Proper motion of the radio pulsar B1727−47 and its association with the supernova remnant RCW 114

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Abstract. We report preliminary results of the analysis of the proper motion of the bright radio pulsar B1727−47. Using archival Parkes timing data, as well as original and archival ATCA interferometry observations, we, for the first time, constrain the pulsar proper motion at the level of $148_{-11}^{+14}$ mas yr$^{-1}$. The backward extrapolation of the proper motion vector to the pulsar birth epoch points at the center of the Galactic supernova remnant RCW 114 suggesting the genuine association between the two objects. We discuss the implications of the association and argue that the distance to the system is less than 1 kpc. This value is at least two times lower than the dispersion measure distance estimates. This suggests that the existing Galaxy electron density models are incomplete in the direction to the pulsar.

1. Introduction
Identifying a pulsar (PSR) – supernova remnant (SNR) association leads to valuable conclusions on the properties of both components, such as distances, ages, evolution stages etc. Although there is a little doubt that each PSR was once born in a supernova explosion, only a few associations have been identified so far with high confidence (e.g., [1]). Even if the pulsar position projects on the remnant image, the probability is high that this is due to a chance coincidence [2]. Therefore each possible association should be considered in detail separately, and one of the strongest arguments can come from the measurement of the pulsar proper motion (p.m.) [3]. Here we accomplish this goal for PSR B1727−47 and SNR RCW 114.

2. PSR B1727−47 and its proper motion
PSR B1727−47 was among the first pulsars observed since the beginning of the Pulsar Era. It was discovered in 1968 with the Molonglo observatory [4] and is one of the brightest among the young (< 100 kyr) radio pulsars known. It has the period $P = 0.83$ s, the characteristic age $\tau \equiv P/(2\dot{P}) = 80$ kyr and the dispersion measure (DM) of 123 pc cm$^{-3}$. According to the widely-used NE2001 model of the Galactic electron density distribution [5], the DM-based distance to the pulsar is $D = 2.7$ kpc. However, the more recent model [1] places PSR B1727−47 as far as at 5.5 kpc.
Table 1. PSR B1727−47 p.m. obtained by various methods discussed in the text. CP – by comparing published positions; I – interferometry; T – from interglitch solutions; TN – TEMPONEST results; F – full combined solution. Cartesian components of the p.m. vector in RA (μα) and Dec. (μδ) directions and the total p.m. value μ are given.

|       | CP   | I     | T     | TN    | F     |
|-------|------|-------|-------|-------|-------|
| μα, mas yr⁻¹ | 63 ± 4 | 120 ± 9 | 65 ± 13 | 47 ± 14 | 73 ± 5 |
| μδ, mas yr⁻¹ | −92 ± 21 | −162 ± 34 | −224 ± 28 | −132 ± 37 | −127 ± 13 |
| μ, mas yr⁻¹   | 111 ± 18 | 202 ± 28 | 232 ± 27 | 141 ± 36 | 148 ± 11 |

Figure 1. PSR B1727−47 positions discussed in this work. We show relative offsets in RA (left) and Dec. (right) directions from an auxiliary reference point, whose J2000 coordinates are indicated. Open diamonds correspond to previously published positions [6, 7]. Other positions are obtained in this work. Blue squares: Parkes timing solutions for interglitch epochs; red points: ATCA interferometry positions. Dashed lines bracket the 68 per cent TEMPONEST credible region and black lines are the same for all the data are combined, see text for details.

To the best of our knowledge, despite a long observational history, the p.m. of PSR B1727−47 has never been reported. However, a comparison of the published positions (blue diamonds in figure 1) suggests that its p.m. is significant. The result of a simple linear fit to these data is given in the first column in table 1. At D = 2.7 kpc, the estimated p.m. value μCP = 111 ± 18 mas yr⁻¹ leads to a suspiciously large transverse velocity v⊥ = 1420 ± 230 km s⁻¹ (note that a typical 2D pulsar velocity is about 250 km s⁻¹ [8]). Thus the p.m. of PSR B1727−47 deserves a more detailed study. We have done this using Parkes timing and ATCA interferometry imaging data.

2.1. Parkes timing analysis
We used the processed timing data from the Parkes telescope archive¹. We selected the data obtained from Feb 1993 to Mar 2014. Detailed information on the observations and filterbank systems is described in [7]. For analysis we used 222 times of arrival (TOAs) spanning 21 yr in total (MJD range 49043–56740). For the timing analysis we used the TEMPO2 package [9]. The pulsar is known to be glitching. Four glitches have been already reported [7]. In more

¹ http://data.csiro.au
Figure 2. Hα image image of the RCW 114 field. The apparent radius of RCW 114 is about $2^\circ$. PSR B1727–47 position at the present epoch is marked by the circle, and the 68 per cent credibility region for the pulsar track extrapolated backwards is shown by dashed lines.

recent data we identified two new glitches, however the space limitations preclude us from the discussion of their parameters here. To measure the p.m., we first constructed timing solutions for seven inter-glitch periods in our data. The positions obtained in this way are shown in figure 1 with blue squares and the corresponding p.m. obtained from these positions is given in the ‘T’ column in table 1. The construction of the coherent solution for the full data span is complicated not only due to the presence of glitches but also because of the strong timing noise. To get rid of this, we employed the Bayesian TEMPONEST utility [10] which simultaneously optimizes the timing solution, glitches’ parameters and timing noise model. The obtained p.m. is given in the ‘TN’ column of table 1, and the resulting 68 per cent credibility pulsar track is shown in figure 1 within red dashed lines.

2.2. ATCA radio interferometry analysis
PSR B1727–47 was observed with ATCA in 2004–2005 (project C1323) and in 2011 November (project C2566). For the C1323 observations, we used the data set obtained on 2005 March 26, as this session provides sufficient uv-coverage for accurate position measurements. The details of the array configurations and correlator modes can be found in the ATCA archive. The data were processed and analyzed in a standard way using the MIRIAD package [11]. The measured pulsar positions revealed a significant shift between the epochs in a direction compatible with the timing measurements (figure 1). To verify that the shift is not caused by some systematic effects, we performed observations (project CX367) of the pulsar with ATCA on 2016 September 15 using Director’s time. All ATCA positions are shown in figure 1 with red dots, and the corresponding p.m. values are given in the ‘I’ column in table 1.

The interferometric and timing observations give qualitatively similar results. Taking the weighted mean of all the data (namely, ATCA positions, older published positions and TEMPONEST results) we obtain our final result given in the last column in table 1. The corresponding pulsar track uncertainty is constrained in figure 1 within black lines at 68 per cent credibility level.

3. Supernova remnant RCW 114
The backward extrapolation of the measured p.m. vector to the PSR B1727–47 birth epoch (using $\tau = 80$ kyr; the trajectory distortion due to effect of Galactic potential is negligible for this age) points roughly at the center of the nearby Hα nebula RCW 114, also known as SNR G343.0–6.0 [12] (figure 2). This strongly suggests a genuine association between the two objects and independently constrains the system age at $\sim 60 - 80$ kyr. The SNR nature of RCW 114 is supported by a recent discovery of C[IV] emission from the nebula [13]. This detection also
allowed to place an upper limit on the distance to SNR, $D_{\text{SNR}} \lesssim 1$ kpc [13]. On the other hand, detailed spectroscopic analysis of the stars projected on RCW 114 suggests $D_{\text{SNR}} > 0.5$ kpc [14]. The distance range of $0.5 - 1$ kpc is plausible if the SNR is at the snowplough stage [15]. Using expressions from [15] for typical explosion energy of $10^{51}$ erg, ambient density of $\sim 1$ cm$^{-3}$ and $D_{\text{SNR}} = 0.7$ kpc, we estimated the expansion velocity of 96 km s$^{-1}$, which is in accord with the velocity of the faint outer filament of $-80$ km s$^{-1}$ reported in [16].

4. Conclusions

- Based on radio timing and interferometric observations, we find the proper motion of PSR B1727–47 of $148 \pm 11$ mas yr$^{-1}$. For the DM-based distance of 2.7 kpc (5.5 kpc) it leads to extremely high $v_\perp \approx 1900$ km s$^{-1}$ (3900 km s$^{-1}$).
- The proper motion vector points at the center of the SNR RCW 114, suggesting SNR–PSR association. In this case the most plausible distance to the system is $\sim 0.7$ kpc and the p.m.-based age is 60 – 80 kyr, compatible with the pulsar characteristic age. The relatively low distance value can be checked independently by the parallax measurements with very long baseline interferometry.
- Assuming $D = 0.7$ kpc, we find $v_\perp \approx 500$ km s$^{-1}$, which is well in line with the 2D pulsar velocity distribution [8]. This result suggests that the existing models of the electron density in the Galaxy require some tuning in the direction to PSR B1727–47. For instance, inclusion of a nearby ‘clump’ of enhanced electron density [5] in the model can reconcile the high DM value and the low distance inferred here.

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