A catalogue of young runaway Hipparcos stars within 3kpc from the Sun

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ABSTRACT

Traditionally runaway stars are O and B type stars with large peculiar velocities. We want to extend this definition to young stars (up to \( \approx 50 \) Myr) of any spectral type and identify those present in the Hipparcos catalogue applying different selection criteria such as peculiar space velocities or peculiar one-dimensional velocities.

Runaway stars are important to study the evolution of multiple star systems or star clusters as well as to identify origins of neutron stars.

We compile distances, proper motions, spectral types, luminosity classes, \( V \) magnitudes and \( B - V \) colours and utilise evolutionary models from different authors to obtain star ages and study a sample of 7663 young Hipparcos stars within 3 kpc from the Sun. Radial velocities are obtained from the literature.

We investigate the distributions of the peculiar spatial velocity, the peculiar radial velocity as well as the peculiar tangential velocity and its one-dimensional components and obtain runaway star probabilities for each star in the sample. In addition, we look for stars that are situated outside any OB association or OB cluster and the Galactic plane as well as stars of which the velocity vector points away from the median velocity vector of neighbouring stars or the surrounding local OB association/cluster although the absolute velocity might be small.

We find a total of 2547 runaway star candidates (with a contamination of normal Population I stars of 20 per cent at most). Thus, after subtraction of those 20 per cent, the runaway frequency among young stars is about 27 per cent.

We compile a catalogue of runaway stars which will be available via VizieR.

Key words: catalogues – stars: early-type – stars: kinematics.

1 INTRODUCTION

Almost fifty years ago, Blaauw (1961) found that many O and B type stars show large peculiar space velocities (> 40 km/s). For that reason they were assigned the term “runaway” stars. Many studies concerning O and B type runaway stars have been published since then covering different selection methods (e.g. Vitrichenko et al. 1965; Cruz-González et al. 1974; Gies & Bolton 1986; Stone 1991; Moffat et al. 1998).

Two theories on the formation of runaway stars are accepted:

(i) The binary supernova (SN) scenario (BSS) (Blaauw 1961) is related to the formation of the high velocity neutron stars: The runaway and the neutron star are the products of a SN within a binary system. The velocity of the former secondary (the runaway star) is comparable to its original orbital velocity.

Runaway stars formed in the BSS share typical properties such as enhanced helium abundance and a high rotational velocity due to mass and angular momentum transfer during binary evolution. The kinematic age of the runaway star is smaller than the age of its parent association.

(ii) In the dynamical ejection scenario (DES) (Poveda et al. 1967) stars are ejected from young, dense clusters via gravitational interactions between the stars.

The (kinematic) age of a DES runaway star should be comparable to the age of its parent association since gravitational interactions occur most efficiently soon after formation.

Which scenario is dominating is still under debate; however, both are certainly taking place (one example for each identified by Hoogerwerf et al. 2001: BSS – PSR B1929+10/\( \zeta \) Oph; DES – AE Aur/\( \mu \) Col/\( \iota \) Ori).

The selection criteria for runaway stars of previous studies were either based on spatial velocities (e.g. Blaauw 1961), tangential velocities (e.g. Moffat et al. 1998) or radial velocities (e.g.
Cruz-González et al. 1974) alone. According to Stone (1979) the velocity distribution of early type stars can be explained with the existence of two different velocity groups of stars: a low velocity group containing normal Population I stars and a high velocity group containing the runaway stars (see, e.g., Fig. 1). Since both groups obey a Maxwellian velocity distribution also runaway stars with relatively low velocities exist. We want to combine previous methods in order not to miss an important star because the radial velocity may be unknown (hence no spatial velocity) or its tangential or radial velocity component may be significantly larger than the other component (hence one would miss it in one direction). Moreover, we also want to identify the lower velocity runaway stars by searching for stars that were ejected slowly from their parent cluster. Furthermore, we want to use the term "runaway" star not only for O and B type runaway stars but all young (up to \( \approx 50 \) Myr) runaway stars to account for the possibility of less massive companions of massive stars (which soon after formation explode in a SN) and low-mass stars in young dense clusters which also may be ejected due to gravitational interactions.

In section 2 we describe the selection procedure of our sample of young stars. In section 3 we apply different identification methods for runaway stars and assign runaway probabilities to each star. A catalogue containing our results will be available via VizieR soon after publication.

We give a summary and draw our conclusions in section 4.

2 THE SAMPLE OF YOUNG STARS

We start with all stars from the Hipparcos catalogue (Perryman et al. 1997), 118218 in total, and collect spectral types as well as \( V \) magnitudes and \( B - V \) colours from the catalogue. According to the errata file provided with the Hipparcos catalogue, we correct erroneous spectral types. From the new Hipparcos reduction (van Leeuwen 2007) we obtain parallaxes (\( \pi \)) and proper motions (\( \mu_\alpha, \mu_\delta \)). We restrict our sample to lie within 3 kpc from the Sun (\( \pi - \sigma_\pi \geq 1/3 \) mas with \( \sigma_\pi \) being the 1\% error on \( \pi \)). Furthermore, we remove stars in the regions of the Large and Small Magellanic Clouds having accidentally \( \pi - \sigma_\pi \geq 1/3 \) mas (cf. Hohle et al. 2010). This gives us an initial set of 103217 stars. In the cases where the Hipparcos catalogue does not provide sufficient spectral types, we take the spectral type from either the Simbad or VizieR databases (Skiff 2009; Kharchenko & Roenser 2009; Abrahamyian 2007; Kharchenko et al. 2007; Bobylev et al. 2006; Wright et al. 2003; Buscombe & Foster 1999; Grenier et al. 1999; Gontcharov et al. 2004, 2006, Malaroda et al. 2006, Karatas et al. 2004, Barbieri-Brossat & Figon 2000, Grenier et al. 1999, Reid et al. 1997) and Evans (1967).

Since we look for young stars, our first goal is to obtain star ages. For that reason we check our star sample for pre-main sequence stars and find 236 of them either in catalogues (Chauvin et al. 2010; Ducourant et al. 2005; Hernández et al. 2005; Wichmann et al. 2005; Valenti et al. 2003; Köhler et al. 2000; Neuhäuser et al. 2000; Teixeira et al. 2000; Bertout et al. 1999; van den Ancker et al. 1997; Kenyon & Hartmann 1995; Neuhäuser et al. 1995; The et al. 1994) and/ or fulfilling the lithium criterion from Neuhäuser (1997) (for individual stars see also König 2003; Cutispoto et al. 2002; Neuhäuser et al. 2002; Song et al. 2002; Lawson et al. 2001; Montes et al. 2001; Zuckerman et al. 2001; De Medeiros et al. 2000; Gaidos et al. 2000; Strassmeier et al. 2000; Teixeira et al. 2000; Torres et al. 2000; Zuckerman & Webb 2000; Webb et al. 1999; Gaidos 1998; Neuhäuser & Brandner 1998; Soderblom et al. 1998; Favata et al. 1997; Micela et al. 1997; Tagliaferri et al. 1997; Jeffries 1995; White et al. 1989).

For the 236 pre-main sequence stars in the sample we used pre-main sequence evolutionary models from D'Antona & Mazzitelli (1994, 1997), Bernasconi (1996), Baraffe et al. (1998), Pallà & Stahler (1999), Siess et al. (2000), Maeder & Behrend (2002) and Marques et al. (2008)\(^1\) to estimate their masses and ages.

For main sequence and post-main sequence stars we used evolutionary models starting from the zero-age main sequence (ZAMS) from Schaller et al. (1992), Claret (2004), Pietrinferni et al. (2004)\(^2\), Bertelli et al. (2008, 2009) and Marques et al. (2008). For stars on or above the ZAMS all models yield masses and ages based on luminosity and effective temperature. Stars which lie below the model ZAMS (mainly due to large uncertainties in the parallax, thus in the luminosity) are shifted towards the ZAMS, hence will be treated as ZAMS stars. For early-type stars this has no effect on the age selection (see equation 1) because they are younger than 50 Myr even if the actual position in the HRD would be above the ZAMS. For most mid-F to mid-G stars age determination is difficult and the error on the age is larger than the age value itself (expressing the time the star would evolve without moving in the HRD), thus they will not enter our list of young stars due to our age criterion (see equation 1). Even later late-type stars (later than mid-G) are already older than 50 Myr on the ZAMS.

We used Solar metallicity for all 101628 stars in our sample with known magnitudes and spectral types; we obtained masses and ages from luminosities and temperatures. For stars with unknown luminosity classes are modest and the error of the luminosity \( L \) is mainly caused by the error on the parallax.

\(^1\) Since we are working with individual stars we do not correct for statistical biases (Smith & Eichhorn 1996). In any case, for the stars in our sample the Smith-Eichhorn corrected parallaxes do not differ significantly from the measured ones.

\(^2\) For some stars with unknown luminosity class we assume luminosity class V. For the effective temperature \( T_{\text{eff}} \) differences between different models in the list of Hohle et al. (2010) who used additional colours to determine \( L \). Thus, for those stars, we adopt their luminosities (without Smith-Eichhorn correction).

For having full kinematics, we obtain radial velocities from Simbad or the following VizieR catalogues: Zwitter et al. (2008), Kharchenko et al. (2007, 2004), Bobylev et al. (2006), Gontcharov (2006), Malaroda et al. (2006), Karatas et al. (2004), Barbieri-Brossat & Figon (2000), Grenier et al. (1999), Reid et al. (1997) and Evans (1967).

\(^3\) http://www.astro.up.pt/corot/models/cesam

\(^4\) http://albione.ou-teramo.inaf.it/
nosity class, we adopt luminosity class V. For some stars where also the spectral type is uncertain to ±5 sub-types, we calculate masses and ages for all spectral sub-types (e.g. for a G star: G0 to G9) to derive the mean and the standard deviation of mass and age. We define a star to be "young" if its age is ≤ 50 Myr. This limit is set for the following reason arising from the BSS formation scenario of runaway stars (section 1): It is desirable to identify the (now isolated) neutron star which was formed in the SN that released the runaway star. This would also yield the runaway's origin. For neutron stars the radial velocity is unknown, thus must be treated with a probability distribution (Tetzlaff et al. 2010). For that reason the error cone of the spatial motion is large and the position of a neutron star can be determined reliably only for a few million years, optimistically ≈ 5 Myr. This is the maximum runaway time (the kinematic age) of the runaway star (as well as the neutron star) such that the neutron star could be identified. The latest spectral type on the main-sequence for stars to explode in a SN and eventually become a neutron star is B3. These stars live about 35 Myr before they end their lives in SNe. We allow for an uncertainty of 10 Myr and find the maximum star age (not the kinematic age) of the BSS runaway for which the associated neutron star should still be identifiable to be ≈ 50 Myr. Despite that, a larger age would mean a longer timespan to trace back the star to identify its origin (if it is a DES runaway). This would cause large error bars on the past position of the runaway star that would make it less reliable to find the origin. However, star ages often suffer from large uncertainties due to large errors in distances and strong uncertainties in evolutionary models. That is why we choose the following criterion on the star age τ*: (the median from all evolutionary models applied) for a star to be young within our definition:

\[ \text{both } \tau_* + \sigma_{\tau_*} \leq 100 \text{ Myr and } \tau_* - \sigma_{\tau_*} \leq 50 \text{ Myr}, \]  

where \( \sigma_{\tau_*} \) is the median deviation of \( \tau_* \) for different models. With this criterion we allow for an error of \( \tau_* \) that is of the order of \( \tau_* \) itself but also exclude stars with accurately known ages above our limit of 50 Myr. Unfortunately, ages of supergiants are rather uncertain and we miss many of them applying the criterion. For that reason we add all stars of luminosity classes I and II as well as stars certain and we miss many of them applying the criterion. For that reason, we derive

\[ \text{the kinematic centre of the stars in our sample as follows. We calculate spatial velocity components of the 4195 stars with complete kinematic data (in a right-handed coordinate system with the } x \text{ axis pointing towards the Galactic centre and } y \text{ is positive in the direction of galactic rotation) corrected for Galactic differential rotation using Keplerian orbits:} \]

\[ \begin{align*}
\hat{U} &= U - U_{\text{rot}}, \\
\hat{V} &= V - V_{\text{rot}} + V_{\odot, \text{rot}}, \\
W &= W,
\end{align*} \]

where \( U, V \) and \( W \) are the heliocentric velocity components (in the \( x, y \) and \( z \) direction, respectively) and \( U_{\text{rot}} \) and \( V_{\text{rot}} \) the components of the rotational velocity of the star moving around the Galactic centre. \( V_{\odot, \text{rot}} = 225 \text{ km/s} \) is the rotational velocity of the Sun around the Galactic centre. To avoid significant contamination of high velocity stars, we exclude stars with \( \hat{v} > 50 \text{ km/s} \) (that is approximately two times the median of \( \hat{v} = \sqrt{U^2 + V^2 + W^2} \)). Fitting a Gaussian to each velocity component, we find

\[ (U_{\odot}, V_{\odot}, W_{\odot}) = (10.4 \pm 0.4, 11.6 \pm 0.2, 6.1 \pm 0.2) \text{ km/s}. \]

The agreement of our LSR with the classical value of Delhaye (1965) [9(11,6) km/s] is remarkable. In comparison with the most recent value published by Aumer & Binney (2009) [9(9.96 ± 0.33,5.25 ± 0.54,7.07 ± 0.34) km/s], the V component differs significantly; however, Aumer & Binney (2009) obtained their results by examining the correlation between LSR and colour \( B - V \), i.e. star age, and extrapolating the curves to zero velocity dispersion and also ignoring stars with \( B - V \leq 0 \) (see also Dehnen & Binney 1998) because they are probably not yet mixed. Such stars are over-abundant in our sample of young stars. From Figure 3 in Dehnen & Binney (1998) one may easily see that our result agrees well with their findings. In the following section we will use equation 3 to correct the velocities for Solar motion. The peculiar velocity is the velocity of a star corrected for Solar motion and Galactic rotation.

### 3 YOUNG RUNAWAY STARS

Classically, a star is assigned to be a runaway star if its peculiar space velocity \( v_{\text{pec}} \) exceeds 40 km/s (Blauw 1961). Later on, Vitrinchenko et al. (1965) and Cruz-González et al. (1974) used radial velocities \( v_r \) alone to investigate the population of runaway stars defining a more general definition of \( |v_r \text{-pec}| > v_{\text{crit,1D}} \) with \( v_{\text{crit,1D}} = 3\sigma \), where \( \sigma \) is the mean velocity dispersion in one dimension of the low velocity stars. Based on this definition Moffat

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**Table 1. Ages \( \tau_* \) (in Myr), masses \( M_* \) (in solar masses) and spectral types for 7663 young stars (sorted by their HIP number). \( \tau_* \) and \( M_* \) are medians obtained from different evolutionary models (see section 2.1). For 2250 stars only the spectral type is given since models infer a larger age, however they are probably also young (as inferred from spectral type and luminosity class). Here the first five entries are shown, the full table will be available via VizieR soon after publication.**

| HIP   | other name | \( \tau_* \) [Myr] | \( M_* \) [\( M_\odot \)] | SpT   |
|-------|------------|---------------------|-----------------------------|-------|
| 32    | HD 247576  | 10.0 ± 7.6          | 2.8 ± 0.1                   | B8    |
| 85    | CD-25 16747 | 39.8 ± 28.8         | 1.8 ± 0.1                   | A2    |
| 106   | HD 224870  | –                   | –                           | G7-III|
| 124   | HD 224893  | 44.7 ± 5.4          | 7.6 ± 0.4                   | F0III |
| 135   | HD 224908  | 45.7 ± 22.9         | 1.0 ± 0.1                   | G5    |

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5 For the effective temperature \( T_{eff} \) differences between different luminosity classes are modest and the error of the luminosity \( L \) is mainly caused by the error on the parallax.
et al. (1998) investigated tangential velocities \( v_t \) to identify runaway stars. We now want to combine and extend all these methods.

### 3.1 Runaway stars identified from their peculiar space velocity

Runaway stars were firstly described as the stars that are responsible for the longer tail in the velocity distribution such that it is not sufficiently describable with one Maxwellian distribution (Blauw 1961). Stone (1979) generalised the definition such that runaway stars are the members of the so-called high velocity group. These are stars with large peculiar velocities that can be represented by an additional Maxwellian distribution. The other Maxwellian distribution incorporates stars with lower velocities, thus the low velocity group (normal Population I stars). He pointed out that by applying a velocity cutoff to identify the runaway stars, a certain fraction of them would be missed. However, this issue can only be handled for the determination of space frequencies (see Stone 1991) and a velocity cutoff is still inevitable for the identification of runaway star candidates. To obtain a reasonable cutoff, we fit the distribution of the peculiar space velocities \( v_{pec} \) of the sample stars (4180 with full kinematics) with two Maxwellsians (Fig. 1). We evaluate the velocity errors utilising a Monte-Carlo simulation varying \( \pi, \mu_\alpha^*, \mu_\delta \) and \( v_r \) within their confidence intervals.\(^6\) We find that

\[
\begin{align*}
\sigma_L &= 9.2 \pm 0.2 \text{ km/s}, \\
\sigma_H &= 24.4 \pm 1.2 \text{ km/s}, \\
f_H &= 27.7 \pm 1.9\%, 
\end{align*}
\]

where \( \sigma_L \) and \( \sigma_H \) are the average velocity dispersions of the low and high velocity groups, respectively, and \( f_H \) is the relative frequency of the high velocity group. The derived dispersions are in agreement with those found by Stone (1979) (with \( \sigma_H \) being slightly smaller) whereas \( f_H \) is smaller; however published values for \( f_H \) vary from 34 \pm 14\% (Blauw 1961, corrected – see Stone 1991) to 55 \pm 12\% (Stone 1979). Furthermore, Stone’s star sample contains a much smaller number of stars than ours. In addition, to make sure that the low mass stars in our sample do not distort the results, we check whether the outcome differs from a subsample comprising only O and B type stars as well as Wolf-Rayet stars (2368 stars with full kinematics). Since we do not find significant differences we conclude that young stars, no matter if of low or high mass, share the same kinematic properties. The Maxwellian functions of both groups intersect at 28 km/s. Following Stone (1979), a star is a probable member of the high velocity group if

\[
v_{pec} > 28 \text{ km/s}.
\]

For that reason this will be our velocity cutoff defining runaway stars. In theory, with this definition we are able to identify 73 per cent of the high velocity group members while the contamination of low velocity stars is nine per cent.

We perform a Monte-Carlo simulation varying the observables \( \pi, \mu_\alpha^*, \mu_\delta \) and \( v_r \) within their uncertainty intervals and evaluate the probability of a star being a runaway star (the probabilities are given in Table 4). For 972 stars, the probability is higher than 50 per cent. Allowing for a nine per cent contamination of low velocity stars, this means a probability criterion of 50 per cent allows us to identify 78 per cent of the high velocity members.

\(^6\) Note that the velocity errors are not symmetric due to the inverse proportionality regarding \( \pi \).
Table 2. Fit results and curve intersection points for the different velocity components. The first column gives the velocity component examined. Columns 2 and 4 give the centre velocities $v_{cL}$ and $v_{cH}$ (for the 1D cases, i.e. Gaussian fit) and Columns 3 and 5 give the velocity dispersions $\sigma_L$ and $\sigma_H$ of the low and high velocity groups, respectively. All errors are formal 1σ errors. In Column 6 the intersection points of the curves representing the low and high velocity groups are given (for the 1D cases two intersection points exist (negative and positive sides of the distribution), they are approximate since the distribution is not exactly symmetric). The last column names the figure in which the particular distribution is shown.

| $v_{cL}$ [km/s] | $\sigma_L$ [km/s] | $v_{cH}$ [km/s] | $\sigma_H$ [km/s] | intersection [km/s] | Fig. |
|-----------------|-------------------|-----------------|-------------------|---------------------|-----|
| $U$             | $-0.3 \pm 0.3$    | $10.7 \pm 0.3$  | $4.1 \pm 1.5$     | $26.3 \pm 1.0$      | $\pm 23$ 2(a) |
| $V$             | $0.0 \pm 0.2$     | $10.7 \pm 0.1$  | $-4.7 \pm 1.0$    | $24.2 \pm 1.0$      | $\pm 23$ 2(b) |
| $W$             | $0.0 \pm 0.1$     | $5.3 \pm 0.1$   | $-3.8 \pm 0.5$    | $17.3 \pm 0.6$      | $\pm 12$ 2(c) |
| $v_{r,pec}$     | $0.2 \pm 0.3$     | $11.9 \pm 0.2$  | $-4.9 \pm 1.1$    | $28.5 \pm 0.9$      | $\pm 25$ 3    |
| $v_{t,pec}$     | $\approx -7.4 \pm 0.1$ | $\approx 7.4 \pm 0.1$ | $\approx 21.7 \pm 0.6$ | $\approx 21.7 \pm 0.6$ | $\approx 20$ 4 |
| $v_{b,pec}$     | $-2.7 \pm 0.1$    | $8.9 \pm 0.1$   | $\approx -2.6 \pm 0.7$ | $\approx 27.3 \pm 0.8$ | $\approx 27.3 \pm 0.8$ | $\approx 20$ 5(a) |
| $v_{t,pec}$     | $0.6 \pm 0.1$     | $5.3 \pm 0.1$   | $-3.3 \pm 0.4$    | $18.3 \pm 0.7$      | $\pm 11$ 5(b) |

Figure 2. Distribution of $U$, $V$ and $W$ (shaded histograms) – the 1D components of $v_{pec}$. The dashed curves represent the low velocity group while the dashed-dotted curves display the high velocity group. The two curves intersect at $U \approx \pm 23 \text{ km/s}$, $V \approx \pm 23 \text{ km/s}$ and $W \approx \pm 12 \text{ km/s}$, respectively. The total distribution as the sum of the two is represented by the full line.

Figure 3. Distribution of the peculiar 1D radial velocity $v_{r,pec}$ (shaded histogram). The dashed curve represents the low velocity group while the dashed-dotted curve displays the high velocity group. The two curves intersect at $v_{r,pec} \approx \pm 25 \text{ km/s}$. The total distribution as the sum of the two is represented by the full line ($\chi^2_{red} = 0.33$).

For those reasons, as for the peculiar spatial velocity $v_{pec}$, we choose the intersection points of the curves also for the 1D cases as well as $v_{r,pec}$ to define the runaway criteria. In Table 3, we specify the selection criteria, theoretical expectations concerning the possible identifications as well as the number of runaway star candidates identified (stars with a runaway probability higher than 50 per cent). Allowing for the specific contamination of low velocity group members, the number of identifications is generally in agreement with our theoretical predictions (Table 3).

With 972 runaway star candidates found in section 3.1 and 1381 identifications in Table 3 ($N_{new}$), we find a total of 2353 runaway star candidates with a runaway probability higher than 50 per cent regarding at least one velocity investigated (Table 4, the full table will be available via VizieR soon after publication).

3.3 Stars with higher peculiar velocities compared to their neighbourhood or surrounding OB association/cluster

Still, some high velocity group stars may not yet have been identified. For that reason we look for additional stars which show a different motion compared to their neighbouring stars. Since stars in clusters and associations share a common motion, runaway stars, i.e. stars that experienced some interaction (see section 1), can be identified through deviations from the common motion, especially if the velocity vector points towards a different direction than the cluster mean motion. From the previous investigations we can be sure that we identified all the runaway stars with high peculiar velocities. The most important criterion now is the direction of a star’s velocity vector compared to its neighbouring stars.
Table 4. Runaway probabilities for 2353 runaway star candidates as found in the previous section. Columns 3 to 10 list the individual probabilities $P$ for each velocity component. We regard stars with $P \geq 0.50$ in at least one velocity as runaways. The peculiar space velocities $v_{pec}$ and peculiar tangential velocities $v_{t,pec}$ are given in the last two Columns. Here the first five entries are shown, the full table will be available via VizieR soon after publication.

| HIP | other name | $P_{v,pec}$ | $P_U$ | $P_V$ | $P_W$ | $P_{v_{tr},pec}$ | $P_{v_{t,pec}}$ | $P_{v_{b,pec}}$ | $v_{pec}$ [km/s] | $v_{t,pec}$ [km/s] |
|-----|------------|-------------|-------|-------|-------|-----------------|-----------------|-----------------|----------------|----------------|
| 85  | CD-25 16747 | 0.89        | 0.93  | 0.47  | 0.22  | 0.01           | 0.96            | 0.52            | 0.99           | 52.9$^{+22.8}_{-37.2}$ |
| 135 | HD 224908   | -           | -     | -     | -     | -              | 0.99            | 0.00            | 1.00           | 22.1$^{+4.1}_{-2.1}$ |
| 145 | 29 Psc      | 0.13        | 0.00  | 0.95  | 0.31  | 0.00           | 0.00            | 0.00            | 22.4$^{+3.9}_{-2.0}$ |
| 174 | HD 240475   | 1.00        | 0.52  | 1.00  | 0.00  | 1.00           | 0.04            | 0.04            | 59.6$^{+1.4}_{-1.0}$ |
| 278 | HD 225095   | 0.45        | 0.13  | 0.23  | 0.04  | 0.51           | 0.03            | 0.02            | 27.3$^{+9.9}_{-7.1}$ |

Figure 4. Distribution of the peculiar 2D tangential Galactic velocity $v_{t,pec}$ (shaded histogram). The dashed curve represents the low velocity group while the dashed-dotted curve displays the high velocity group. The two curves intersect at $v_{t,pec} = 20$ km/s. The total distribution as the sum of the two is represented by the full line ($\chi^2_{red} = 2.58$, see comment to Fig. 1).

We select a sphere with a diameter of 24 pc$^7$ around each individual star to define its neighbourhood. All sample stars within this sphere are chosen as comparison stars. We calculate the vectors of the peculiar velocities $\vec{v}_{pec} = (U, V, W)$ and the peculiar tangential velocities $\vec{v}_{t,pec} = (v_{t,pec}, v_{b,pec})$ varying the observables within their confidence intervals. The neighbourhood velocity $\vec{v}_{neigh}$ is defined as the median velocity of the comparison stars. We define the runaway criterion such that $\vec{v}$ must not lie within the $3\sigma$ error cone of $\vec{v}_{neigh}$ (Fig. 6). Varying the observables within their confidence intervals, we obtain runaway probabilities for each star (10000 Monte-Carlo runs).

Figure 5. Distribution of the 1D components of the peculiar 2D tangential Galactic velocity $v_{t,pec}$: $v_{r,pec}$ and $v_{b,pec}$ (shaded histograms). The dashed curves represent the low velocity group while the dashed-dotted curves display the high velocity group. The two curves intersect at $v_{t,pec} \approx \pm 19$ km/s and $v_{b,pec} \approx \pm 11$ km/s, respectively. The total distribution as the sum of the two is represented by the full line.

In addition, we compare the velocity vectors of each OB association and cluster listed in Tetzlaff et al. (2010)$^8$ with the velocity vectors of each individual star situated within the association boundaries as listed in Tetzlaff et al. (2010) (assuming the associations/clusters are spherical, see Fig. 7 for the Orion OB1 association as an example). From $\vec{v}_{pec}$, we identify 126 additional runaway star candidates. Another 58 runaway star candidates are identified from their $\vec{v}_{t,pec}$. All runaway star candidates (192 for $v_{pec}$, 221

Table 3. Runaway selection criteria $|v| > v_{crit}$ for the different velocity components. The limits correspond to the intersection points of the curves representing the low and high velocity groups. Columns 3 and 4 give the theoretical expectations concerning possible identifications of high velocity group members (the fraction of high velocity group stars $f_{d,th}$ satisfying the selection criteria) and the contamination of low velocity group members (the fraction of low velocity group stars $f_{c,th}$ that also satisfy the selection criteria) while in the last two Columns the number of runaway star candidates $N$ and the number of new identifications $N_{new}$ (compared to section 3.1 and previous lines in the table) is quoted. Note that for $U$, $V$, $W$ and $v_{pec}$ only 4180 stars could be analysed whereas for $v_{t,pec}$, $v_{b,pec}$ and $v_{r,pec}$ the whole sample of 7663 stars was used.

| $v_{crit}$ [km/s] | $f_{d,th}$ [%] | $f_{c,th}$ [%] | $N$ | $N_{new}$ |
|------------------|---------------|---------------|-----|----------|
| $|U|$             | 23            | 39            | 17  | 776      |
| $|V|$             | 23            | 35            | 19  | 452      |
| $|W|$             | 12            | 50            | 12  | 609      |
| $|v_{r,pec}|$     | 25            | 39            | 20  | 588      |
| $v_{t,pec}$      | 20            | 66            | 9   | 1513     |
| $v_{b,pec}$      | 19            | 49            | 18  | 1162     |
| $v_{r,pec}$      | 11            | 56            | 15  | 1266     |

$^a$ 643 of them without $v_r$ measurements
$^b$ 33 of them without $v_r$ measurements
$^c$ 265 of them without $v_r$ measurements

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This is twice the median extension of all associations listed by Tetzlaff et al. (2010).

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We exclude Cas-Tau from the analysis owing to its large size (cf. de Zeeuw et al. 1999, their Table 2).
Table 5. Runaway probabilities for runaway star candidates found by comparison with OB associations and clusters (as listed in Tetzlaff et al. 2010). 192 runaway stars are identified from \( \vec{v}_{\text{pec}} \) and 221 from \( v_{\text{t,pec}} \). 124 stars are included in both lists. Columns 3 and 4 list the runaway probability \( P \) as well as the association/cluster. The absolute velocity values are given in columns 5 and 6. Errors correspond to 68 per cent confidence. The last column indicates whether the star was already identified as a runaway star in sections 3.1 and 3.2 (“prev” for previous identification; “new” for new identification). Here the first 5 entries for \( \vec{v}_{\text{pec}} \) and \( v_{\text{t,pec}} \), respectively, are shown, the full table will be available via VizieR soon after publication.

| HIP  | other name   | \( P \) | Assoc./ cluster | \( v_{\text{pec}} \) [km/s] | \( v_{\text{t,pec}} \) [km/s] | new ident. |
|------|--------------|--------|----------------|--------------------------|--------------------------|------------|
| 490  | HD 105       | 1.00   | \( \beta \) Pic-Cap | 11.0_{-1.1}^{+2.9}   | 10.6_{-1.1}^{+2.9}   | new        |
|      |              | 0.99   | ABDor          |                          |                          |            |
| 1481 | HD 1466      | 1.00   | Tuc-Hor        | 10.8_{-1.1}^{+2.9}   | 10.7_{-1.1}^{+2.9}   | new        |
|      |              | 1.00   | \( \beta \) Pic-Cap |                          |                          |            |
|      |              | 1.00   | ABDor          |                          |                          |            |
| 1623 | HD 1686      | 1.00   | Tuc-Hor        | 27.7_{-1.1}^{+1.9}   | 27.5_{-1.1}^{+2.9}   | prev       |
|      |              | 1.00   | \( \beta \) Pic-Cap |                          |                          |            |
| 1803 | BE Cet       | 1.00   | Tuc-Hor        | 27.4_{-1.1}^{+2.9}   | 27.1_{-1.1}^{+2.9}   | prev       |
|      |              | 1.00   | \( \beta \) Pic-Cap |                          |                          |            |
|      |              | 1.00   | ABDor          |                          |                          |            |
| 1910 | GSC 08841-00065 | 0.65 | \( \beta \) Pic-Cap | 13.1_{-1.1}^{+2.9} | 13.0_{-1.1}^{+2.9} | new        |

Figure 6. Definition for identifying runaway stars by comparing with neighbouring stars. The neighbourhood is defined as a sphere around an individual star with a diameter of 24 pc (footnote 7) or as the OB association/cluster (assumed to be spherical) inside which the star currently lies. The neighbourhood velocity \( \vec{v}_{\text{neigh}} \) is given by the median velocity of the stars within the sphere or the mean motion of the association/cluster member stars as listed in Tetzlaff et al. (2010), respectively. If the velocity vector \( \vec{v} \) points into the grey shaded region, the star clearly moves away from its neighbouring stars and is hence a runaway star. The grey shaded area lies outside the 3σ error cone of \( \vec{v}_{\text{neigh}} \) (dotted lines mark 1σ). Note that the length of \( \vec{v} \) and \( \vec{v}_{\text{neigh}} \) (\( v_{\text{pec}} \) or \( v_{\text{t,pec}} \)) is not important here.

Figure 7. Motion of Ori OB1 member stars. The red cross marks the centre of the association, the dotted ellipse its boundaries (assuming spherical shape). The red thick arrow shows the mean peculiar tangential motion of the whole association (Blaha & Humphreys 1989; Brown et al. 1999; Dambis et al. 2001; see also Tetzlaff et al. 2010), green squares are runaway star candidates satisfying the criterion defined by Fig. 6 whereas blue stars mark runaway star candidates already defined by their large peculiar velocity (section 3). The length of the arrows is scaled with distance to indicate tangential velocities.
We do not use the individual ages of the stars owing to the large uncertainty included them as potential runaway stars to not miss them only due to their large error bars.

Additional young stars situated well outside any OB association/cluster and the Galactic plane (see section 3.4 for criterion), i.e. runaway star candidates. Columns 3 to 4 give the distance $z$ to the Galactic plane as well as the star’s velocity $v_{pec}$ in this direction. The absolute velocity values are given in columns 5 and 6. Errors correspond to 68 per cent confidence. Although some stars would be consistent with $z = 0$ within $2\sigma$ and might be outliers we include them as potential runaway stars to not miss them only due to their large error bars.

### Table 6. Additional young stars situated well outside any OB association/cluster and the Galactic plane

| HIP    | Other name   | $z$ [pc]   | $W_{pec}$ [km/s] | $v_{pec}$ [km/s] | $v_z, pec$ [km/s] |
|--------|--------------|------------|------------------|------------------|------------------|
| 5805   | HD 7598      | $-477^{+110}_{-135}$ | $-350^{+110}_{-135}$ | $-16.3^{+10.0}_{-8.0}$ | $12.0^{+11.0}_{-9.0}$ |
| 11242  | HD 14920     | $-609^{+210}_{-200}$  | $-350^{+210}_{-200}$  | $-10.2^{+8.0}_{-6.0}$  | $25.4^{+9.1}_{-7.0}$  |
| 50684  | RS Sex       | $555^{+250}_{-230}$   | $547^{+250}_{-230}$   | $13.1^{+12.9}_{-11.1}$ | $15.9^{+16.0}_{-14.0}$ |
| 54769  | HD 97443     | $517^{+75}_{-70}$     | $520^{+75}_{-70}$     | $14.3^{+7.9}_{-6.0}$  | $8.0^{+6.0}_{-4.0}$  |
| 56473  | 90 Leo       | $488^{+280}_{-290}$   | $506^{+280}_{-290}$   | $13.9^{+12.3}_{-11.0}$ | $9.0^{+6.0}_{-4.0}$  |
| 70000  | HD 125504    | $544^{+310}_{-300}$   | $529^{+310}_{-300}$   | $12.0^{+10.0}_{-8.0}$ | $25.4^{+9.1}_{-7.0}$ |

#### 3.4 Stars outside OB associations/clusters and the Galactic plane

As runaway stars were ejected from their birth site, i.e. its host OB association/cluster or the Galactic plane, they are supposed to be isolated (outside any OB association/cluster and the Galactic plane). Thus, we look for young stars that are clearly outside any OB association/cluster listed in Tetzlaff et al. (2010) (outside three times the association radius which corresponds to approximately $3\sigma$) and probably outside the Galactic plane ($z > 500$ pc$^3$).

72 stars are situated well outside any OB association/cluster and the Galactic plane; six of them were not identified as runaway star candidates in the previous sections. Those six are listed in Table 6. If they did not form in isolation they are runaway stars.

#### 3.5 Comparison with other authors

We compare our sample of runaway star candidates with lists from other authors (most important sources: Blaauw 1961; Bekenstein & Bowers 1974; Cruz-González et al. 1974; Stone 1979; Gies & Bolton 1986; Leonard & Conlon 1990; Conlon et al. 1990; Philp et al. 1996; Moffat et al. 1999; Hoogerwerf et al. 2001; Mdzinarishvili & Chargeishvili 2005; de Wit et al. 2005; Martin 2006). 24 proposed runaway candidates which satisfy our initial sample criteria (HIP star, $\pi - \sigma_\pi \leq 1/3$ mas, equation 1), i.e. are contained in our young star sample, were not identified as runaway stars by us. They are listed in Table 7 along with the respective publication source.

We add three of the missing stars, namely HIP 3881 (=35 And), HIP 48943 (=OY Hya) and HIP 102195 (=V4568 Cyg) as well as HIP 26241 (=ε Ori) due to its DES origin (see individual discussion in appendix B).

As indicated by the discussion in appendix B, several problems may lead to mis- or non-identification of runaway stars. The major issue here is certainly the distance of a star that highly affects the calculated velocities. Since we used precise Hipparcos parallaxes (while previous studies often used ground-based distances) our results are not significantly influenced by that. Moreover, we derive runaway probabilities accounting for the errors on all observables instead of evaluating only a single velocity.

Another problem arises from the multiplicity of stars, e.g. 390 stars in our young star sample are spectroscopic binaries (Pourbaix et al. 2009; Pedoussaut et al. 1988). We obtained radial velocities from catalogues which typically list the systemic radial velocity.

#### Table 7. Runaway star candidates from Hipparcos proposed in the literature that are absent from our sample of 2543 runaway stars.

| HIP    | Ref.                      |
|--------|---------------------------|
| 102195 | Blaauw (1961); Bekenstein & Bowers (1974) |
| 35412  | Cruz-González et al. (1974) |
| 40328  | Cruz-González et al. (1974) |
| 81736  | Cruz-González et al. (1974) |
| 18246  | Stone (1979)               |
| 100214 | Stone (1979)               |
| 114104 | Stone (1979)               |
| 117221 | Stone (1979)               |
| 67279  | Leonard & Duncan (1990)    |
| 3881   | Hoogerwerf et al. (2001)   |
| 20330  | Hoogerwerf et al. (2001)   |
| 38455  | Hoogerwerf et al. (2001)   |
| 48943  | Hoogerwerf et al. (2001)   |
| 86768  | Hoogerwerf et al. (2001)   |
| 92609  | Hoogerwerf et al. (2001)   |
| 103206 | Hoogerwerf et al. (2001)   |
| 69640  | Mdzinarishvili & Chargeishvili (2005) |
| 73720  | Mdzinarishvili & Chargeishvili (2005) |
| 80338  | Mdzinarishvili & Chargeishvili (2005) |
| 90074  | Mdzinarishvili & Chargeishvili (2005) |
| 104361 | Mdzinarishvili & Chargeishvili (2005) |
| 1415   | de Wit et al. (2005)       |
| 37074  | de Wit et al. (2005)       |
| 97757  | de Wit et al. (2005)       |

4 SUMMARY AND CONCLUSIONS

We analysed the distributions of the peculiar velocities of 7663 young Hipparcos stars (4180 with full kinematics) in three, two as well as one dimension to identify members of the high velocity group, i.e. stars which show different kinematics than normal Population I objects and hence experienced some interaction (BSS or DES) which provides them with an additional velocity. As expected, the velocity component due to runaway formation is isotropic.

Performing Monte-Carlo simulations varying the observables $\pi$, $\mu_{\alpha}^*$, $\mu_{\delta}$, $v_{\gamma}$ and $v_{\pi}$ within their uncertainty intervals we assigned each star a probability for being a member of the high velocity group, i.e. a runaway star. We did that for the 3D velocity $v_{pec}$, its 1D components $U$, $V$ and $W$, the 1D radial velocity $v_{r, pec}$ as well as the 2D tangential velocity $v_{t, pec}$ and its 1D components $v_{r, pec}$ and $v_{\theta, pec}$ to identify as many members of the high velocity group as
possible, also those with a relatively low velocity. We found 2353 runaway star candidates, i.e. stars for which the runaway probability was higher than 50 per cent in at least one velocity component examined. The contamination of low velocity members is about 20 per cent at most. However, those high velocity group members with very small velocities (as inferred for a Maxwellian distribution they exist) could still not be identified due to the velocity thresholds set. Therefore, we compared the velocity vector (in 3D, \( v_{\text{pec}} \), and 2D, \( v_{\text{t,pec}} \)) of each individual star with the one defined by the stars in its neighborhood or its surrounding OB association/cluster (\( v_{\text{neigh}} \)). If the velocity of the star clearly pointed away from \( v_{\text{neigh}} \) (see Fig. 6), the star was assigned being a runaway star. 184 new identifications were made. Additionally, we find six additional young stars which are situated well outside any OB association/cluster and the Galactic plane. Finally, we compared our list of runaway star candidates with previously published lists and added four stars (see discussion in appendix B).

We will provide Tables 1, 4, 5 and 6 within an electronic catalogue available via VizieR.

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Figure 8. Distributions of \( v_{\text{t,pec}} \) and \( v_{\text{pec}} \). Light grey histograms represent the whole star sample whereas dark grey histograms show the distributions of runaway star candidates. The velocity distributions of the high velocity group is drawn with dashed-dotted lines (cf. Figs. 4 and 1).
Monte-Carlo runs the star’s position is located within the boundaries of Cygnus OB7 about $11.1^{+3.2}_{-3.0}$ Myr in the past which is in excellent agreement with the association age of 13 Myr (Uyaniker et al. 2001). Due to the large number of parameters involved (position and velocity of the star and association) the fraction of successful runs is expected to be small (cf. Hoogerwerf et al. 2001; Tetzlaff et al. 2010). Hence, we include this star into our runaway star sample.

The twelve stars identified by Cruz-González et al. (1974), Stone (1979) and Mdzinarishvili & Chargeishvili (2005) are not re-identified by us simply because the authors used photometric distances which are systematically too large, thus generating large peculiar velocities (this can be directly seen from comparison between Columns 5 and 6 of Table 1 in Mdzinarishvili & Chargeishvili 2005), whereas we used parallactic distances to determine peculiar velocities.

HIP 67279 was included by Leonard & Duncan (1990) owing to its large distance from the Galactic plane of $z = 1$ kpc (according to the author’s definition of a runaway star $z$ must be larger than $20 \text{ km/s}$ times the main-sequence lifetime of the star, cf. footnote 9). The photometric distance of 1.17 kpc that the authors adopted from Kilkenny et al. (1975) is however once more too large and the actual distance from the Galactic plane derived from the parallax (parallactic distance is $427^{+182}_{-130}$ pc) is $z = 397^{+80}_{-130}$ pc. With this $z$ and an age $\tau_\odot = 3.0 \pm 2.1$ Myr as inferred from evolutionary models (see section 2), HIP 67279 would need a vertical velocity component as large as $W = 1300 \text{ km/s}$ to have originated from the Galactic plane. Similarly, de Wit et al. (2005) identified the three stars listed in Table 7 only from their distance to the Galactic plane again using photometric distances. With the better parallactic distances they do not satisfy the criterion applied by the authors ($z > 250$ pc).

Four of the seven runaway candidates listed by Hoogerwerf et al. (2001) (HIP 20330, 86768, 92609, 103206) are not recognised as runaway stars by us due to different input data (especially $\pi$) as Hoogerwerf et al. (2001) used the old Hipparcos reduction (Perryman et al. 1997) (smaller $\pi$ in all four cases) whereas we used the latest published data by van Leeuwen (2007). In the case of HIP 48943, the radial velocity adopted by Hoogerwerf et al. (2001) of $v_r = 39.0 \pm 5.0$ km/s differs from our value of $v_r = 29.6 \pm 3.6$ km/s (Kharchenko et al. 2007) resulting in different peculiar space velocities ($30.7^{+14.9}_{-5.3}$ km/s and $22.6^{+3.9}_{-4.1}$ km/s, respectively).

Since HIP 48943 is an astrometric binary (Makarov 2007), we account for uncertainties in the radial velocity and include it into our sample of runaway star candidates. For another one, HIP 38455, Hoogerwerf et al. (2001) adopted $v_r = -31.0 \pm 5.0$ km/s. According to Haefner & Drechsel (1986) HIP 38455 is a spectroscopic binary with a systemic radial velocity of 29.5 km/s. This significantly different radial velocity changes the peculiar spatial velocity dramatically ($v_r = -31 \text{ km/s}$; $v_{pec} = 47 \text{ km/s}$, $v_r = 29.5 \text{ km/s}$; $v_{pec} = 14 \text{ km/s}$), hence the star is not a runaway. Moreover, Hoogerwerf et al. (2001) corrected the velocities for Solar motion using the LSR published by Dehnen & Binney (1998) which results in somewhat larger space velocities than ours (which is why we did not find some of their runaway stars) but does not accurately reflect the motion of young stars relative to the Sun (see section 2). For HIP 3881 Hoogerwerf et al. (2001) suggested a birth association (Lacerta OB1). We find that in 1.8 per cent of 10000 Monte-Carlo runs the star’s position coincided with the boundaries of Lacerta OB1 ($6.6^{+0.8}_{-0.6}$ Myr in the past). Like HIP 102195 (see above), we include this star into our runaway star sample. In addition, we include HIP 26241 ($\epsilon$ Ori, highly eccentric spectroscopic binary)

### APPENDIX A: THE VELOCITY DISPERSION OF THE HIGH VELOCITY GROUP OF STARS

For normal Population I stars, i.e. members of the low velocity group, the velocity dispersion in the $z$ direction, $\sigma_W$, is smaller than the velocity dispersion in the $x$ and $y$ directions (in the Galactic plane) due to the Galactic potential that attracts the stars onto the Galactic plane. Since all stars initially belong to the low velocity group there must be a difference between $\sigma_{U/V}$ and $\sigma_W$ also for high velocity group members. Since the velocity distribution in each direction is Gaussian,

$$
\begin{align*}
\sigma_{H,U}^2 &= \sigma_{L,U}^2 + \sigma_{w}^2, \\
\sigma_{H,V}^2 &= \sigma_{L,V}^2 + \sigma_{w}^2, \\
\sigma_{H,W}^2 &= \sigma_{L,W}^2 + \sigma_{w}^2,
\end{align*}
$$

where $\sigma_w$ is the velocity dispersion due to runaway formation. Initially, we assume the additional velocity to be isotropic. For the low velocity group we find that

$$
\begin{align*}
\sigma_{L,W} &\approx \sigma_{L,U} - (5 \text{ km/s}), \\
\sigma_{L,V} &\approx \sigma_{L,U}.
\end{align*}
$$

Thus,

$$
\sigma_{H,W}^2 = \sigma_{H,U/V}^2 - 10 \text{ km/s} \cdot \sigma_{L,W} - 25 \text{ km/s}^2.
$$

With $\sigma_{H,U/V} \approx 25 \text{ km/s}$ and $\sigma_{L,W} \approx 5 \text{ km/s}$, it follows that $\sigma_{H,W} \approx 23 \text{ km/s}$ theoretically. However, since the runaway formation occurred some time in the past for BSS runaways in the sample this timespan might be comparable with the age of the star before the supernova), the Galactic potential makes an impact on the higher velocities. For that reason, we expect to measure a somewhat lower value $\sigma_{w,H}$ for the high velocity group than the predicted value of $23 \text{ km/s}$, thus the found value of $\sigma_{W,H} \approx 17 \text{ km/s}$ is in good agreement with our predictions and we conclude that runaway formation leads to an additional velocity that is isotropic.

### APPENDIX B: AN INDIVIDUAL DISCUSSION ON RUNAWAY STARS FOUND IN THE LITERATURE

The classical runaway HIP 102195 was not identified by us since its peculiar spatial velocity is rather small ($v_{pec} = 16.6^{+2.1}_{-2.0}$ km/s). Note that Blaauw (1961) also quote a small velocity ($\approx 23 \text{ km/s}$). As proposed by the authors, HIP 102195 apparently originated from the Lacerta OB1 association. However, using 3D data, we cannot confirm this origin but instead find that in 10.0% of 10000
since it was very probably part of a former triple system (together
with the classical runaways HIP 24575 = AE Aur and HIP 27204
= µ Col), thus ejected via DSS from the Trapezium cluster (e.g.
Hoogerwerf et al. 2001) and a member of the high velocity group.