New Radial Velocities for 30 Candidate Runaway Stars and a Possible Binary Supernova Origin for HIP 9470 and PSR J0152−1637

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We report new radial velocity measurements for 30 candidate runaway stars. We revise their age estimates and compute their past trajectories in the Galaxy in order to determine their birthplaces. We find that seven of the stars could be younger than ∼100 Myr, and for five of them we identify multiple young clusters and associations in which they may have formed. For the youngest star in the sample, HIP 9470, we suggest a possible ejection scenario in a supernova event, and also that it may be associated with the young pulsar PSR J0152−1637. Our spectroscopic observations reveal seven of the stars in the sample of 30 to be previously unknown spectroscopic binaries. Orbital solutions for four of them are reported here as well.

1 Introduction

The first studies of high velocity stars were carried out by A. Blaauw and collaborators as early as the 1950’s (Blaauw 1952; Blaauw & Morgan 1954, 1956). Blaauw (1961) examined a number of O- and B-type stars and found that many of them had space velocities in excess of 40 km/s. He referred to these objects as “runaway stars”, a term that has been used ever since.

Runaway stars are mainly produced via two mechanisms. The binary supernova scenario (BSS) was first proposed by Blaauw (1961). It is also related to the formation of high velocity neutron stars. The runaway and the neutron star are the products of a supernova within a binary system. The velocity of the former secondary (the runaway star) may be as large as its original orbital velocity (Tauros & Takens 1998). The kinematic age of a BSS runaway star is smaller than the age of its parent association since the primary star needed some time to evolve and experience a supernova. In the alternate dynamical ejection scenario (DES) that was suggested by Poveda et al. (1967), stars are ejected from young, dense clusters via gravitational interactions between the cluster members. The (kinematic) age of a DES runaway star should be comparable to the age of its parent association since gravitational interactions are most efficient soon after formation.

To investigate the frequency of runaway stars among all stars in the Galaxy, Stone (1991) proposed fitting the velocity distribution with two Maxwellians, one representing normal Population I stars, the second one explaining the group of runaway stars. While many studies aiming at identifying runaway stars were based on space velocities (e.g. Blaauw 1961), tangential velocities (e.g. Moffat et al. 1998) or radial velocities (e.g. Cruz-González et al. 1974) alone, we recently constructed a unified catalogue of young runaway stars by evaluating all these criteria as well as the direction of motion compared to its neighbourhood (Tetzlaff et al. 2011b).

Although absolute 3D velocities are not essential to identify runaway stars, they are necessary for constructing stellar orbits. Past stellar trajectories can be used to identify the parent association or cluster of a star and its runaway origin. Some runaway stars have been proposed as former companion candidates to the progenitors of neutron stars (Hoogerwerf et al. 2001; Tetzlaff 2013; Tetzlaff et al. 2011a, 2012). Such an association may explain the spectral properties of a runaway star, such as a high Helium abundance or high rotational velocity or even enhanced α element abundances as supernova debris (Blaauw 1993; Przybilla et al. 2008).

In this paper we investigate the nature of 30 of the candidate runaway stars proposed by Tetzlaff et al. (2011b). Kinematic information for these objects was previously incomplete because of missing radial velocities (v_r). Here we present multiple measurements of v_r for these stars, and in addition we revise their age estimates from the work mentioned above. With this information we construct and trace back the Galactic orbits for the young stars in the sample to investigate their origin and possible connection with young clusters and neutron stars. Seven of the targets are revealed to be spectroscopic binaries, and orbits for four of them are reported here.

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2 Spectroscopy and Radial Velocities

Spectroscopic observations of our 30 targets were gathered using the Tillinghast Reflector Echelle Spectrograph (TRES, Füzesi 2008) on the 1.5 m Tillinghast reflector at the F. L. Whipple Observatory (Mount Hopkins, Arizona, USA), from 2011 April to 2013 October. Individual stars were observed for periods ranging from ~1 yr to a little over 2 yr. The spectra cover the wavelength range ~3900–8900 Å, and were taken with a typical resolving power of R ~ 44,000 with the medium fiber of the instrument. The signal-to-noise ratios for the individual exposures range between 23 and 230 per resolution element of 6.8 km/s, and refer to the region of the Mg I b triplet (~5200 Å). All spectra were reduced and extracted using standard procedures as described by Buchhave (2010) and Buchhave et al. (2010).

Radial velocities were obtained by cross-correlation against a synthetic template taken from a large library computed by John Laird, based on model atmospheres by R. L. Kurucz and a line list developed by Jon Morse (see Buchhave 2012). These templates cover a 300 Å window centred at 5200 Å, which generally contains most of the velocity information, and have a spacing of 250 K in temperature (T eff), 0.5 dex in surface gravity (log g) and metallicity ([Fe/H]), and a variable step in the projected rotational velocity (v sin i). The optimum template for each star was determined by cross-correlating all observations against the entire library of templates, and choosing the one giving the highest correlation coefficient averaged over all exposures (Torres et al. 2002). The best-matched template provides an estimate of the stellar parameters, although their accuracy is limited by degeneracies that are present among T eff, log g, and [Fe/H]. The template parameters that affect the velocities the most are T eff and v sin i. To suppress correlations, in a second iteration we held the metallicity fixed at the solar value and log g at values determined with the help of stellar evolution models as described in the next section. We then redetermined T eff and v sin i, and recomputed the velocities.

The zero point of our velocity system was monitored by observing standard stars each night with the same instrumental setup. Individual heliocentric velocities for each of our candidate runaway stars are reported in Table 1 (the complete table is available as supplementary material). In Table 2 we report the average v r of each star, along with the template parameters and other pertinent information.

### 2.1 Binary systems

Seven of our targets have variable radial velocity and are spectroscopic binaries. For four of them we gathered sufficient observations to solve for the orbital elements, which are presented in Table 3. In two cases (HIP 101219 and HIP 113787) the eccentricities turned out not to be significant; the solutions presented for those stars assume the orbits to be circular. The velocities listed for these binaries in Table 2 correspond to the systemic velocity. The other three variables show only long-term drifts over the time span of our observations, and their orbital periods are likely to be several years. Therefore, the mean velocities listed for these stars in Table 2 do not necessarily represent the true centre-of-mass velocity. The orbital solutions are shown graphically in Fig. 1, along with the time histories of the three objects with long-term trends.

Three of the four stars with spectroscopic orbits (HIP 9470, HIP 101219, and HIP 113787), as well as the three with long-term trends, are slowly rotating G or K giants (see below) and their orbital periods are long. The other binary with a spectroscopic orbit (HIP 8414) has a short period, and the rapidly rotating primary star is an F dwarf. Its measured rotation (v sin i = 42 km/s) is consistent with the star being pseudo-synchronized with motion in the slightly eccentric orbit (Hut 1981).

### 3 Past Trajectories

In order to construct the past orbits of our sample stars, stellar ages are required. In our previous study (Tetzlaff et al. 2011b) we already reported age estimates by comparison with evolutionary models in order to focus on the younger runaway candidates, as past orbits become too uncertain for older objects. The temperatures of the stars used to place them on the H-R diagram were based on published spectral types, and the conversion table of Schmidt-Kaler (1982). However, because of variations in chemical composition the zero-age main sequence (ZAMS) has some spread at a given effective temperature, which could not be resolved for the objects in our earlier study because we lacked estimates of the metallicity. To be conservative and not miss potentially
young objects, late-type stars that were found to fall below the solar-metallicity ZAMS in the H-R diagram were shifted upwards in luminosity onto the model ZAMS. This most likely resulted in underestimated ages for those stars.

For the 30 stars in the present sample we now have available the spectroscopic temperatures determined by cross-correlation. To compute stellar luminosities $L$, we determined the distances from their HIPPARCOS parallaxes (van Leeuwen 2007) using equation 2.11 of Francis (2013). This prescription yields results that are on average less affected by the bias towards larger distances arising from the parallax errors and the reciprocal relation between distance and parallax. Two of the stars, HIP 39228 and HIP 103533, are the secondaries in visual pairs, and their nominal parallaxes have very large uncertainties caused by the presence of the brighter primaries, and may be biased for the same reason. For those stars we adopted the catalogue values listed for the primaries. We further used the $V$ magnitudes as re-

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| HIP   | $V$     | $T_{\text{eff}}$ | $\log g$ | $v \sin i$ | $v_r$ | $N$ | span | Notes                                      |
|-------|---------|------------------|----------|------------|------|----|------|----------------------------------|
| 8414  | 8.50    | 6600±100         | 4.23     | 42±4       | −13.06±0.22 | 16  | 835  | SB1, $P = 1.74$ d, additional visual companion at 1.7" (Lampens et al. 2007), implying a triple system SB1, $P = 558$ d |
| 9470  | 6.54    | 5000±100         | 1.54     | 8±2        | −11.91±0.10 | 12  | 749  |                                           |
| 10784 | 6.88    | 4600±100         | 1.92     | 4±1        | +34.85±0.05 | 7   | 400  |                                           |
| 18549 | 8.51    | 8000±250         | 4.16     | 151±15     | +3.97±1.35  | 6   | 351  |                                           |
| 27802 | 10.39   | 4700±100         | 4.19     | 2±1        | +14.75±0.06 | 11  | 436  |                                           |
| 39228 | 10.06   | 5600±100         | 4.56     | 1±1        | −4.51±0.05  | 8   | 396  | Secondary in double system with HIP 39226 |
| 42331 | 7.60    | 4050±100         | 1.27     | 4±1        | +3.83±0.37  | 17  | 774  |                                           |
| 43043 | 7.99    | 7400±100         | 4.20     | 56±4       | +25.11±0.09 | 9   | 396  |                                           |
| 49820 | 10.36   | 7150±100         | 4.29     | 51±4       | +9.12±0.13  | 13  | 632  |                                           |
| 60065 | 10.36   | 7350±150         | 4.32     | 152±15     | −15.58±0.79 | 9   | 388  |                                           |
| 70995 | 10.60   | 5900±100         | 4.56     | 2±1        | −3.39±0.07  | 9   | 388  |                                           |
| 82163 | 7.91    | 4200±100         | 1.54     | 4±1        | −64.77±1.12 | 16  | 773  | Long-term drift                          |
| 82304 | 7.35    | 3850±100         | 1.16     | 6±1        | −27.41±0.04 | 9   | 416  |                                           |
| 83627 | 8.46    | 7700±100         | 4.21     | 11±2       | −20.56±0.11 | 10  | 347  |                                           |
| 84385 | 7.12    | 3650±100         | 1.03     | 7±2        | +15.00±0.17 | 19  | 768  |                                           |
| 85271 | 7.74    | 3800±100         | 1.31     | 6±1        | −53.01±0.06 | 14  | 768  |                                           |
| 91545 | 8.32    | 7350±150         | 4.25     | 159±15     | −43.99±0.89 | 7   | 360  |                                           |
| 96045 | 7.61    | 4100±100         | 1.37     | 5±1        | −52.12±0.05 | 8   | 530  |                                           |
| 98019 | 8.16    | 4500±100         | 1.79     | 6±1        | −4.22±0.03  | 7   | 381  |                                           |
| 98443 | 6.98    | 4050±100         | 1.43     | 6±1        | −42.54±1.37 | 15  | 731  | Long-term drift, primary in triple system (Anosova et al. 1987) SB1, $P = 483$ d |
| 101219| 7.50    | 3700±100         | 0.98     | 4±1        | −5.00±0.06  | 15  | 895  |                                           |
| 101320| 7.68    | 4900±100         | 1.95     | 5±1        | −18.74±0.01 | 7   | 377  |                                           |
| 102000 | 9.14    | 9150±100         | 4.28     | 80±4       | +2.76±0.47  | 14  | 751  |                                           |
| 103533 | 8.61    | 5500±150         | 3.02     | 15±20      | +26.67±4.03 | 12  | 751  | Secondary in double system with HIP 103537 |
| 104581 | 10.09   | 5300±100         | 4.61     | 2±1        | −21.54±0.06 | 6   | 514  | Primary in double system with K3 type star |
| 104608 | 11.01   | 7250±100         | 4.17     | 50±4       | +3.23±0.25  | 6   | 509  |                                           |
| 106291 | 9.25    | 7250±100         | 4.32     | 20±3       | +5.21±0.03  | 6   | 514  |                                           |
| 111607 | 8.06    | 4350±100         | 1.76     | 3±1        | +21.64±0.05 | 7   | 718  |                                           |
| 113787 | 6.56    | 4800±100         | 2.04     | 5±1        | +4.40±0.02  | 13  | 589  | SB1, $P = 467$ d |
| 117998 | 8.30    | 7450±100         | 4.23     | 94±5       | +12.25±0.50 | 8   | 414  |                                           |

Note: The $\log g$ values were estimated from stellar evolution models based on preliminary temperature estimates, and were held fixed (along with an assumed solar metallicity) to infer the final temperatures reported here (see text). The uncertainties reported for the velocities are the standard error of the mean.

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Two of the stars, HIP 39228 and HIP 103533, are the secondaries in visual pairs, and their nominal parallaxes have very large uncertainties caused by the presence of the brighter primaries, and may be biased for the same reason. For those stars we adopted the catalogue values listed for the primaries. We further used the $V$ magnitudes as re-

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The distance formula by Francis (2013) is strictly valid for parallax errors below 20 per cent. Although many of the stars in our sample exceed this limit, we have chosen to use the same expression because numerical simulations of a sample of 20,000 stars show that the resulting distances are still closer to the true distances than the nominal values. This procedure is also preferable to other approaches such as that of Smith and Eichhorn (1996), as shown by the same simulations.
Table 3  Orbital solutions for four binary stars.

| Element | HIP 8414 | HIP 9470 | HIP 101219 | HIP 113787 |
|---------|-----------|----------|------------|------------|
| $P$ [d] | 1.740469 ± 0.000020 | 556.5 ± 1.5 | 545 ± 23 | 467.12 ± 0.94 |
| $\gamma$ [km/s] | −13.06 ± 0.22 | −11.912 ± 0.099 | −4.995 ± 0.055 | 4.402 ± 0.016 |
| $K$ [km/s] | 24.77 ± 0.43 | 10.174 ± 0.088 | 0.56 ± 0.08 | 3.932 ± 0.022 |
| $e$ | 0.165 ± 0.018 | 0.3508 ± 0.0064 | 0 (fixed) | 0 (fixed) |
| $\omega$ [deg] | 92.60 ± 3.7 | 159.06 ± 0.83 | … | … |
| $T$ [HJD] | 2456205.734 ± 0.017 | 2456194.6 ± 2.4 | 2456178 ± 13 | 2455985.20 ± 0.44 |
| $a_1$ sin $i$ [Gm] | 0.5847 ± 0.00009 | 72.73 ± 0.74 | 4.17 ± 0.64 | 25.26 ± 0.13 |
| $f(M)$ [$M_\odot$] | $(2.63 ± 0.12) \times 10^{-3}$ | $(4.95 ± 0.15) \times 10^{-2}$ | $(9.7 ± 4.1) \times 10^{-6}$ | $(2.943 ± 0.048) \times 10^{-3}$ |
| $M_2$ sin $i$ | $(M_1 + M_2)^{3/2} [M_\odot]$ | 0.1380 ± 0.0021 | 0.3672 ± 0.0036 | 0.0213 ± 0.0030 | 0.14330 ± 0.00078 |
| number of observations | 16 | 12 | 15 | 13 |
| span of observations [d] | 834.8 | 748.9 | 894.6 | 588.6 |
| $\sigma$ [km/s] | 0.81 | 0.06 | 0.20 | 0.05 |

Fig. 1  Orbital solutions for four binary stars and time histories of three objects with long-term trends.

Ages and masses were inferred by comparison with several series of stellar evolution calculations (Bertelli et al. 2008, 2009; Pietrinferni et al. 2004; Schaller et al. 1992), accounting for all uncertainties by utilizing a Monte Carlo method. The corresponding log $g$ values were used to help establish the spectroscopic temperatures, as described earlier. However, the limitation due to the unknown metallicities remains, as we cannot determine [Fe/H] reliably from our spectroscopic material due to the strong correlations with $T_{\text{eff}}$ and log $g$ mentioned in section 2 Therefore, we do not determine ages and masses for nine stars that fall below the solar-metallicity ZAMS (Fig. 2): those objects are likely old in any case, which prevents a reliable determination of their Galactic orbits. The masses and ages determined for the remaining 21 stars are listed in Table 4.

We note that among these 21 stars there are 14 stars that are located in the upper right part of the HR diagram and, hence, are possibly evolve stars. Some of them are probably already old.

With knowledge of the distance and kinematics (proper motions and our new $v_r$ measurements), we used the fourth-order Runge-Kutta algorithm implemented in MATLAB to calculate the past stellar trajectories. We adopted an axisymmetric Galactic potential that contains a Miyamoto-Nagai potential for the disk (Miyamoto & Nagai 1975), a Hernquist potential for the bulge and the inner halo (Hernquist 1990) and a logarithmic potential for the dark halo, see Harding et al. (2001). For seven stars that could clearly be younger than 100 Myr (marked with an asterisk in Table 4), we compared the past flight paths reported in the Tycho-2 catalog (Hog et al. 2000) converted to the Johnson system, and an estimate of the extinction based on the $B - V$ indices (converted from the Tycho-2 measurements) and standard colours for main sequence and giant stars (see Tetzlaff et al. 2011 and Tetzlaff 2013). Approximately half of our stars are found to be evolved.

2 Isochrones from Schaller et al. (1992) and Schaller et al. (1993) were obtained from the database http://webast.ast.obs-mip.fr/eqepipe/stellar/Lejeune & Schaerer 2001). For Pietrinferni et al. (2004), see also the BaSTI web tools (http://albione.oa-teramo.inaf.it/).

3 We consistently use proper motions and parallaxes from HIPPARCOS (van Leeuwen 2007).
Table 4  Evolutionary ages \( \tau_* \) and masses \( m_* \) for 21 stars. The errors include the uncertainty on the parallax, \( V \) magnitude, \( B-V \) colour, \( T_{\text{eff}} \), the spread between different evolutionary models as well as a lower metallicity of \( \text{[Fe}/\text{H}] = -0.4 \). The nominal values for mass and age represent the respective median for solar metallicity. Stars that are marked with an asterisk (*) could clearly be younger than 100 Myr, the other stars are most probably a few hundred up to a few thousand Myr old. Note that we did not consider HIP 82304, HIP 83627, HIP 111607 and HIP 117998 young stars. For the first three of these stars, median ages up to a few thousand Myr old. Note that we did not consider HIP 82304, HIP 83627, HIP 111607 and HIP 117998 young stars. For the first three of these stars, median ages suggest that the stars are not young and the lower age bound does not clearly fall below our 100 Myr limit. For HIP 117998 the lower age bound is relatively small suggesting that the star is older than 100 Myr.

\[
\begin{array}{|c|c|c|}
\hline
\text{HIP} & \tau_* [\text{Myr}] & m_* [\text{M}_\odot] \\
\hline
8414 & 8414 & 8414 \\
9470^* & 9470^* & 9470^* \\
10784^* & 10784^* & 10784^* \\
27802 & \sim 14000^a & 27802 \\
39228 & \sim 10000^a & 39228 \\
42331 & 42331 & 42331 \\
43043 & 43043 & 43043 \\
82163 & 82163 & 82163 \\
82304 & 82304 & 82304 \\
83627 & 83627 & 83627 \\
48385^* & 48385^* & 48385^* \\
85271 & 85271 & 85271 \\
91545 & 91545 & 91545 \\
96045 & 96045 & 96045 \\
98019^* & 98019^* & 98019^* \\
98443^* & 98443^* & 98443^* \\
101219 & 101219 & 101219 \\
101320^* & 101320^* & 101320^* \\
111607 & 111607 & 111607 \\
113787^* & 113787^* & 113787^* \\
117998 & 117998 & 117998 \\
\hline
\end{array}
\]

\(^a\) These stars are too old for precise age estimate with our methods.

\(^b\) The upper age limit of HIP 85271 cannot be constrained by our methods.

with those of young associations (see Tetzlaff et al. 2010 2012 and 42 stellar clusters with ages between 40 and 150 Myr from Bukowiecki et al. 2012 for which 3D kinematic data are available. The kinematic properties of the clusters where obtained from Dias et al. (2006), Kharchenko et al. (2005), Wu et al. (2009) and Vandenberg et al. (2010), or derived as the mean values of members listed in the WEBDA database [Mermilliod & Paunzen

\[ \text{Fe}/\text{H}] = -0.4, \text{respectively.} \]

Fig. 2  The 30 stars in our sample shown on the H-R diagram. Objects indicated by a star are possibly young (up to \( \sim 100 \text{Myr} \)) stars. The solid and dashed lines indicate the mean model ZAMS for solar metallicity and \([\text{Fe}/\text{H}] = -0.4\), respectively. Owing to the positional uncertainties of the associations/clusters that increase with time because of their velocity dispersion, we calculate the past flight paths only up to 150 Myr. For the same reason, we did not account for association/cluster expansion or evaporation effects because the positional uncertainties dominate.

For five stars, we found multiple possible birth clusters (for flight times below 150 Myr) that we list in Table 5 along with the flight time and the cluster age. In these cases, taking the positional and kinematic uncertainties into account, the runaway star was probably inside the boundaries of the association/cluster within the past 150 Myr.

The flight time to reach the Galactic plane is smaller than the stellar ages for all cases as half the period of the vertical oscillation is smaller than the stellar age. Therefore, we cannot make statements about whether any of these stars were born in the Galactic plane.

We also calculated the past trajectories of young neutron stars in order to find possible encounters with runaway stars. We note, however, that only about 35 per cent of former runaway star/neutron star pairs can be recovered due to the large uncertainties on the observables (Tetzlaff 2013). Owing to the unknown radial velocity of neutron stars, their flight paths can only be traced back up to a maximum of a few Myr (we use 5 Myr, e.g. Tetzlaff 2013 [Tetzlaff et al. 2011a 2010]). This also sets a limit on the maximum age of the runaway star. Assuming that the neutron star is 5 Myr old and that the mass of its progenitor was the minimum mass required for a supernova progenitor (\(\sim B3\), implying a lifetime of \(\sim 30 - 40\) Myr), the only suitable runaway star in our sample is HIP 9470 (allowing for some Myr uncertainty on the progenitor lifetime and the stellar age).

To search for a neutron star that may potentially be related to HIP 9470, we apply a Monte Carlo method as done
Table 6  Predicted current parameters of PSR J0358+5413 and PSR J0152−1637 and supernova position and time for a possible past encounter with HIP 9470.

Neutron star parameters: heliocentric radial velocity \(v_r\), distance \(d\) or parallax \(\pi\), proper motion \(\mu^*\), peculiar space velocity \(v_{sp}\); Predicted supernova position: distance of the supernova to Earth at the time of the supernova \((d_{\odot,SN})\) and as seen today \((d_{\odot,today})\); Galactic coordinates (Galactic longitude \(l\), Galactic latitude \(b\), J2000.0) as seen from the Earth today; Predicted time of the supernova in the past \(\tau\). For the derivation of the parameters we refer the reader to the work of Tetzlaff et al. 2010.

| Present-day parameters | PSR J0358+5413 | PSR J0152−1637 |
|------------------------|----------------|----------------|
| \(v_r\) [km/s]         | 211±114        | 134±117        |
| \(\pi\) [mas] or \(d\) [pc] | 0.7±0.1       | 833±119        |
| \(\mu^*\) [mas/yr]    | 9.2±0.2        | 2.9±1.1        |
| \(\mu^*\) [mas/yr]    | 8.3±0.4        | 3.1±1.2        |
| \(v_{sp}\) [km/s]     | 266±101        | 175±86         |

Predicted supernova position and time since the explosion

|                        | Predicted   | Measured    |
|------------------------|-------------|-------------|
| \(d_{\odot,SN}\) [pc] | 453±109     | 464±97      |
| \(d_{\odot,today}\) [pc]| 451±57     | 578±90     |
| \(l\) [°]              | 149.4±2.4   | 149.9±2.2  |
| \(b\) [°]              | −49.8±1.5   | −49.7±1.6  |
| \(\tau\) [Myr]         | ∼5          | 2.1±0.5    |

\(\text{a}\) Distance from dispersion measure for two models of the Galactic electron density \(\text{Cordes \\& Lazio 2002; Taylor \\& Cordes 1993}\). Proper motion from Brisen et al. 2003.

\(\text{b}\) Chatterjee et al. 2004.

Table 5  Possible birth clusters for five young sample stars along with the flight time of the star. Ages are taken from Kharchenko et al. 2005, Dias et al. 2006, Vande Putte et al. 2010 and Bukowiecki et al. 2012.

| HIP  | cluster | flight time [Myr] | cluster age [Myr] |
|------|---------|-------------------|-------------------|
| 9470 | NGC 103 | 135±10            | 112 − 134         |
|      | NGC 1444| 36±5              | 79 − 92           |
|      | NGC 2353| 91±5              | 89 − 126          |
| 8438 | NGC 103 | 92±10             | 112 − 134         |
|      | NGC 436 | 109±2             | 84 − 126          |
|      | NGC 2353| 50±4              | 89 − 126          |
|      | Pismis 16| 63±5              | 52 − 79           |
|      | NGC 6694| 67±1              | 79 − 85           |
|      | NGC 1513| 59±1             | 79                |
|      | NGC 7086| 94±7             | 112 − 139         |
| 98019 | NGC 7086| 105±10            | 112 − 139         |
|      | NGC 2353| 100±37            | 89 − 126          |
|      | NGC 5617| 100±8             | 79 − 112          |
| 98443 | BH 92  | 58±2              | 56                |
|      | NGC 7086| 150±4             | 112 − 139         |
| 113787 | NGC 7788| 120±7             | 30 − 158          |
|      | NGC 1778| 134±4             | 126 − 151         |
|      | NGC 2186| 101±2             | 55 − 200          |

previously by Hoogerwerf et al. 2001, Bobylev & Bajkova 2009, and by ourselves (Tetzlaff et al. 2014, 2011a, 2009, 2010, 2012, 2013), to account for all errors on the observables. Among all young nearby neutron stars in the ATNF pulsar database with available distance and proper motion (105 neutron stars in total, see Tetzlaff 2013), we find two candidates for a common origin with HIP 9470: PSR J0358+5413 and PSR J0152−1637. The present neutron star parameters and the position and time of the predicted supernova event are given in Table 6. The kinematic age (flight time) of PSR J0358+5413 is \(\sim 5\) Myr if HIP 9470 is its former companion. This exceeds the spin-down age by one order of magnitude \(\tau_{sd} = 564\) kyr, period \(P\) and its derivative \(\dot{P}\) from Bobylev & Bajkova (2009). Noutsos et al. (2013) determined the kinematic age as \(0.5±0.2\) Myr assuming that the pulsar was born in the Galactic plane which is in good agreement with \(\tau_{sd}\). Therefore, we do not consider it likely for the progenitor of PSR J0358+5413 to have been a former companion of HIP 9470. The pulsar was probably born in the Galactic plane half a million years ago.

The spin-down age of PSR J0152−1637 of 10.1 Myr \((P \text{ and } \dot{P})\) from Bobylev & Bajkova (2004) is a factor of five larger than our predicted kinematic age. For many neutron stars, \(\sim 5\) Myr. As the spin-down age only gives a rough estimate of the order of magnitude of the true age, neutron stars with spin-down ages up to \(50\) Myr were selected for investigation allowing for an uncertainty on the age of one order of magnitude to be conservative.

\(\text{5}\) Because of the large uncertainties on the observables of neutron stars and the unknown radial velocity, their flight paths can only be traced back up to a maximum of \(\sim 5\) Myr.\n
\(\text{6}\) Pulsar database operated by the Australia Telescope National Facility, Manchester et al. 2005, http://www.atnf.csiro.au/research/pulsar/psrcat/.
If PSR J0152 happens to be a binary star, as revealed by our spectroscopic monitoring. If PSR J0152—1637 along with the flight time distribution is shown in Fig. 3. The solid line in the bottom panel represents the theoretical curve for the case that both objects met at the same position in space and in good agreement with the $\tau_{\text{ed}}$ histogram (see e.g. Tetzlaff et al. 2011a, 2013). The distance of the pulsar is rather uncertain and no parallax has been measured to date. Depending on the Galactic electron density model, dispersion measured distances range from about 500 to 800 pc (Cordes & Lazio 2002, Taylor & Cordes 1993). Our predicted distance of 533 ± 115 is in reasonable agreement with these estimates.

The distribution of separations $d_{\text{min}}$ between HIP 9470 and PSR J0152—1637 along with the flight time distribution is shown in Fig. 3. The solid line in the bottom panel represents the theoretical curve for the case that both objects met at the same position in space and in good agreement with the $d_{\text{min}}$ histogram (see e.g. Tetzlaff et al. 2011a, 2013 and Tetzlaff et al. 2014 for similar cases)$^7$. The encounter position cannot be associated with any particular stellar group that might have hosted the supernova, i.e., the predicted supernova event happened in isolation. This is possible if the neutron star progenitor itself was a runaway star. The former companion candidate HIP 9470 happens to be a binary star, as revealed by our spectroscopic monitoring. If PSR J0152—1637 and HIP 9470 were ejected during the same supernova event, this implies that the progenitor must have been at least a hierarchical triple system. This is not unlikely since stars ejected via gravitational interactions can be single, binary or triple stars (e.g. Leonard 1989). The wide orbit of the binary might be a result of the supernova explosion.

4 Conclusions

We have carried out high-resolution spectroscopic monitoring of 30 stars previously included in the catalogue of candidate young runaway stars of Tetzlaff et al. (2011b), for the purpose of measuring their radial velocities accurately. With this and other existing information we were able to calculate their Galactic orbits and investigate their origin in the context of runaway star scenarios. Ages for the targets were revised from previous estimates, and seven of the stars were found to be consistent with being younger than 100 Myr, and therefore still plausible as runaway stars. The remaining 23 objects are old enough that we no longer consider them to be candidate runaway stars. We computed the past orbits of the seven younger stars, and for five of them we identified several young clusters or associations with known kinematics with which they appear to have crossed paths in the recent past, suggesting this may be their place of birth. Of these five stars, the properties of HIP 9470 are consistent with it having had a recent close encounter with the neutron star PSR J0152—1637, but not simultaneously with any of the clusters. Seven of the 30 stars in the sample are found to be spectroscopic binaries, and orbital solutions for four of them are reported here.

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$^7$ The theoretical curve shows the distribution of differences between two 3D Gaussians that are centred at the same point in space (see e.g. Hoogerwerf et al. 2001, Tetzlaff et al. 2012), i.e., from the distribution we assume that the two stars were at the same spatial position about 2 Myr ago.
