Field ZAMS stars in the solar neighborhood: Where have they come from? *

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ABSTRACT

In the course of an all-sky survey for young stars in the solar neighborhood we have found a tight kinematic group of ten F-G type zero-age main sequence stars in the field. Here we discuss the origin of these stars. Backtracking the space motions of these stars we argue that likely candidates for the parent association are the Perseus OB3 (Per OB3), Upper Centaurus-Lupus (UCL), and Lower Centaurus-Crux (LCC) associations, and that we are witnessing the ongoing diffusion of (at least one of) these associations into the field.

Key words: Surveys – solar neighborhood - Stars: kinematics – Stars: late-type

1 INTRODUCTION

We have recently performed an all-sky survey for nearby young stars, the results of which are published in Wichmann et al. (2003). The candidate sample for this survey was obtained by cross-correlating the ROSAT All-Sky Survey (RASS) with the TYCHO catalogue and selecting stars with $B-V > 0.54$ (i.e. F8 and later) with (TYCHO) parallax errors better than 3.5σ. In addition, stars very far above the main sequence (giants) and very far below (erroneous parallaxes) were discarded, resulting in a total sample size of 754 stars. Because of these selection procedures, the majority of our candidate stars are located within 60 pc of the Sun.

The spectroscopic follow-up investigations of 748 stars out of this sample resulted in the detection of 10 G-type stars (HD 13183, HD 35850, HD 36869, HD 43989, HD 49855, HD 77407, HD 105070, HD 129333, HD 171488, and HD 202917), which share the following properties: (1) They all have lithium equivalent widths $W_{Li}$ in excess of the Pleiades upper limit of their respective spectral type; (2) They show very high X-ray activity ($\log L_X/L_{bol} = -3.49 \pm 0.07$); and (3) They show a very narrow distribution of their galactic velocity components ($U = -1.0 \pm 2.5$, $V = -16 \pm 3.4$, $W = 1.7 \pm 3.1$).

All of these observational indicators strongly suggest that these stars are quite young: The observed excess lithium, the high X-ray activity and the narrow velocity dispersion (cf., Wielen 1977) suggest an age no more than about 50 Myrs for these stars. While the youth of some of these stars has been known prior to our study, the fact that these stars do form a very tight kinematic group, despite their being distributed more or less uniformly over the whole sky with distances of up to about 100 pc from each other, has remained unnoticed so far. For a detailed discussion of our survey and these 10 ZAMS stars in our sample we refer to our main survey paper (Wichmann et al. 2003).

We note specifically that this kinematic group of stars was identified on the basis of their lithium equivalent widths, i.e. without applying any kinematic criteria. In principle these stars – now distributed over the whole sky – could have formed in an unrelated fashion with a chance alignment of their current velocity vectors. However, we feel that a far more natural explanation for this tight kinematic group of 10 ZAMS stars found in our study is to assume that they have some common origin. This begs the question: where do they come from?

2 THE ORIGIN OF THE ZAMS SAMPLE

Any reasonable candidate for the formation of these stars should be close to the Sun, because the youth of these stars and their small velocities of a few km s$^{-1}$ w.r.t. the local standard of rest (LSR) shows that they cannot have moved very far from their birthplace(s). At the same time, they must originate from a large star forming region (SFR), since an extrapolation based on a normal initial mass function...
(IMF; c.f. Kroupa et al. 1993) shows that these 10 stars correspond to a total mass of about 120 $M_\odot$.

Furthermore, the tight velocity distribution of our ten stars shows that they cannot have been ejected by three-body interactions, rather they must have slowly dispersed from their birth regions. Thus, any likely candidate should show similar galactic velocities, and its trajectory should intersect those of the 10 ZAMS stars at some point at most $\approx 50$ Myr in the past.

We can safely rule out the Taurus-Auriga SFR because of the grossly inconsistent velocity, as well as the Pleiades because they are too old. After reviewing all known star forming regions close to the Sun, we find that the best candidates for the origin of our ten ZAMS stars are the following three associations: Perseus OB3 (a Persei), Lower Centaurus Crux (LCC), and Upper Centaurus Lupus (UCL).

### 3 DATA

The current position of the centres of the Per OB3, LCC, and UCL associations are based on the membership lists by de Zeeuw et al. (1999). These membership lists were obtained from the HIPPARCOS catalogue by applying a combination of two different methods. The first is a modern implementation of the convergent point method as described by de Bruijne (1999), while the second is a kinematic member selection method developed by Hoogerwerf & Aguilar (1999). This kinematic method also uses the HIPPARCOS parallax information, which is neglected in the convergent point method. Only members confirmed by both methods were retained.

Per OB3 is located at a distance of about 180 pc and comprises 30 OB stars. Its age is estimated to $\approx 50$ Myr (de Zeeuw et al. 1999). The LCC/UCL associations (together with a third, the Upper Scorpius association) are subgroups of the Sco OB2 association. For this entire complex, Blaauw (1964) estimated an expansion age of $\approx 20$ Myr. The LCC is at a distance of $\approx 120$ pc and comprises 36-42 OB stars, while the UCL is $\approx 140$ pc distant and has 58-66 OB-type members (Maiz-Apellániz 2001, de Zeeuw et al. 1999, Hoogerwerf et al. 2001). From Monte-Carlo simulations, de Zeeuw et al. (1999) estimate that about 10 out of 79 members of Per OB3, some 50 out of 221 members of UCL, and some 30 out of 180 members of LCC might be interlopers, i.e. field stars unrelated to the association.

The most recent determination of the velocities of the Sco-Cen sub-groups, using HIPPARCOS data as well as radial velocities from various sources (listed in Asai et al. 1999a), has been carried out by Asai et al. (1999b). The space velocities as listed in their Table 3 were used for this work. The current spatial extent of the LCC and UCL associations can be approximated by a Gaussian with $\sigma \approx 25 - 30$ pc (Benítez et al. 2002). The nuclear ages as deduced by de Mamajek et al. (2002) are 15-17 Myr for the LCC, and 16-18 Myr for the UCL.

The turnoff age of Per OB3 is estimated to about 50 Myr by de Zeeuw et al. (1999), and the spatial extent to about $3^\circ \times 3^\circ$ (corresponding to a radius of about 4.6 pc), with a halo of 10$^\circ$ (31 pc). The radial velocity of Per OB3 (-1 km s$^{-1}$) determined by de Zeeuw et al. (1999) is the median velocity compiled from the HIPPARCOS Input Catalogue.

### 4 MOTION BACKTRACKING

#### 4.1 Epicyclic approximation

We introduce a coordinate system ($\xi$, $\eta$, $\zeta$) centered on the projection of the Sun's position on the Galactic plane (we use $\zeta_0 = 27$ pc from Chen et al. 2001) and in a circular orbit around the galactic centre with angular velocity $\omega_c$ and radius $\varpi_0$. The $\xi$-axis points away from the galactic centre, the $\eta$-axis points in the direction of rotation, and the $\zeta$-axis toward the galactic pole.

In this coordinate system, the equations of motion in the ($\xi$, $\eta$) plane are:

$$
\ddot{\xi} - 2\omega_c\dot{\eta} - 4\omega_c A\xi = 0,
$$

$$
\ddot{\eta} + 2\omega_c\xi = 0
$$

if the stars move in an axisymmetric central potential and $\xi \ll \varpi_0$, $\eta \ll \varpi_0$ ($A$ is Oort's constant). I.e. Eqs. (1) neglects deviations from an axisymmetric potential due to local density variations, and is valid for small eccentricities only (which is true for our 10 ZAMS stars). The derivation of Eqs. (1) is given in Chap. 5 of Chandrasekhar (1942), although these equations of motion were already stated without proof - by Lindblad (1936).

Following Chandrasekhar (1942), the general solution of Eqs. (1) can be written as:

$$
\xi = \xi_{11} \cos qt + \xi_{21} \sin qt + C_1 t + C_2,
$$

$$
\eta = \lambda_1 (\xi_{11} \sin qt - \xi_{21} \cos qt) + C_3 t + C_4,
$$

where $t$ is the time, $\xi_{11}$, $\xi_{12}$, $C_1$, $C_2$, $C_3$, $C_4$ are integration constants to be fixed by the initial conditions, $q_1 = 2\sqrt{\omega_c/(\omega_c - A)}$, and $\lambda_1 = -\sqrt{\omega_c/(\omega_c - A)}$ ($q_1$ is called the epicyclic frequency, and often also denoted by $\kappa$). From Eqs. (1) one can see that $C_1 = 0$, $C_3 = -2AC_2$, and thus Eqs. (2) can be rewritten as:

$$
\xi = \xi_{11} \cos qt + \xi_{21} \sin qt + \lambda_2 \xi_{12},
$$

$$
\eta = \lambda_1 (\xi_{11} \sin qt - \xi_{21} \cos qt) + \lambda_2 (\xi_{12} t - \xi_{22}),
$$

with integration constants $\xi_{21}$, $\xi_{22}$, and $\lambda = 1/[2(\omega_c - A)]$, $\lambda_2 = -A/(\omega_c - A)$, which is the solution stated by Lindblad (1942).

Table 1. Data for UCL, LCC, and Per OB3. For the definition of the ($\xi$, $\eta$, $\zeta$) coordinate system see text. $U$, $V$, and $W$ are the galactic velocity components (expressed in the LSR) towards the galactic centre, the direction of rotation, and the galactic pole, respectively (i.e. $U = -\dot{\xi}$, $V = \dot{\eta}$, and $W = \dot{\zeta}$). For LCC/UCL, ages are nuclear ages from de Mamajek et al. (2002), positions are from Maiz-Apellániz (2001), and velocities from Asai et al. (1999b). all data for Per OB3 are from de Zeeuw et al. (1999).

| Subgroup      | (Yr)   | $\xi$ | $\eta$ | $\zeta$ | $U$  | $V$  | $W$  |
|---------------|--------|-------|-------|---------|------|------|------|
| LCC           | 15-17  | -62   | -100  | 37      | -4.9 | -15.6| 1.2  |
| UCL           | 16-18  | -119  | -67   | 58      | -8.3 | -15.4| 2.8  |
| Per OB3       | $\approx 50$ | 149   | 100   | 9       | 4.4  | -19.8| -0.2 |

Table 1 summarizes the relevant data on the associations considered here.
Figure 1. Current location of the 10 field ZAMS stars (filled circles, annotated with HD numbers) and their trajectories backwards to $t = -15\text{Myr}$, with 1σ error ellipses for the positions at $t = -15\text{Myr}$ (see text). Also plotted are the trajectories of the LCC/UCL OB associations, with circles centered on their positions at $t = -15\text{Myr}$ indicating their 2σ radii.

Figure 2. Same as Fig. 1 but for Per OB3 at $t = -50\text{Myr}$.

This solution describes an elliptical motion with the centre of the ellipse (of axis ratio $1/\lambda_1$) located at $\xi = -\lambda_1\xi_0$ and moving parallel to the $\eta$-axis with a velocity of $\lambda_2\xi_0$. For this reason, the approximation presented above is known as epicyclic approximation. If the initial values $\xi_0$, $\eta_0$, $\xi_0$, and $\eta_0$ at $t = 0$ are known, the integration constants can be evaluated to:

$$\xi_1 = \frac{\xi_0}{\lambda_1}, \quad \xi_2 = \frac{1}{\lambda_2} \left( \frac{\lambda_1\xi_0}{\lambda_1} + \eta_0 \right),$$

$$\xi_2 = \eta_0 - \lambda_1q_1\xi_0, \quad \xi_1 = \lambda_2\xi_0 - \lambda_0\eta_0.$$

4.2 Error propagation

Any error in the velocity will lead to increasing position errors with time when tracing the trajectory backwards, and must be accounted for carefully. In our error budget, we include the errors in the proper motions as given in the HIPPARCOS catalogue, as well as errors in the radial velocities measured by us ($\approx 1.5\text{ km s}^{-1}$).

The formalism presented above does not account for local density fluctuations. We treat this effect as an additional error, leading to random velocity variations and accordingly to a diffusion of the orbits. The rms variations of the galactic velocity components as a function of time have been studied empirically by Wielen (1977). Errors in right ascension and declination are small, and thus we neglect them, while errors in the parallax are taken into account. For the constants in Eq. 3 we use $\omega_c = 27.19\text{kpc/Myr}$ and $A = 14.82\text{kpc/Myr}$ (Feast & Whitelock 1997).

We then proceed by performing, individually for each star, a Monte-Carlo simulation to determine an error ellipse for the position at $t = -15\text{Myr}$ (for LCC) and $t = -50\text{Myr}$ for Per. We draw random proper motions and radial velocities from a Gaussian distribution with mean value and dispersion corresponding to the measured values and their errors, compute the galactic UV velocities, and add random Gaussian noise according to Table 2 of Wielen (1977) to account for local density fluctuations. We then compute the backward trajectory for 15 Myr. After 10 000 trials, we finally fit a 2σ error ellipse around all trial positions (at $t = -15\text{Myr}$ and $t = -50\text{Myr}$ respectively). This error ellipse is computed by the following procedure: first, the centre of the distribution of positions is computed. A straight line is fitted to the distribution and adopted as major axis. The axis ratio is determined by the ratio of the dispersions along the major and minor axes. Finally, the length of the major axis is chosen such that 95 percent of the positions are located within the ellipse.

In Fig. 1 we show the resulting error ellipses, as well as the trajectories for the measured velocities. In Fig. 2 we also plot the trajectories for the LCC and UCL associations, and the 2σ radii of 50 pc (Benítez et al. 2002) for the LCC/UCL associations, centered at the position at $t = -15\text{Myr}$. In Fig. 2 the trajectory for Per OB3 is shown, along with its position at $t = -50\text{Myr}$. The radius for Per OB3 corresponds to the $10\text{^o}$ (30 pc) halo.

4.3 Motion perpendicular to the plane

In the approximation of a flattened, homogeneous mass distribution, the equation of motion in the $\zeta$-direction is

$$\ddot{\zeta} + \frac{\partial^2 \Psi}{\partial \zeta^2} \zeta = 0,$$

where $\Psi$ is the gravitational potential (c.f. Chandrasekhar 1942). This is solved by

$$\zeta = \zeta_1 \cos q_3 t + \zeta_2 \sin q_3 t - C_5 t + C_6,$$

with $q_3 = \sqrt{4\pi G \rho_0}$ and integration constants $C_5 = C_6 = 0$, $\zeta_1 = \zeta_0$, and $\zeta_2 = \zeta_0$. Here, $G$ is the gravitational constant, $\rho_0$ the volume density in the galactic plane, and $\zeta_0, \dot{\zeta}_0$ are the initial conditions at $t = 0$. We neglect the (small) term $2(2A - \omega_c)\omega_c$ in the more general expression for $q_3$ (c.f. Michalas & Routy 1968).
5 DISCUSSION

We are aware that some of these 10 stars have been assigned to several small star forming regions. In particular, HD 13183 is claimed by Torres et al. (2000) as a probable member of the Horologium association, and HD 35850 by Zuckerman et al. (2001) as a member of the β Pic association.

However, considering the very small observed velocity dispersion, we consider it unlikely that these stars have formed in different and unrelated star forming regions. We do not think that this is in contradiction to the results of Zuckerman et al. (2001) or Torres et al. (2000), because membership assignment in an association is invariably based on statistical criteria which always have some error of the second kind (i.e. accepting membership for a non-member).

Also, we note that (a) it is not clear whether the Horologium association really forms a tight kinematic group, because Torres et al. (2000) adjusted unknown parallaxes of supposed members in order to minimize the velocity dispersion, and (b) according to its location in the HR diagram (see Fig. 4 in Wichmann et al. 2003), the age of HD 35850 is in between that of the β Pic association (20 ± 10 Myr according to Barrado y Navascués et al. 1999) and Per OB3, and within errors consistent with UCL/LCC, Per OB3, or β Pic, so its association with β Pic is no more likely than our proposed ‘common origin’ scenario may be.

While we clearly cannot rule out that some of these stars have formed in unrelated SFRs, we wish to explore here the consequences of the assumption of a common origin. From Fig. 1 we can see that at \( t = -15 \) Myr, the error ellipses of all of our ZAMS stars except HD 77407 and HD 129333 are located well within the 2σ radius of UCL in the (\( \xi , \eta \)) plane. We have checked the consistency of our results by backtracking the motion in the \( \zeta \)-direction. We find that at \( t = -15 \) Myr the error ellipses of all our ZAMS stars overlap with both the LCC and UCL associations.

de Zeeuw et al. (1999) have found 66 B-type stars in UCL, and 42 in LCC. Their estimated field star contamination is 5 – 12 (UCL) and 4 – 7 (LCC), respectively. With a normal IMF (e.g. Kroupa et al. 1993), these numbers translate into some 200 (UCL) and 141 (LCC) G-type stars in the mass range of the field ZAMS stars found by us. Clearly, only a tiny fraction of these stars need to escape into the field to explain our results.

For the Per OB3 association, we find that its trajectory crosses those of our 10 ZAMS stars at about \( t = -50 \) Myr, i.e. the age of Per OB3. Again, we have checked the \( \zeta \)-motion for consistency. With \( \approx 30 \) B-type stars, Per OB3 is also large enough to explain our findings. However, Per OB3 is spatially rather compact, and only 3 – 4 of our stars’ error ellipses overlap with it. Thus, from the point of view of kinematics, we clearly prefer an LCC origin for our lithium excess stars.

The age of the ten field ZAMS stars from our survey can only approximately be determined. From their lithium equivalent widths and X-ray activity, we conclude that they are younger than the Pleiades, i.e. < 70 Myrs. In addition, it has been shown by Wielen (1977) that random fluctuations in the local density will increase the velocity distribution with time. From Table 2 in his paper, we can infer an upper limit of of 50 – 100 Myr (Wichmann et al. 2003). From their positions in the HR diagram (see Fig. 4 in Wichmann et al. 2003), we infer a lower limit of about 20 – 30 Myr, while ages of 50 Myrs and somewhat older are preferred. We note that the absolute calibration of the evolutionary tracks may not be without any problems; also, the evolutionary tracks are computed from models without rotation, while our stars are fast rotators (Wichmann et al. 2003). At any rate, from the HR diagram’s point of view Per OB3 would be the preferred parent association.

We thus conclude that we cannot uniquely identify a parent association for our ZAMS stars. From the point of view of the kinematics, the LCC/UCL associations are ideal, but with respect to age they may be too young. On the other hand, the trajectories of Per OB3 and our stars intersect at a more convenient age, but our backtracking shows that our stars are dispersed over a much large area, and only 3 – 4 of them can be reconciled with the location and extent of Per OB3 at \( t = -50 \) Myr.

In Fig. 1 – 2 the current extents of the LCC, UCL, and Per OB3 associations have been plotted. Naturally, these need not coincide with the past extents. This problem has been investigated by Asiain et al. (1999), who denote the Sco-Cen association as a moving group B1. Studying a spatially concentrated sub-group of the Sco-Cen association, they find that in \( \xi \) and \( \eta \), the minimum radius in the past has been about two thirds of the current radius, while in \( \zeta \) it has been equal to the current radius. If these results are applicable to the individual associations discussed here, our conclusions are not affected.

If one assumes that these associations are surrounded by an isotropic spherical halo of dispersed stars, then from the 10 G-type stars in the solar vicinity we estimate the mass of that halo to about half of the stellar mass of the associations themselves (as derived from the number of B-type stars). However, both from observations and from theory (e.g. Wielen 1977) it is known that isotropic dispersion (in the sense of equipartition of energy) will not lead to an isotropy of the velocity dispersions. In particular, the velocity dispersion in \( W \) is smallest, because on average half of the energy gained by perturbations is in potential energy. Therefore the shape of such a halo would be flattened along \( \zeta \), and the amount of mass required in this halo would be smaller.

The associations considered here (Per OB3, and the LCC/UCL associations) are not gravitationally bound (de Zeeuw et al. 1999), and therefore it is inescapable that stars from these associations will diffuse into the field. We argue that the group of field ZAMS stars we have found in our survey represents the ongoing dissolution of an OB association into the field.

Given the similar trajectories, it may be that some of the 10 stars from our survey originate from Per OB3, and others from the UCL/LCC associations. This may not represent that much of a difference, after all, because the trajectories of Per OB3 and the UCL/LCC complex intersect at \( -50 \) Myr – corresponding to the age of Per OB3 –, so we speculate that the Per OB3 and LCC/UCL associations may have formed out of the same molecular cloud.

If the scenario sketched in this paper is correct, there must be many more young low-mass stars and brown dwarfs in the immediate vicinity of the Sun, independent of whether they originated in the Per OB3 or LCC/UCL associations. It is a challenge to find them.
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