Is it possible to reveal the lost siblings of the Sun?

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ABSTRACT

We present the results of our numerical experiments on stellar scattering in the galactic disc under the influence of the perturbed galactic gravitation field connected with the spiral density waves and show that the point of view according to which stars do not migrate far from their birthplace, in general, is incorrect. Despite close initial locations and the same velocities after 4.6 Gyrs members of an open cluster are scattered over a very large part of the galactic disc. If we adopt that the parental solar cluster had \(\sim 10^3\) stars, it is unlikely to reveal the solar siblings within 100 pc from the Sun. The problem stands a good chance to be solved if the cluster had \(\sim 10^4\) stars.

We also demonstrate that unbound open clusters disperse off in a short period of time under the influence of spiral gravitation field. Their stars became a part of the galactic disc. We have estimated typical times of the cluster disruption in radial and azimuth directions and the corresponding diffusion coefficients.

Key words: Galaxy: solar neighborhood - stars: kinematics and dynamics - Galaxy: structure

1 INTRODUCTION

The fate and history of the Sun have a special significance since its influence on the Earth. Moreover, as it was demonstrated by Bland-Hawthorn & Freeman (2004) and Bland-Hawthorn et al. (2010) in-depth study of our star and discovery its siblings (the stars which were born along with the Sun in the same open cluster) will supply us by a valuable information about the early epoch of our galaxy Milky Way formation and its evolution.

In a recent paper, Portegies Zwart (2009) has revised the problem of searching the solar family. According to Portegies Zwart, if we adopt that the parental cluster had \(\sim 10^3\) stars, about 10 to 60 solar siblings are now located within a distance of 100 pc so they can be identified by means of next generation telescopes (see the first attempt of searching the solar relatives in Brown et al. 2010).

The presence of solar parental cluster members in the close vicinity from the Sun is a necessary but not sufficient condition to reveal them. It is obvious, in order to recognize the siblings among \(\sim 10^7\) close stars we need some additional marks like strong chemical elements similarity to the solar abundances, special velocity pattern in space, etc. (see the above papers).

In the modeling, Portegies Zwart (2009, see also Brown et al. 2010) adopts that both the Sun and its cluster members move along close and almost circular trajectories. Consequently, the authors derive an obvious result: the best place to find the solar kin is a ring-like segment close to the solar trajectory. Moreover, according to Portegies Zwart opinion one should not expect that the siblings can drift far from the Sun independently of their birth-place within the cluster since stellar velocity dispersion in the parental cluster is small (\(\sim 1\) km s\(^{-1}\)).

The reason why Portegies Zwart and his coworkers came to their conclusion is obvious: they consider an oversimplified axisymmetric model for the galactic gravitation field. The above assumptions, introduced by Portegies Zwart and Brown et al. in their model, are broken up if we take into account stellar interactions with perturbations of the galactic gravitation field due to spiral density waves, especially near the corotation resonance. Indeed, as it was shown by Lepline et al. (2003) and Acharova et al. (2004), in the vicinity of the resonance, a star is subjected to a great wander over the galactic radius (\(\sim 3\) kpc). So, we expect that in the course of solar life-time, open clusters will diffuse in the galactic disc under the influence of spiral perturbations of the galactic gravitation field and, in general, they will be scatter over a very large part of the disc.

The goal of the present paper is to demonstrate the above effects.

2 MODEL DESCRIPTION

We consider motion of an ensemble of probe particles, imitating stars of the solar parental cluster, in the galactic gravitation field perturbed by the density waves, which are responsible for spiral arms. So, the potential of the galactic gravitation field \(\varphi_G\) is repre-
sent as a sum:
\[ \varphi_0 = \varphi_0 + \varphi_S, \]
where \( \varphi_0 \) is the unperturbed axisymmetric part, \( \varphi_S \) is its perturbation due to galactic spiral density waves.

Notice here. We are not intended to reconstruct the evolution of the Galaxy as in the cited above papers by Bland-Hawthorn and his co-authors. Our aim is narrower: we only plan to demonstrate that, during the solar life-time \((\sim 4.6 \text{ Gyr})\), stars with close initial coordinates can be scattered over a very large part of the galactic disc due to interactions with the perturbed gravitation field so that, in general, in the close vicinity of any star from the parental cluster we do not reveal many its siblings as it was proclaimed by Portegies Zwart (2009). That is why we do not simultaneously consider the galactic evolution and stellar diffusion but suppose the perturbed potential as being given.

In our approach the unperturbed gravitational force is in balance with the centrifugal one (the galactic disc rotates in its plane), i.e.: \( d\varphi_0/dr = r\Omega^2 \), \( \Omega(r) \) is the angular rotation velocity of the disc, \( r \) is the galactocentric distance. The perturbed gravitational potential we write in a form of running spiral wave:
\[ \varphi_S = A \cos(\chi). \]
Here \( A < 0 \) is the wave amplitude,
\[ \chi = m[\cot(p) \log(r/r_0) - \theta + \Omega_p t], \]
is the wave phase (the condition \( \chi = \text{const} \) is the equation for a spiral arm shape), \( m \) is the number of spiral arms, \( p \) is the pitch angle of arms (for trailing arms \( p < 0 \)), \( \theta \) is the azimuth angle in the galactic plane (for simplicity we only consider stellar trajectories lying in the galactic plane), \( \Omega_p \) is the angular rotation velocity of density waves, \( t \) is time, \( r_0 \) is a normalizing radius. It is important to recall, that whereas the galactic matter rotates differentially (i.e. \( \Omega \) is a function of \( r \)), density waves rotate as a solid body \((\Omega_p = \text{const})\). The distance \( r_C \) where both the velocities coincide, i.e. \( \Omega(r_C) = \Omega_p \), is called the corotation radius. Here the particles resonantly interact with spiral perturbations of the galactic gravitation field.

Several words about the details of the galactic gravitation field model. For the rotation curve we adopt the same model by Allen and Santillán (1991) with the scale for the present solar galactocentric distance \( r_S = 8.5 \text{ kpc} \) as in Portegies Zwart and his collaborators papers (the normalizing radius, \( r_0 \), in the above expression for \( \chi, r_0 = r_S \)).

In our paper, we consider both the quasi-stationary density waves (Lin et al. 1969) and transient ones (e.g. Sellwood & Binney 2002 and papers therein). In the both cases the spiral wave amplitude, \( A \), is defined by means of fixing the perturbed force amplitude
\[ F = mcot(p)A/(\Omega r)^2 \] at solar distance (Lépine et al. 2003; Acharova et al. 2004; Antoja et al. 2009).

To determine the value of \( \Omega_p \) we set the location of the corotation radius, \( r_C \). After that, for the given rotation curve, \( \Omega_p \) is computed by means of equation (1). For the quasi-stationary wave pattern 2 values of the corotation radius were examined: 1) the corotation resonance is situated close to the present solar position \((r_C = r_S = 8.5 \text{ kpc})\); see e.g. Mishurov et al. 1997; Amaral & Lépine 1997; Mishurov & Zenina 1999 a,b; Lépine et al. 2001 and papers therein) and 2) \( r_C = 3.5 \text{ kpc} \)(e.g. Weinberg 1994; Dehnen 2000).

For the number of spiral arms 3 models were considered: 1) pure 2-armed \((m = 2)\) structure; 2) pure 4-armed \((m = 4)\) structure and 3) superposition of \( m = 2 + 4 \) wave harmonics (Lépine et al. 2001, details see below).

If the galactic spiral structure is a succession of transient density waves we assume that the corotation radius is confined within the region from 4 to 15 kpc, correspondingly for the adopted rotation curve \( \Omega_p \) belongs to the interval \( 14.2 - 51.8 \text{ km s}^{-1} \text{ kpc}^{-1} \). Further, we generate random values of \( \Omega_p \) uniformly distributed in the above region supposing that a spiral event of pattern speed \( \Omega_p \) is steady during life-time \( \tau_p \) for which 2 values were considered: \( \tau_p = 100 \) and 500 Myr. In all generated events we suppose patterns to be two-armed \((m = 2)\) with amplitudes and pitch angles as above.

Now let us discuss the initial conditions for the probe particles. To formulate them Portegies Zwart (2009), first of all, integrated the backward (in time) solar motion and found out its birth-place that he adopts as the initial location for the parental cluster center. Then, Portegies Zwart randomly distributed 1000 probe stars on the galactic plane within a circle of radius 3 pc centered at the above computed point.

But if we take into account the perturbations due to density waves the trajectories happen to be very tangled (especially near the corotation resonance). More over, as it will be shown below they are very sensible to the initial locations of particles. Hence we can not indicate more or less unambiguously the birth-place of the Sun despite the galactic gravitation field is regular (in the case of transient spiral structure the situation is much worse because of the random values of \( \Omega_p \)).

Hence, unlike Portegies Zwart we assume that at the initial moment of time the cluster center is located at some point with coordinates \((r_{co}, \vartheta_{co})\). Further, following Portegies Zwart, we randomly distribute 1000 probe particles with constant surface density in a ring region on the galactic plane centered at the above point and of radius 3 pc. Then the stars were assigned the same rotation velocities corresponding to the galactocentric distance \( r_{co} \) plus the additional peculiar velocity -10.1 km/s in radial direction and 15.5 km/s in the direction of galactic rotation independently of their positions.

After that, we compute the final locations of the cluster members at present time assuming that the solar and cluster age to be 4.6 Gyrs.

Since we cannot indicate more or less exactly the solar birth-place, instead of estimation the number of siblings in the close vicinity of the Sun, we compute a number of stars from the parental cluster which have the siblings in their close vicinity and estimate the number of kin.

Simultaneously our experiments enable to quantitatively estimate the rate of stellar diffusion in radial and azimuth directions after the open cluster started to fall apart.

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2 As it was said in Introduction, that could be done because Portegies Zwart adopts a very simple model for the galactic gravitation field neglecting by perturbations due to spiral density waves. It is well known that in an axisymmetric galactic field stellar trajectories in the galactic plane represent simple epicyclic lines (cycloid like), the trajectories in this case being stable in the sense that small deviations in initial coordinates of stars do not lead to a significant response in their final locations, at least in radial directions.

3 In the cluster, stellar velocities are additionally randomly perturbed. But the results do not significantly depend on the inclusion of these perturbations since the chaotic velocities of the cluster members are small.
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3 RESULTS AND DISCUSSION

We performed a lot of experiments trying to understand the scatter of stars under the influence of perturbations from spiral gravitational field associated with galactic density waves. Below will be presented some of our model results derived for various parameters. However, to compare in relief our conclusion with the one of Portegies Zwart (2009) in Fig. 1 we show the computed final positions of the probe particles when the spiral perturbations of the galactic gravitation field is not taken into account. Indeed, in this case after 4.6 Gyr the stars are lined up in a ring-like segment.

Further, our results of the cluster members scatter under the influence of spiral perturbations are described.

3.1 Stationary spiral structure

1) Number of spiral arms $m = 2$, corotation radius $r_C = r_S$, pitch angle $p = -12^\circ$. Below are shown the final (4.6 Gyr after the solar cluster birth) stellar positions derived for the same initial galactocentric distance of the parental cluster ($r_{cc} = 8.5$ kpc) but for 2 initial its locations relative to spiral arms. In the first case (Fig. 2), the stars happen to be spread over a very large part of the galactic disc. So, the supposition of Portegies Zwart that stars, which were born close to the Sun, can not drift far from it, in general is incorrect. Our computations demonstrate that, at the final stage, in the close vicinity of any star from this sample we can find no more than 3 - 5 siblings.

In Fig. 3 we present the final positions of the cluster members for another initial azimuth angle. Here the final stellar locations on the galactic plane happen to be rather compact: there are about 70 stars in the close vicinity of which from 50 to 80 siblings can be found.

However the above space pattern of stars is destroyed if we slightly move the initial position of the cluster, say decrease the distance of its centre, $r_{cc}$, by 0.5 kpc, keeping the same its azimuth (see Fig. 4). For this case we do not find more than 10 siblings in the close vicinity of any star from the cluster members.

2) Corotation radius $r_C = 3.5$ kpc, pitch angle $p = -12^\circ$. Besides the spiral wave pattern with the corotation close to the
Figure 4. The same as in Fig. 3, but the initial galactocentric distance of the cluster (shown by large open circle) center is 8 kpc, the initial its azimuth being the same.

Figure 5. The same as in Fig. 2, but for the corotation resonance located in the inner part of the galactic disc at \( r_C = 3.5 \) kpc (filled circles). Number of arms \( m = 2 \).

Figure 6. The same as in Fig. 5, but for \( m = 4 \).

is obvious, such sharply distinct behavior of the stellar ensemble from the previous case is explained by more frequent oscillation (in azimuth angle) of the perturbed gravitation field which leads to less scattering effect.

3) Superposition of two density wave harmonics: \( m = 2 + 4 \) patterns. On the basis of various observational data - Cepheid kinematics, regions of ionized hydrogen and radio emission of neutral hydrogen in 21 cm line - Lépine et al. (2001, hereafter LMD) proposed a model of galactic spiral wave pattern as a superposition of 2 wave harmonics: \( m = 2 \) and \( m = 4 \) (see Fig. 3 in their paper). A similar structure was derived by Drimmel & Spergel (2001) in their study of IR emission. Below we describe the LMD model in some details and consider the cluster members scatter.

According to LMD we represent the perturbed spiral gravitation potential as:

\[
\varphi_S = \varphi_2 + \varphi_4,
\]

where \( \varphi_m \) is the corresponding \( m \)-th wave harmonic (\( m = 2 \) or \( m = 4 \)), \( \varphi_m = A_m \cos(\chi_m) \), \( A_m \) and \( \chi_m \) are their amplitude and phase, \( \chi_m = m [\cot(p_m) \log(r/r_0) - \vartheta + \Omega_P t] + \Delta \chi_m \), \( p_m \) is the corresponding pitch angle, \( \Delta \chi_m \) is the phase shift (to set the coordinate system relative to 2-armed pattern let \( \Delta \chi_2 = 0 \), then \( \Delta \chi_4 = 200^\circ \)). Notice that both the patterns rotate with the same rotation velocity \( \Omega_P \). We choose it so that the corotation resonance lies close to the Sun \( r_C = r_S \); as a consequence for the 4-armed pattern inner lindblad resonance is situated at about 6 kpc, the outer one at 11 kpc). In what follows, we slightly modified the parameters of LMD model since the radial scale in the last paper, \( r_S \), was adopted to be 7.5 kpc whereas in the present paper \( r_S = 8.5 \) kpc. To adjust the pitch angle of LMD model to our present scale we assume \( p_2 = -7^\circ \), correspondingly \( p_4 = -14^\circ \). The wave amplitude for two-armed pattern is derived as above. The ratio of amplitudes \( A_2/A_4 = 0.8 \) (details see in LMD).

In the framework of this model, the final positions of the cluster members are shown in Fig. 7. Again, the stars happen to be spread over a large space volume, so in the close vicinity of any star we can reveal no more than 3 - 5 siblings. However, for another initial azimuth of the cluster we get rather compact final stellar dis-
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Figure 7. The same as in Fig. 2, but for superposition of 2 wave harmonics $m = 2 + 4$, see text. The spiral lines shown by thin solid and dashed lines are the loci of $\text{min}(\varphi_m)$.

Figure 8. The same as in Fig. 7, but for another initial cluster azimuth.

Figure 9. The same as in Fig. 2, but for transient spiral structure and short life-time of a pattern with given $\Omega_P \tau_P = 100$ Myr. The location of spiral arms is not shown since the pattern changes with time. The picture is shown in non-rotating coordinate system.

Figure 10. The same as in Fig. 9, but for long life-time $\tau_P = 500$ Myr.

3.2 Transient spiral structure

In Fig. 9 is shown the final picture for stellar scattering in the case of short life-time of a pattern event of speed $\Omega_P$, i.e. $\tau_P = 100$ Myr, in Fig. 10 for long life-time $\tau_P = 500$ Myr. It is seen that the stars again are scattered over a very large region, so that in the close vicinity of a star we can only reveal 3 - 4 stars from the parental cluster. Our experiments show that, in general, this conclusion is kept independently of a particular set of random $\Omega_P$ and slightly depends on life-time of a pattern event.

3.3 Open cluster decay and stellar scattering as a diffusion process

Our results, illustrated by the above figures, show that, if we take into account the influence of spiral arms on stellar motion, in general, their trajectories are unstable: being born within small space volume, several billion years stars are scattered (predominantly chaotically) over a very large part of the galactic disc after. So we
can treat the cluster stellar migration as a diffusion process and to estimate radial and azimuth diffusion coefficients.\(^4\)

To derive the diffusion coefficients in radial and azimuth directions (correspondingly, \(D_r\) and \(D_ϑ\)) we consider the stellar ensemble as "clouds" in \(r\) and \(ϑ\) spaces. The location of the cloud along \(r\) or \(ϑ\) axis as a whole is determined by its mean coordinates \(<r>\) and \(<ϑ>\), and \(<r>−<r>\) = \(\sum r_i/N\), where \(N\) is the number of probe particles in the ensemble, \(r_i\) is the radial coordinate of \(i\)-th star and the summation is taken over all stars from the ensemble, the similar formula should be written for mean azimuth). The typical sizes of the "clouds", imitating the stellar ensemble in \(r\) and \(ϑ\) spaces, are given by the root mean squares \(σ_r\) and \(σ_ϑ\), the radial dispersion as usual being \(σ_r^2 = \sum (r_i−<r>)^2/(N−1)\) and the expression for \(σ_ϑ^2\) to be written by analogy with \(σ_r^2\). Since at the initial moment of time cloud sizes in \(r\) and \(ϑ\) directions are small, the ones can be represented as \(δ\)-functions of \(r−r_{cc}\) and \(ϑ−ϑ_{cc}\). In what follows, for simplicity we consider the diffusion process separately in \(r\) and \(ϑ\) directions and use the well known one-dimensional (Cartesian - like) solution of the diffusion equation to connect the radial and azimuth dispersions with the diffusion coefficients:

\[
2σ_r^2 c = \int_0^t D_r c dτ',
\]

(e.g. Landau & Lifshitz 1986; their expression for the diffusion coefficient was extended for the case when the coefficient depends on time, see below).

Further, by means of our numerical experiments we compute \(σ_r^2\) and \(σ_ϑ^2\) and from the above equation derive the diffusion coefficients \(D_r\) and \(D_ϑ\).

In Figs. 11 and 12 is shown the evolution of \(σ_r^2\) and \(σ_ϑ^2\) with time. It is seen that during the first 1 or 2 Gyr the both dispersions happen to be very small. Detail analysis shows that at this epoch, the dispersions vary slowly, but after 1 - 2 Gyr the above regime breaks down abruptly and \(σ_r^2\) begin to increase sharply. So we can regard the stellar scatter as the diffusion process only for \(t \geq 1 - 2\) Gyr. Let us call this period of time as the diffusion stage.

It is worthwhile to notice that the dispersions do not vary monotonically. They oscillate around some (growing) trend (the most distinctly it becomes apparent for \(σ_ϑ^2\)).

The above pictures suggest that the behavior of our system should be understood in terms of dynamical chaos. However, the detail analysis of this question is beyond the scope of our paper.

\(^4\) Strictly speaking, except for the case with transient density waves, in our approach, stellar motion is reversible since we do not take into account their random collisions with, say, molecular clouds or other objects (transient density waves represent stochastic fluctuations of galactic gravitation fields and stellar interactions with such fluctuations are a kind of collisions). Nevertheless, random initial conditions of the parental cluster stars introduce a chaotic element in evolution of the stellar ensemble as a whole although (except for the case of transient density waves) the acting on stars force is regular. So, at least, starting with some moment of time the spreading of stars can be described in terms of diffusion despite the absence of stellar collisions.

\(^5\) In case "c" \(σ_ϑ^2\) stepwise increases from very low value to ~ 1 kpc\(^2\) after about 1 Gyr and then oscillates, the trend being almost flat. This means that in radial direction the size of the ensemble does not grow in average, it simply oscillates at some new mean value (\(δ\)-dispersion demonstrates the growing trend but it is dozens of times less than in other cases, see Fig. 12). This result reflects the more or less compact final positions of the probe stars in Fig. 8.

Approximation of the time dependence of \(σ_r^2\) at the diffusion stage by the linear trend corresponds to constant \(D_r\) in kpc\(^2\) Gyr\(^{-1}\); \(\sim 1.6\) (case "a"); \(\sim 1.4\) (case "b") and \(\sim 4.2\) (case "d").\(^6\)

As it was expected, the largest stellar migration takes place in the variant of transient density waves: the corresponding diffusion coefficient more than 2 times exceeds \(D_r\) derived in other models. By means of \(D_r\) we can estimate a region \(Δr\) which will be occupied by stars, born in an open cluster, during the life-time of the galactic disc \(T_D \sim 10\) Gyr. The region is: \(Δr \sim (D_r T_D)^{1/2} \sim 4 - 6\) kpc.

The diffusion stage in azimuth evolution of the stellar "cloud" comes after \(~2\) Gyr (see Fig. 12; for the case "c" \(σ_ϑ^2\) occurs to be about 20 times less than in other cases, so we will not interpret this case in terms of diffusion although the growing trend is obvious). However, unlike \(σ_r^2\) the azimuth dispersion \(σ_ϑ^2\) grows in time with acceleration, at least, quadratically, so that \(D_ϑ\) (in rad\(^2\) Gyr\(^{-1}\)) happens to be: \(\approx −22 + 11t\) (case "a"); \(\approx −23 + 9t\) (case "b"); and \(\approx −15 + 4t\) (case "d"). In azimuth direction the rms effective cloud radius sometimes exceeds 360\(^o\) which means that many stars overtake others more than one period.

It is interesting to explore in more detail the evolution of the dispersions at the very early epoch. Indeed, according to Bland-Hawthorn et al. (2010), the most part of forming open clusters are unbound and analysis of various data shows that most of them are disrupted during first 100 Myr. By means of our experiments we can estimate the decay time \(Δt_{r,ϑ}\) during which the typical cluster size (\(2σ_{r,ϑ}\)) increases, say 10 times (this threshold value we interpret as a border which separates the state when the stars still belong to a cluster, from the one when they have become a part of the galactic disc.).

There is an important difference in time evolution of \(r\) and \(ϑ\) dispersions. From Figs. 11,12 it is seen that at the diffusion stage both the dispersions oscillate with time. In general, such behavior is kept at early epoch, but during several first tens Myr after the open cluster formation \(σ_r^2\) grows almost monotonically. So, we can state: for cases "a, b, d" the azimuth decay time \(Δt_ϑ\) is of the order of 50 - 70 Myr whereas for the radial one \(Δt_r\) happens to be ~1.1 - 1.4 Gyr. Such large difference in the corresponding typical time periods is obviously connected with different radial and azimuth resilience of stellar ensemble as a part of the galactic disc.

4 CONCLUSION

The problem of searching solar siblings is a very exciting but difficult one. Indeed, we have to recognize the members of solar family among the close \(~10^5\) stars. The only chance is to find a group of, say, several tens stars with particular properties: close ages and chemical element abundances, special velocity pattern in space, etc.

In the present paper, we tried to answer the question: is the situation so optimistic as it was inferred by Portegies Zwart (2009)? Our conclusion is as follows. If we take into account perturbations of the galactic gravitation field from spiral density waves, stellar motion strongly deviates from quasi-circular epicyclic trajectory. In general, Portegies Zwart’s supposition that stars do not drift far from the Sun, is broken. Unlike Portegies Zwart’s opinion, stars that were born within a small space volume can drift far from the cluster members. In spite of that they have small differences in their initial positions (\(< 6\) pc) and the same initial velocities, in general, after 4.6 Gyrs the siblings are scattered over an unexpectedly large

6 Case "c" we exclude from interpretation in terms of diffusion.
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However, if we adopt that the parental cluster had \( \sim 10^4 \) stars (instead of \( 10^3 \), like in Portegies Zwart model) the task becomes less hopeless.

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part of the galactic disc. Most of our experiments demonstrate that in the close vicinity of the Sun we do not have a hope to discover more than several solar relatives if we adopt that the solar parental cluster had \( \sim 10^3 \) stars as in Portegies Zwart (2009) model. Notice also that we did not take into account the effects of additional stellar scattering due to interaction with molecular clouds and velocity dispersion.

Nevertheless, in some cases we derive sufficiently compact final locations of siblings, so that in the close vicinity of the Sun we have a hope to reveal several tens of the parental cluster members.

Figure 11. Filled circles: evolution in time the radial dispersion \( \sigma_r^2 \). Case a corresponds to Fig. 2; b - to Fig. 4; c - to Fig. 8; d - to Fig. 9.

Figure 12. The same as in Fig. 11 but for \( \sigma_\theta^2 \).