The origin of the Guitar pulsar

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ABSTRACT

Among a sample of 140 OB associations and clusters, we want to identify probable parent associations for the Guitar pulsar (PSR B2224+65) which would then also constrain its age. For this purpose, we are using an Euler-Cauchy technique treating the vertical component of the Galactic potential to calculate the trajectories of the pulsar and each association into the past. To include errors we use Monte-Carlo simulations varying the initial parameters within their error intervals. The whole range of possible pulsar radial velocities is taken into account during the simulations.

We find that the Guitar pulsar most probably originated from the Cygnus OB3 association ≈ 0.8 Myr ago inferring a current radial velocity of \( v_r \approx -30 \text{ km/s} \), consistent with the inclination of its bow shock.

Key words: stars: early-type – stars: kinematics – pulsars: individual: PSR B2224+65.

1 INTRODUCTION

There have been several attempts of identifying parent associations of neutron stars (recently e.g. Hoogerwerf et al. 2001; Bobylev 2008; Bobylev & Bajkova 2009; Motch et al. 2009; Tetzlaff et al. 2009, thereafter Paper I). Due to large uncertainties of the observables, mainly parallax or distance, and the unknown radial velocity, such investigations are statistical adventures requiring Monte-Carlo simulations to treat the errors. Unlike previous authors we do not initially define a small interval for the radial velocity but cover a wide spectrum instead.

The probably most spectacular neutron star in terms of its motion is PSR B2225+65, the pulsar that creates the so-called Guitar nebula, a bow shock generated by the enormous speed indicated by the large transverse velocity component of \( > 1500 \text{ km/s} \) at a distance of \( \approx 1.9 \text{ kpc} \) from the Sun (Harrison et al. 1993; Taylor & Cordes 1993; ATNF database1; Manchester et al. 2005). In contrast to that, the pulsar shows quite ordinary properties of a radio pulsar such as no timing anomalies (Hui & Becker 2007; Bandiera 2008). Unlike the “Magnificent Seven” (radio-quiet soft X-ray sources, Treves et al. 2001) which have been discussed in Paper I, the characteristic spin-down age of the Guitar pulsar of 1.1 Myr (Hobbs et al. 2004; ATNF database) is also consistent with cooling models. Thus, we expect to find its kinematic age close to that value. In this Letter we investigate a total number of 140 OB associations and clusters (Paper I) kinematically to find associations which are likely to have hosted the supernova which formed the Guitar pulsar. After selecting the candidate birth places we are able to give constraints on the radial velocity.

2 PROCEDURE

Different approaches have been made to calculate past trajectories of objects starting with the traditional method of straight lines through space. The effect of the galactic potential can be included utilising either numerical methods such as a Runge-Kutta algorithm (e.g. Asiain et al. 1999; Hoogerwerf et al. 2001) or the classical epicycle approximation (Lindblad 1959; Wielen 1982). The latter holds only if the velocity of an object with respect to the Local Standard of Rest (LSR) is sufficiently low. For that reason, since the Guitar pulsar is the fastest pulsar known, we use a different approach, applying a simple Euler-Cauchy algorithm with a fixed time step of \( 10^4 \text{ years} \) to include only the vertical component of the galactic potential which was adopted from Perrot & Grenier (2003) (and references therein). Utilising this technique is fully sufficient for a treatment of some million years and consistent with results applying more complex methods such as a Runge-Kutta numerical integration method applying a more complicated potential such as given in Harding et al. (2001) and references therein (cf. comparison of methods in Tetzlaff 2009).

To investigate the origin of PSR B2224+65 we used the same procedure as we did in our previous paper (Paper I) which has been suggested by Hoogerwerf et al. (2001). Applying Monte-Carlo simulations varying the parameters within their error intervals, we calculated the trajectories of the pulsar and any association centre into the past and simultaneously their separation at every time step. We
then find the minimum separation and the associated time in the past. Since the radial velocity of neutron stars is not directly measurable so far, we vary the radial velocity randomly between −1500 and 1500 km/s. This is somewhat different to our previous work (Paper I) where we used the distribution for pulsar space velocities from Hobbs et al. (2005) to derive a radial velocity distribution. Since the Guitar pulsar already shows a transverse velocity of ≈ 1600 km/s this approach would not cover a wide spectrum of radial velocities.

We take the pulsar position from Hobbs et al. (2004) and its proper motion from Harrison et al. (1993). Taylor & Cordes (1993) give us the current distance of the pulsar needed is 1.86 kpc (Manchester et al. 2005) to determine the parallax (derived from the mean distance of 1.92 kpc) and its error (note that this error does not include measurement uncertainties but only corresponds to the maximum deviation between the parallax derived from the mean distance and its lower and upper limit derived from the two cited distance values, those values are given without errors in the literature cited; see also footnote 2):

\[
\begin{align*}
\alpha &= 336^\circ 47, \quad \delta = 65^\circ 59, \\
\pi &= 0.52 \pm 0.03 \text{ mas}, \\
\mu_\alpha^\ast &= 144 \pm 3 \text{ mas/yr}, \quad \mu_\delta = 112 \pm 3 \text{ mas/yr},
\end{align*}
\]

where \(\mu_\alpha^\ast\) is the proper motion in right ascension corrected for declination. Heliocentric coordinates and velocity components of our sample of 140 OB associations and clusters (we use the term “association” in the following for both) are available in the Appendix of Paper I.

### 3 RESULTS

We initially perform 100,000 Monte-Carlo runs for each of the 140 associations in our sample to find those for which close encounters with the Guitar pulsar are possible in the past 5 Myr. Then we select those associations for which the smallest separation between its centre and the pulsar found at some time in the past was within three times the association radius or smaller than 100 pc and repeated the procedure carrying out another one million runs. Table 1 lists those 9 associations for which the smallest separation found (column 2) during the second cycle of investigation was consistent with the association boundaries.\(^2\)

Four of them show a peak in their \(\tau-d_{\text{min}}\) contour plot that is consistent with the respective association radius. Table 2 gives this region of higher probability (columns 2 and 3; boundaries were chosen such that they reflect an approximate 68% decline from the peak – see Figure 1 as an example) along with present-day parameters which the Guitar pulsar would have if it was born in the particular association. The last three columns indicate the distance of the potential supernova to the Sun as well as its equatorial coordinates. For the definition of selecting the values given in columns 4 to 10 we refer to our Paper I, section 5. It should just be mentioned that the errors given specify 68% intervals, however are not 1\(\sigma\) errors.

Owing to its large transverse velocity we expect the radial velocity to be very small. Infact, Chatterjee & Cordes (2004) investigated the bow shock which the pulsar is generating due to its high speed motion and measured an inclination of 90±20 degrees. This means that the radial velocity is nearly zero. Indeed, we find an association in our Table 2 which is consistent with that: If the pulsar originated from the Cygnus OB3 association (Cyg OB3) its radial velocity would be \(-27\pm81\) km/s. For Vulpecula OB1 (Vul OB1) the current radial velocity would also be relatively small (≈ 190 km/s); however this is significantly larger than for Cyg OB3. The other two parent association candidates infer a substantial larger radial velocity. We thus conclude that Cyg OB3 is most probably the birth association of the Guitar pulsar.

Note that NGC 6871, Byurakan 1, Byurakan 2 and NGC 6883 are clusters associated with Cyg OB3. They also appear in Table 1. Their distances to the Sun are still under discussion so that they cover a range between 1.6 to 2.3 kpc. Since NGC 6871 is generally

| Association | \(d_{\text{min}}\) [pc] | \(R_{\text{Assoc}}\) [pc] |
|-------------|----------------|------------------|
| Vul OB1     | 1.4            | 115              |
| NGC 6823    | 0.2            | 34               |
| Cyg OB3     | 0.8            | 53               |
| NGC 6871    | 0.3            | 7                |
| Byurakan 1  | 0.5            | 6                |
| Byurakan 2  | 0.8            | 6                |
| NGC 6883    | 1.7            | 4                |
| Cyg OB1     | 2.1            | 71               |
| Cyg OB8     | 0.8            | 39               |

Figure 1. Distribution of the number of runs in the \(\tau-d_{\text{min}}\) space for the Guitar pulsar and the centre of Cyg OB3. The ellipse marks the region for determination of the parameters given in Table 2.

\(^2\) Increasing the parallax error even by a factor of ten does not affect the results significantly. Four additional associations with small possible separations between their centres and the pulsar are found (Vul OB4, Cyg OB9, Cyg OB7, Cep OB2); however the current distance of the pulsar needed is always found to be less than 1.4 kpc which is much smaller than dispersion measure implies (≈ 2 kpc). Moreover, even if we follow the suggestion of Chatterjee & Cordes (2004) that the pulsar could have a distance of only 1 kpc, the radial velocities needed are found to be > 500 km/s which is highly unlikely regarding the large transverse velocity of the pulsar.
Table 2. Potential parent associations of the Guitar pulsar (PSR B2224+65).
Columns 2 and 3 mark the boundaries of a 68% area in the $\tau-d_{\text{min}}$ contour plot for which the current neutron star parameters (columns 4 to 7, radial velocity $v_r$, proper motion $\mu_\alpha$ and $\mu_\delta$ and parallax $\pi$) were obtained and columns 8 to 10 indicate the distance to the Sun $d_\odot$ and equatorial coordinates (J2000.0) of the potential supernova. Underneath, we give present positions (equatorial coordinates, distances $d$) and radii $R$ for the respective associations (see Paper I for the complete data including kinematics).

| Association | $d_{\text{min}}$ | $\tau$ | $v_r$ | $\mu_\alpha$ | $\mu_\delta$ | $\pi$ | $d_\odot$ | $\alpha$ | $\delta$ |
|------------|-----------------|--------|-------|--------------|-------------|------|----------|---------|---------|
| Vul OB1a   | 28.0±1.10       | 1.06   | 1.18  | 193±70       | 144±13      | 112±3 | 52477±2630 | 295.82±0.66 | 23.3±26.2 |
| NGC 6823b  | 25.1±1.07       | 0.95   | 0.82  | 144±13       | 112±3       | 52230±2390 | 295.97±0.63 | 23.5±26.3 |
| Cyg OB3c   | 20.0±0.82       | 0.74   | 0.82  | 144±13       | 112±3       | 52285±2385 | 302.08±0.64 | 36.7±38.2 |
| Cyg OB1d   | 45.8±2.00       | 0.50   | 0.57  | 144±13       | 111±3       | 1640±1760 | 303.35±0.55 | 39.54±0.26 |

$^a\alpha=295.8^\circ, \delta=23.3^\circ, d=1.6$ kpc, $R=115$ pc (Blaha & Humphreys 1989; Dambis et al. 2001)

$^b\alpha=295.8^\circ, \delta=23.3^\circ, d=2.3$ kpc, $R=34$ pc (Wolff et al. 2007)

$^c\alpha=301.7^\circ, \delta=35.9^\circ, d=2.3$ kpc, $R=53$ pc (Blaha & Humphreys 1989; Dambis et al. 2001)

$^d\alpha=304.7^\circ, \delta=38.0^\circ, d=1.7$ kpc, $R=71$ pc (Blaha & Humphreys 1989; Dambis et al. 2001)

Table 3. Progenitor masses calculated for the difference between different ages for Cyg OB3 ($age_{\text{CygOB3}}$) and a pulsar age of 0.8 Myr. Evolutionary models are taken from Tinsley (1980) (T80), Maeder & Meynet (1989) (MM89) and Kodama (1997) (K97).

| $age_{\text{CygOB3}}$ | $T80$ | $MM89$ | $K97$ |
|-----------------------|-------|--------|-------|
| [Myr]                 | [M$_\odot$] | [M$_\odot$] | [M$_\odot$] |
| 2                     | > 50   | > 100  | > 100 |
| 5                     | 46     | 47     | 42    |
| 8                     | 37     | 25     | 21    |
| 12                    | 24     | 16     | 15    |

presumed to be the nucleus of Cyg OB3, we repeat our calculations for NGC 6871 adopting the distance of the Guitar pulsar (2.5 kpc). The results do not change significantly: The smallest separation $d_{\text{min}}$ found is 0.4 pc and the peak in the $\tau-d_{\text{min}}$ contour plot is located outside the boundary of NGC 6871 (radius of 7 pc). We conclude that the Guitar pulsar was born somewhere within the Cyg OB3 association $\approx 0.8$ Myr in the past.

Given the age of Cyg OB3 of 8 to 12 Myr (Reitsema 1989; Uyanik et al. 2001; Southworth et al. 2004) we can derive the mass of the progenitor star of the Guitar pulsar (the difference between the association age and the kinematic neutron star age yields the progenitor lifetime) of 15 M$_\odot$ (B1 on the main sequence) for an association age of 12 Myr) to 37 M$_\odot$ (O6 on the main sequence) for an age of Cyg OB3 of 8 Myr under the assumption that all association members formed at once, see Table 3. There is some dispute about the association age since it contains younger clusters (e.g. NGC 6871 is 2 to 5 Myr old according to Massey et al. 1995). According to Reipurth & Schneider (2008), the most massive star in Cyg OB3 is the O4I star HD 190429A with an age of 1.6 ± 1.0 Myr (models from Schaller et al. 1992; Claret 2004) suggesting a younger age for Cyg OB3 or an age spread within the association. We therefore estimate the progenitor mass also for younger ages. However, from Table 3 we can exclude young ages of the pulsar’s birthsite since the masses derived are larger than the upper limit for neutron star formation ($\approx 30$ M$_\odot$, Heger et al. 2003), hence a black hole would have formed. Nonetheless, since, as mentioned above, Cyg OB3 consists of a number of smaller clusters with different ages ranging from 2 to $\approx 30$ Myr (see Appendix of Paper I), it is well possible that the Guitar pulsar was born within an intermediate aged cluster of Cyg OB3. Fitting isochrones from Girardi et al. (2002) to the HR diagram of members of Cyg OB3 listed by Humphreys (1978), we find an age range, namely that stars in Cyg OB3 formed from 6 to 11 Myr ago.

4 CONCLUSIONS

We have investigated the past trajectory of the Guitar pulsar (PSR B2224+65) as well as those of 140 OB associations and clusters (Paper I) to identify the parent association of the pulsar. Utilising statistical techniques we have taken the errors on the observables and, more importantly, a wide spectrum of radial velocities into account. However, the radial velocity may in principle be restricted to nearly zero due to the determination of the inclination of its bow shock (Chatterjee & Cordes 2004). Although we initially did not include constraints on the radial velocity, we find an association which fulfills this requirement. Hence, we conclude that the Guitar pulsar was born in the Cyg OB3 association $\approx 0.8$ Myr ago with its current radial velocity being $\approx -30$ km/s. Its kinematic age is slightly smaller than the characteristic age of 1.1 Myr derived from timing (Hobbs et al. 2004) which is an upper limit for the pulsar age. For an age of Cyg OB3 of 8 Myr (Uyanik et al. 2001) we estimate a progenitor mass of 21 to 37 M$_\odot$ (O6 to O9.5 on the main sequence, Schmidt-Kaler 1982).

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