The origin of the young pulsar PSR J0826+2637 and its possible former companion HIP 13962

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ABSTRACT

We aim to identify the birth place of the young pulsar PSR J0826+2637 in order to determine its kinematic age and give constraints on its radial and spatial (kick) velocity. Since the majority of neutron star (NS) progenitors are in associations or clusters, we search for a possible origin of the NS inside such stellar groups. We trace back the NS and the centres of possible birth associations and clusters to find close encounters. The kinematic age is then given by the time since the encounter. We use Monte Carlo simulations to account for observational uncertainties and the unknown radial velocity of the NS. We evaluate the outcome statistically. In order to find further indication for our findings, we also search for a runaway star that could be the former companion if it exists. We find that PSR J0826+2637 was probably born in the small young cluster Stock 7 ~ 3 Myr ago. This result is supported by the identification of the former companion candidate HIP 13962 (runaway star with spectral type G0Ia). The scenario predicts a near-zero radial velocity of the pulsar implying an inclination angle of its motion to the line of sight of 87° ± 11°. We also present the chemical abundances of HIP 13962. We do not find enhanced α element abundances in the highly evolved star. However, the binary supernova (SN) scenario may be supported by the overabundance of r-process elements that could have been ejected during the SN and accreted by the runaway star. Also, a high rotational velocity of $v \sin i \sim 29 \text{ km s}^{-1}$ of HIP 13962 is consistent with evolution in a pre-SN binary system.

Key words: stars: abundances – stars: individual: HIP 13962 – stars: kinematics and dynamics – pulsars: individual: PSR J0826+2637.

1 INTRODUCTION

PSR J0826+2637 (PSR B0823+26) was discovered 45 years ago by Craft, Lovelace & Sutton (1968). Its spin period $P = 0.53 \text{ s}$ and period derivative $\dot{P} = 1.71 \times 10^{-13} \text{ s/s}$ (Hobbs et al. 2004) yield a characteristic age of 4.92 Myr. It is a middle-age field pulsar that has been detected in X-rays (Sun et al. 1993). Becker et al. (2004) found that a power law with photon index $\alpha = 2.5^{+0.9}_{-0.7}$ already fits the energy spectrum of PSR J0826+2637. Adding a blackbody model does not change the fit significantly. So, there is only little thermal contribution from the neutron star (NS). However, Becker et al. (2004) obtained $3\sigma$ upper limits for the temperature of the polar cap ($<1.17 \times 10^8 \text{ K}$) and for the temperature if they assume that the emission comes from the whole surface ($<0.5 \times 10^8 \text{ K}$). Unfortunately, these temperatures do not allow us to derive a cooling age of the NS. Considering different cooling models (e.g. from Gusakov et al. 2005; Pons, Miralles & Geppert 2009; Popov et al. 2010), a lower age limit of a few kyr is estimated (assuming a $1.4 \text{ M}_\odot$ NS).

Beside the spin-down age, the only way to estimate the pulsar’s age is to do it kinematically. The knowledge of the birth place then also yields the lifetime of the NS progenitor (hence, its mass) given by the difference between the age of the parent association or cluster and the kinematic age of the NS. Furthermore, if place and time of the supernova (SN) were known, the radial and spatial (kick) velocity could be constraint. These quantities are not directly measurable. So far, the only way to estimate the radial velocity is to model a bow shock that is created while the NS moves supersonically through the interstellar medium (ISM; van Kerkwijk & Kulkarni 2001). Unfortunately, for PSR J0826+2637, no such bow shock (nor pulsar wind nebula) has been reported yet. If the radial velocity was known, the three-dimensional velocity could be constructed. This is also important to investigate the spin-velocity alignment of pulsars and provides further input to study the kick mechanism in the SN.

Accepting the spin-down age as a rough estimate (or often an upper limit) of the true age of the NS, PSR J0826+2637 is
sufficiently young to trace back its trajectory and identify its birth place. Kinematic ages have been determined for a number of NSs (e.g. Hoogerwerf, de Bruijne & de Zeeuw 2001; Pellizzia et al. 2005; Kaplan, van Kerkwijk & Anderson 2007; Bobylev 2008; Tetzlaff et al. 2011b, 2012, 2013; Mignani et al. 2013).

Here, we aim to derive the kinematic age of the young pulsar PSR J0826+2637 by identifying its birth place. It is reasonable to assume that NSs are born in young stellar groups such as associations and clusters since the majority of massive stars are observed in associations and clusters (>70 per cent; e.g. Mason et al. 1998; Maíz-Apellániz et al. 2004).

2 METHOD

We apply the same method as we did in preceding papers (Tetzlaff, Neuhäuser & Hohle 2009; Tetzlaff et al. 2010, 2011b, 2012), so we refer to these publications for details. We construct a few million past trajectories of PSR J0826+2637 and young associations/clusters (Tetzlaff et al. 2010, 2012; Tetzlaff 2013) as well as runaway stars (Tetzlaff, Neuhäuser & Hohle 2011a; Tetzlaff 2013) throughout Monte Carlo simulations by varying the observables (parallax, proper motion and radial velocity) within their error intervals. For the radial velocity of PSR J0826+2637, we assume a reasonable probability distribution derived from the pulsar space velocity distribution (Hobbs et al. 2005). From all pairs of trajectories (NS and association/cluster or NS and runaway star), we evaluate the smallest separation \( d_{\text{min}} \) and the past time \( \tau \) at which it occurred. The distribution of separations \( d_{\text{min}} \) is supposed to obey the distribution of absolute differences of two 3D Gaussians (see e.g. Hoogerwerf et al. 2001; Tetzlaff et al. 2012). Since the actual (observed) case is different from the simple model (no 3D Gaussian distributed positions, due to e.g. the Gaussian distributed parallax that goes into the position reciprocally, complicated radial velocity distribution, etc.), we adapt the theoretical formulae (equations 1 and 2 in Tetzlaff et al. 2012; here, we use the symbols \( \mu \) and \( \sigma \) for the expectation value and standard deviation, respectively) only to the first part of the \( d_{\text{min}} \) distribution (up to the peak plus a few more bins; see Tetzlaff et al. 2012). The derived parameter \( \mu \) then gives the positional difference between the two objects.

This procedure was already successfully applied by Hoogerwerf et al. (2001), Bobylev (2008), Bobylev & Bajkova (2009) and us (Tetzlaff et al. 2009, 2010, 2011b, 2012, 2013). We performed an investigation of (artificial) test cases that showed that it is well possible to recover place and time of the formation of an NS. If the former companion to the NS progenitor (if it exists) could be identified, the kinematic age is well consistent with the true NS age for 90 per cent of the test cases (Tetzlaff 2013). While the rate of identifying the birth association or cluster of a nearby NS is 70 per cent, the former companion could be identified for 35 per cent of the test cases.

For PSR J0826+2637, we adopt the following parameters for the right ascension \( \alpha \), declination \( \delta \) (J2000), parallax \( \pi \) and proper motion \( (\mu_\alpha^*, \mu_\delta) \): \n\begin{align*}
\alpha &= 08^h 26^m 51.3833^s, \\
\delta &= +26^\circ 37' 23.79'' \\
(\text{Hobbs et al. 2004}), \\
\pi &= 8.16 \pm 0.80 \text{ mas} \quad \text{(Gwinn et al. 1986)}, \\
\mu_\alpha^* &= 325.9 \pm 2.3 \text{ mas yr}^{-1}, \\
\mu_\delta &= -59.2 \pm 2.1 \text{ mas yr}^{-1} \quad \text{(Lyne, Anderson & Salter 1982),}
\end{align*}

where \( \mu_\alpha^* \) is the proper motion in right ascension corrected for declination.

Positional and kinematic data of young Hipparcos runaway stars are taken from Tetzlaff et al. (2011a, see also Tetzlaff 2013).

3 RESULTS

By tracing back the past trajectories of PSR J0826+2637 and a large sample of young associations and clusters (see Tetzlaff et al. 2010, 2011b, 2012), seven associations and clusters were found for which the NS could have been inside their boundaries during the past 5 Myr. These seven associations/clusters are therefore candidates to have hosted the birth place of PSR J0826+2637. The NS either originated in a nearby (<200 pc) association \( \lesssim 1 \) Myr ago or in a more distant one (~600–900 pc) up to ~5 Myr ago (Table 1). In the latter cases, a near-zero radial velocity of the NS is necessary. Two results are given in Table 1 for these cases: (*) using a probability distribution for the NS radial velocity according to Hobbs et al. (2005) and (**) using a uniform distribution in the range from \(-1500\) to \(+1500\) km s\(^{-1}\). Considering the estimated masses of the SN progenitor star given in that table, it is less likely that one of the nearby associations Per OB3 (\( \sigma \) Per) and Cas-Tau is the parent association of PSR J0826+2637 since the predicted masses are smaller than the minimum mass of a star that can experience a core-collapse SN (~8–9 M\(_{\odot}\); e.g. Heger et al. 2003). We note that Hoogerwerf et al. (2001) also suggested Per OB3 being the birth association of PSR J0826+2637 with an age of ~1 Myr, consistent with our result. Their estimated pulsar radial velocity is somewhat smaller (~100 km s\(^{-1}\)), but for a slightly larger kinematic age (~1 Myr), we achieve the same estimate. However, we consider it more probable that PSR J0826+2637 was born ~2–4 Myr ago in an association or cluster with a distance of >700 pc in the Camelopardalis region.

To find further evidence for a particular birth place of PSR J0826+2637, we check whether any runaway star (from Tetzlaff et al. 2011a; Tetzlaff 2013) could have been at the same place at the same time as the NS.

Among 137 runaway stars that could have come close to the NS sometime in the past 5 Myr, only the encounter between PSR J0826+2637 and the runaway star HIP 13962 could have happened inside a possible birth association/cluster of PSR J0826+2637. We also considered whether the SN that ejected both stars occurred outside any association or cluster by evaluating the significance of the encounters. We compare the probability of each possible encounter with a reference probability of an encounter between a randomly chosen NS and a randomly chosen runaway star (the idea was originally developed by Chmyreva, Beskin & Biryukov 2010 and adapted to our work, for details we refer to Tetzlaff et al. 2012; Tetzlaff 2013).

With this method, we did not find evidence for an isolated SN that ejected PSR J0826+2637 and a runaway star, whereas the identification of the GOa type (Turner et al. 2009) runaway star HIP 13962 as a former companion candidate to PSR J0826+2637 supports an origin of both stars in the small cluster Stock 7. The potential SN by which both the runaway star and the NS were ejected was located well inside the cluster boundaries. Considering Monte Carlo runs that yield separations between HIP 13962 and PSR J0826+2637 that are smaller than a few parsecs (the smallest separation found is 0.2 pc) result in distributions of separations between the NS and the cluster centre, and the runaway star and the cluster centre, respectively, that are consistent with that the SN event took place at the centre of Stock 7, i.e. \( \mu = 0 \) in both cases. The standard deviation is \( \sigma = 31 \) pc (in both cases) and consistent with the error-corrected
radius of the cluster.\(^1\) The distribution of separations \(d_{\text{min}}\) between the NS and the runaway star is also consistent with \(\mu = 0\), i.e. they were ejected the same SN event 3.0 ± 0.6 Myr ago (Fig. 1). This kinematic age is comparable to and not larger than the characteristic age of PSR J0826+2637, \(\tau_{\text{char}} = 4.92\) Myr Hobbs et al. (2004). The present NS parameters and position of the predicted SN are given in Table 2.

Turner et al. (2009) propose that HIP 13962 is a member of a previously unknown sparsely populated young cluster (with an age of 9 ± 1 Myr) that is presently dissolving into the field. The existence of that cluster is questionable, however. If existing, the cluster is only marginally detectable as cluster (see fig. 9 in Turner et al. 2009). It is not detectable in infrared data (2MASS JHK; Cutri et al. 2003; Bukowiecki, private communication, see also Bukowiecki et al. 2012 for the method of detection). Moreover, the nine potential member stars listed by Turner et al. (2009) do not share a common proper motion (Fig. 2). Hence, the existence of this cluster is arguable.

The evolutionary age of HIP 13962 as post-main-sequence star is 20 ± 4 Myr (Tetzlaff et al. 2011a), in agreement with the age of its proposed parent cluster Stock 7 (13–16 Myr from isochrone fitting, Loktin et al. 2001; Kharchenko et al. 2005a; 16 ± 4 Myr from isochrones of NGC 433, NGC 1027 and NGC 1444 were taken from Bukowiecki et al. (2012) and are upper limits (Bukowiecki, private communication). Then, more progenitor masses (> 8\(M_{\odot}\)) can be derived.

\(^{1}\) Due to the uncertainties of the kinematic properties of the cluster, the apparent radius increases as the (calculation) time increases to the past. The nominal radius of the cluster \(\sim 2\) pc (Kharchenko et al. 2005b), whereas the error-corrected radius \(R_{\text{corr}}\) = 30 pc.

\(^{a}\) Since small \(v_{t}\) of the NS were predicted using a \(v_{t}\) distribution consistent with the spatial velocity distribution of pulsars by Hobbs et al. (2003) (cases 1), the calculations were repeated using a uniform \(v_{t}\) distribution in the range 1500 – 15000 km s\(^{-1}\) (cases 2). The results did not change significantly (except the SN distance for NGC 1027).

\(^{b}\) These \(M_{\text{prog}} \) estimates are smaller than the minimum mass of a star that can experience a core-collapse SN (\(\sim \) 9–12\(M_{\odot}\); e.g. Heger et al. 2003). However, isochrone ages of NGC 433, NGC 1027 and NGC 1444 are taken from Bukowiecki et al. (2012) and are upper limits (Bukowiecki, private communication). Then, more progenitor masses > 8\(M_{\odot}\) can be derived.

\(^{1}\) The distribution of separations \(d_{\text{min}}\) between the NS and the runaway star is also consistent with \(\mu = 0\), i.e. they were ejected the same SN event 3.0 ± 0.6 Myr ago (Fig. 1). This kinematic age is comparable to and not larger than the characteristic age of PSR J0826+2637, \(\tau_{\text{char}} = 4.92\) Myr Hobbs et al. (2004). The present NS parameters and position of the predicted SN are given in Table 2.

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Then, the possible former companion to PSR J0826+2637 would be a blue straggler as expected for runaway stars that were ejected during an SN in a former binary system (Hoogerwerf et al. 2001).

Using an age range of Stock 7 of 12–45 Myr, the estimated mass of the NS progenitor is $m_1 \lesssim 30 M_\odot$. Further restriction arises from that the SN progenitor must be more massive than its former companion. The mass of HIP 13962 is $\sim 12 M_\odot$ (Tetzlaff et al. 2011a). On the main sequence, this star should have had a comparable mass, since in this mass regime the mass-loss is small ($\sim$0.05 per cent; e.g. Schaller et al. 1992). Hence, the NS progenitor had a mass between 12 and $\sim 30 M_\odot$. This is consistent with that its mass must be higher than the mass of the earliest present member of the parent cluster Stock 7 (HD 15239, B2.5:Vn shell; Moffat & Vogt 1973; Abt et al. 1980, hence mass of $\sim 7–8 M_\odot$; Schmidt-Kaler 1982; Hohle, Neuhäuser & Schutz 2010). The mass ratio of the former binary system is then $m_2/m_1 > 0.4$. This is consistent with observations of massive binaries (e.g. Kobulnicky & Fryer 2007; Sana et al. 2008).

The present parameters of PSR J0826+2637 as well as the time and position of the SN if HIP 13962 is the former companion to the NS are given in Table 2.

If HIP 13962 experienced a nearby SN explosion, the photosphere of the star might be polluted by $\alpha$ process elements which are ejected by SNe into the ISM at high rates. $\alpha$ enhancement was discovered in a few sources like the hypervelocity star HD 217791 (Przybilla et al. 2008) and the optical companions of two black hole binary systems, Nova Scorpii 1994 (Israelian et al. 1999) and V404 Cyg (González Hernández et al. 2011). O, Ne, Mg, Si, S and Ca are expected to be overabundant in the photosphere compared to iron (for SN/hypernova yields; see Nomoto et al. 2006). Hence, we investigated the chemical abundances of HIP 13962.

Based on archival ELODIE (Observatoire de Haute-Provence, resolution $R \sim 42000$) data, the stellar parameters of HIP 13962 were derived (Kovtyukh 2007; Kovtyukh, Gorlova & Belik 2012), effective temperature $T_{\text{eff}} = 5871 \pm 130$ K (Kovtyukh 2007), surface gravity log $g = 1.2$, microturbulence $\xi = 11.5$ km s$^{-1}$ (Kovtyukh et al. 2012) and projected rotational velocity $v \sin i \sim 90$ km s$^{-1}$ (Turner et al. 2009). We determine $v \sin i = 29.0 \pm 2.3$ km s$^{-1}$. This value is still significantly larger than the typical $v \sin i$ for FG supergiants (5–12 km s$^{-1}$; De Medeiros et al. 2002). HIP 13962 is a yellow supergiant at nearly solar metallicity. The abundances for each element relative to hydrogen are given in Table 3.

The source has an unexpectedly high Li abundance (Fig. 3). This can be due to the high rotational velocity (Kovtyukh et al. 2005) and/or a relatively young age, if the star was a pre-main-sequence star (instead of a post-main-sequence star) – consistent with a recent core-collapse SN in its system. The fast rotation can be due to the accretion from the primary during pre-SN binary evolution. The Li enrichment is also seen in the case of V404 Cyg (Martin et al. 1992). The most plausible mechanism is thought to be the neutron-induced spallation of CNO elements on the companion atmosphere (Guissoum & Kazanas 1999). In our case, we suggest energetic protons and $\alpha$ particles from the SN as the source of the spallation of CNO elements. So, Li enrichment might be explained by the spallation on the atmosphere of HIP 13962 due to the SN event.

While it is hard to comment on the whole picture because of the high errors, the nitrogen enrichment seems clear (Figs 3 and 4). However, it is expected in supergiants together with the under-abundance of O and C according to convective dredge up. The low abundance of Mg and a higher abundance of Na are also observed in other supergiants (Luck et al. 2008). S and Si abundances are consistent with that of iron. So, there is no clear $\alpha$ enhancement in HIP 13962. N enrichment is due to the dredge up, but it can also arise from mass accretion from the primary in the pre-SN binary system.

Furthermore, the accretion from the expanding material of the SN also depends on the binary separation; $M_{\text{SN}} = M_{\text{NS}} \cdot R_{\text{SN}}^2/4a^2$, where $M_{\text{NS}}$ is the geometric impacting mass, $R_{\text{SN}}$ is the radius of the secondary and $a$ is the binary separation (Fryxell & Arnett 1981). For example, for a twin binary with mass $12 + 12 M_\odot$ and with binary separation $\gtrsim 800 R_\odot$, the accreted mass is $\lesssim 4 \times 10^{-4} M_\odot$ for an ejected mass of $10 M_\odot$ and a secondary radius of $10 R_\odot$. This is probably too low to be detectable. However, the mechanism is not very well understood and searching for $\alpha$ enhancement is still important.
Table 3. Elemental abundances of HIP 13692 in solar units. The errors are the 1σ uncertainties from the line-to-line scattering. The uncertainties for elements with only one measurement are inferred from the typical uncertainties mentioned in Kovtyukh et al. (2012). The last column shows the number of lines \# used for the measurements.

<table>
<thead>
<tr>
<th>Ion</th>
<th>([\xi/\text{H}])</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li i</td>
<td>0.89 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>C i</td>
<td>−0.06 ± 0.07</td>
<td>6</td>
</tr>
<tr>
<td>N i</td>
<td>0.34 ± 0.03</td>
<td>3</td>
</tr>
<tr>
<td>O i</td>
<td>−0.15 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>Na i</td>
<td>0.14 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>Mg i</td>
<td>−0.18 ± 0.15</td>
<td>3</td>
</tr>
<tr>
<td>Al i</td>
<td>0.11 ± 0.07</td>
<td>4</td>
</tr>
<tr>
<td>Si i</td>
<td>0.07 ± 0.07</td>
<td>13</td>
</tr>
<tr>
<td>S i</td>
<td>0.02 ± 0.10</td>
<td>3</td>
</tr>
<tr>
<td>Ca i</td>
<td>−0.10 ± 0.14</td>
<td>4</td>
</tr>
<tr>
<td>Ti i</td>
<td>0.10 ± 0.13</td>
<td>5</td>
</tr>
<tr>
<td>Ti ii</td>
<td>0.03 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>V i</td>
<td>0.15 ± 0.10</td>
<td>3</td>
</tr>
<tr>
<td>V ii</td>
<td>0.00 ± 0.03</td>
<td>2</td>
</tr>
<tr>
<td>Cr i</td>
<td>−0.01 ± 0.20</td>
<td>3</td>
</tr>
<tr>
<td>Cr ii</td>
<td>0.08 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>Mn i</td>
<td>−0.02 ± 0.05</td>
<td>3</td>
</tr>
<tr>
<td>Fe i</td>
<td>0.02 ± 0.14</td>
<td>55</td>
</tr>
<tr>
<td>Fe ii</td>
<td>0.03 ± 0.08</td>
<td>11</td>
</tr>
<tr>
<td>Ni i</td>
<td>0.01 ± 0.13</td>
<td>13</td>
</tr>
<tr>
<td>Cu i</td>
<td>0.02 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>Y i</td>
<td>0.35 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>Zr ii</td>
<td>0.07 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>Ce ii</td>
<td>0.18 ± 0.15</td>
<td>2</td>
</tr>
<tr>
<td>Pr ii</td>
<td>0.02 ± 0.12</td>
<td>2</td>
</tr>
<tr>
<td>Nd ii</td>
<td>0.36 ± 0.08</td>
<td>3</td>
</tr>
<tr>
<td>Eu ii</td>
<td>0.39 ± 0.20</td>
<td>1</td>
</tr>
<tr>
<td>Gd ii</td>
<td>0.42 ± 0.20</td>
<td>1</td>
</tr>
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</table>

Another point is that the photosphere is rich in rare-earth elements (Table 3). Among these features, europium and gadolinium are mostly r-process elements in solar composition (Burris et al. 2000). Compared to the mean chemical abundances of 64 F- to M-type supergiants given in Luck & Bond (1989), HIP 13692 is slightly enriched in Eu. The nearby SN might be responsible for the r-enrichment. However, an extended sample of such sources is needed. Also, without the proof of the \(\alpha\) enhancement, we cannot be sure of the SN accretion as the reason of the r-enrichment. Surely, another explanation can be the Galactic distribution or local enrichment of r-process elements in the ISM. If this is the reason, we expect that the abundances follow the solar r-process pattern (Burris et al. 2000) like in the case of CS 22892-052 (Sneden et al. 2003). The s-process pattern may deviate due to the evolved state of our source. Future observations with higher resolution and signal-to-noise ratio will show a clearer picture.

Concluding, we can neither confirm nor reject whether HIP 13692 witnessed an SN in a former binary system due to its already evolved state.

4 CONCLUSIONS

We searched for the origin of the young pulsar PSR J0826+2637. In order to account for the uncertainties in the observables as well as the unknown radial velocity of NSs, we performed Monte Carlo simulations and evaluated the outcome statistically.

We found that PSR J0826+2637 was possibly ejected from the small cluster Stock 7 with the G0Ia runaway star HIP 13962 being its possible former companion (Fig. 5). The predicted kinematic age of the NS is 3.0 ± 0.6 Myr. This is comparable to the spin-down age and suggests a braking index of 4.3^{+0.8}_{-0.6} ± 0.8 assuming that the initial spin period was negligible and no glitches occurred.

We cannot prove an \(\alpha\) enhancement of the runaway star mainly due to the highly evolved state of the star. Even if there had been an enrichment, convective mixing concealed it. However, the binary SN scenario may be supported by the overabundance of r-process...
elements such as Eu and Gd that were possibly ejected during the SN and accreted by the runaway star. Also, the high rotational velocity of $v\sin i \sim 29 \text{ km s}^{-1}$ is consistent with former binary evolution. However, we cannot prove that HIP 13962 gained its runaway status in a past SN event and stress that the star remains a former companion candidate to the NS progenitor.

The predicted radial velocity of PSR J0826+2637 is almost zero, implying a 3D velocity of $183 \pm 43 \text{ km s}^{-1}$ and an inclination to the line of sight of the pulsar’s motion of $i = 87^\circ \pm 11^\circ$. This 3D velocity vector can be used to further investigate the orientation between the pulsar’s velocity and spin vectors, if the 3D spin vector was also known. Becker et al. (2004) find an X-ray pulsed fraction of $49 \pm 22$ per cent ($2\sigma$). In principle, with phase-resolved spectroscopy, it is possible to determine the angle between the rotational and magnetic field axes although the current data are not sufficient.

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