Birth Rate of Millisecond Pulsars

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SIR – the characteristic ages of millisecond pulsars are determined from their spin–down rates, but these might not be good estimates of their true ages. We recently reported\(^1\) the discovery of a millisecond binary pulsar (J1012+5307), and the tentative identification of the companion (star X) as a white dwarf. Here we present optical colours and astrometry that confirm star X as the pulsar’s companion, and that it is a white dwarf. The cooling age of the white dwarf is only \(\sim300\) million years, which is an order of magnitude less than the pulsar’s characteristic age. If characteristic ages are generally in error by this amount, the birth rate of millisecond pulsars must be much greater than previously estimated.

The field containing PSR J1012+5307 and star X (see Fig. 2 of ref. 1) was observed on 1994 October 21 and 1995 January 1 during staff time at the Nordic Optical Telescope (NOT), on 1995 January 22 during service time on the Jacobus Kapteyn Telescope (JKT) and 1995 February 3 during staff time at the Schmidt telescope at the Kivistberg observatory. With \(\sim1\) arcsec seeing, we obtained 300 s exposures in B, V, R and I filters on the NOT, 1000 s in V, R and I on the JKT and 3600 s in R at the Schmidt telescope. Photometry for star X was obtained from the NOT data on using the curve of growth technique\(^2\) in the PHOT package within IRAF. We found that \(V=19.58 \pm 0.02, \ B-V=0.20 \pm 0.04, \ V-R=0.09 \pm 0.03\) and \(V-I=0.26 \pm 0.03\). Given the galactic coordinates of J1012+5307 \((l = 160^\circ, b = 51^\circ)\), any reddening effects on these data are negligible.\(^3\)

From the JKT and Schmidt data, using PPM guide star positions, the position of star X at this epoch was found to be R.A.(2000.0)\(=10^h 12^m 33^s.41(5), \ Dec(2000.0)=53^\circ 07^\prime 02^\prime\prime.7(4)\). Further radio observations of PSR J1012+5307 with the 76-m Lovell Telescope as described before\(^1\) have resulted in significant improvements in the accuracy of the position of the pulsar and its period derivative and its orbital elements (see Table 1). Together, these data show a position difference between PSR
J1012+5307 and star X of only 0.2 ± 0.5 arcsec for epochs less than one year apart, making the identification almost certain, given the low stellar density in the field.\textsuperscript{1}

We obtain an upper limit of 33 mas yr\textsuperscript{-1} for the proper motion of star X from this new position and that obtained by Nicastro \textit{et al.}\textsuperscript{1} from the Palomar Sky Survey taken almost 40 yr earlier. At the distance of 520 pc inferred from the dispersion measure of J1012+5307, this implies a transverse speed ≤ 75 km s\textsuperscript{-1} at 520 pc. The pulsar exhibits strong interstellar scintillation, allowing us to obtain a rough estimate of the transverse speed of the binary system. Using standard analysis techniques,\textsuperscript{4} we estimate this to be ∼ 50 km s\textsuperscript{-1}, consistent with the upper limit for star X. Since a transverse speed gives rise to an overestimate of the true period derivative\textsuperscript{5} of Δ\dot{P} = P\dot{v}^2/cd, we find that a better estimate of the intrinsic characteristic age τ = P/2\dot{P} of PSR J1012+5307 is 7 Gyr.

The B–V, V–R and V–I colours of star X are all consistent with a black–body temperature of 9400 ± 300 K. Adopting the mass–radius relation of Savonije\textsuperscript{6}, we estimate the luminosity of a 0.15 M\odot white dwarf at this temperature to be ∼ 4.2 × 10\textsuperscript{-3} L\odot. At a distance of 520 pc, this implies a visual magnitude of 19.3, in good agreement with the observed value. Thus both the colour and magnitude of star X are consistent with it being a 9400 K white dwarf star.

Taking the luminosity \( L_\star = 4.2 \times 10^{-3} \, L_\odot \) from the cooling curve of Iben & Tutukov\textsuperscript{7}, we estimate the age of star X to be ∼ 300 Myr – more than a factor of 20 below the characteristic age of J1012+5307. Given the strong evidence in favour of the association, and the relatively small separation of the binary pair ( ∼ 0.3 R\odot) it is possible that the discrepancy between the observed and predicted luminosities is due to the heating of star X by the spin–down energy loss of J1012+5307. However, a simple calculation shows that this provides only a minor contribution (∼ \( 10^{-2}L_\star \)) to the stellar luminosity. The discrepancy is surely due to the system being much younger than the pulsar characteristic age, implying that the initial spin period of J1012+5307 was similar to the presently observed value.\textsuperscript{8} On much larger time–scales similar, but less certain, discrepancies have been noted\textsuperscript{9–11} for the millisecond pulsar J0437–1715 and the anomalously high characteristic ages of some galactic disk millisecond pulsars which exceed the age of the Galaxy.\textsuperscript{8}

This identification underlines the possible substantial overestimate of the ages of millisecond pulsars by use of their characteristic ages. If this is generally true, we note that the birth rate required to sustain the observed galactic population will be much greater than previous calculations\textsuperscript{12} have suggested.
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| R.A. (J2000) | 10$^h$ 12$^m$ 33$^s$.4326(4) |
| Dec. (J2000) | 53°07′02″.66(1) |
| Period, P | 0.00525574901198(2) s |
| Dispersion measure, DM | 9.0207(4) cm$^{-3}$ pc |
| Epoch of period (MJD) | 49220.0 |
| Observed Period derivative, $\dot{P}$ | 1.46(8) × 10$^{-20}$ |
| Orbital period, $P_b$ | 0.604672713(5) days |
| Semi-major axis, $a_p \sin i$ | 0.581816(6) light-s |
| Eccentricity, $e$ | < 2 × 10$^{-5}$ |
| Epoch of ascending node (MJD) | 49220.447499(1) |

**Table 1.** The radio timing solution of PSR J1012+5307. Figures in parenthesis represent twice the standard errors in the last quoted digit, inferred from a formal fit to the data.