -37.40 ± 28.8 km s^{-1} in RAVE catalogue which, combined with HIP2 astrometry gives a nominal proximity distance of 1.461 pc. The problem is that the proximity position uncertainty (ΔD = 84) is unacceptably large due to the astrometry uncertainties.

We are convinced that the incoming advance in stellar astrometry caused by Gaia mission can significantly improve the accuracy of nearby stars passages close to the Sun. The most important part is the precision of proper motions and parallaxes, augmented with (mainly ground based) precise radial velocity measurements.

5 CONCLUSIONS
The main purpose of this investigation was to study the accuracy of determination of the proximity distance and epoch for stars that can come (in past or in future) close to the Sun and act as stellar perturbers of the long period comet motion. Our study is based on the best available data in the pre-Gaia era, mainly from the HIP2 (van Leeuwen [2011]) and XHIP (Anderson & Francis [2012]) catalogues. We used a numerical integration in the rectilinear, Galactocentric coordinates taking into account the full gravitational potential of the Galaxy in its modern shape (Irwin et al. 2013). For the main purpose (the accuracy assessment) we utilised covariance matrices of astrometric data which is included in the HIP2 catalogue. Each star was substituted by a swarm of 10 000 of its clones according to the respective covariance matrix and radial velocity dispersion. Than we used Principal Component Analysis to present the distribution of the swarm at the proximity epoch.

Limiting our self to the nominal proximity distance of 2 pc we formulated a list of 40 stellar close visitors and among them 10 stars were our independent new findings (three of them were independently pointed out by B-J). We analysed each case in detail and concluded that for more than 50 per cent of stars in our list the accuracy is good or very good because these stars are now close to their proximity epoch. We showed several examples of moderate accuracy for more distant (in space and in time) stars.

We also showed that the linear approximation method can lead to large errors in many cases, especially for more distant stars, where the curvature in their motion induced by a Galaxy gravity cannot be ignored.

We also concluded that for two stars (HIP 33369 and HIP 75311) the extremely large formal errors makes our proximity distance results completely unreliable. We suspect that the result for HIP 63721 is also erroneous due to its probably false parallax in the HIP2 catalogue. We also marked next five stars (HIP 14473, HIP 23415, HIP 26744, HIP 84263 and HIP 87052) as having unacceptably large estimated errors. The first of them might be an important perturber of the long period comets motion since its nominal proximity distance was as small as 0.22 pc about 3.78 Myr ago. The problem is that the proximity position uncertainty (ΔD = 7.84) is unacceptably large due to the astrometry uncertainties.

We are convinced that the incoming advance in stellar astrometry caused by Gaia mission can significantly improve the accuracy of nearby stars passages close to the Sun. The most important part is the precision of proper motions and parallaxes, augmented with (mainly ground based) precise radial velocity measurements.

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