A radio pulsar-B star binary in the small magellanic cloud

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ABSTRACT

We report the discovery of regular Doppler shifts of the pulse period of PSR J0045–7319, the only known pulsar in the Small Magellanic Cloud. The pulsar is in a highly eccentric 51-day orbit with a companion star of mass greater than 4M_S. Optical observations in the direction of the pulsar reveal a 16th magnitude B star companion. The PSR J0045–7319 system is likely an X-ray binary progenitor.

1. INTRODUCTION

The discovery of PSR B1259–63 (Johnston et al 1992) provided the first example of a radio pulsar in a binary system with a non-degenerate companion. PSR J0045–7319 (PSR B0042–73) was discovered in a search of the Magellanic Clouds for radio pulsars (McConnell et al 1991). It is the only known pulsar in the Small Magellanic Cloud (SMC), and has a pulse period of 0.926 s. Although it is a faint source, its large distance makes it the most luminous binary radio pulsar known. The pulse profile is a single peak of duty cycle 4%, typical of most pulsars. Its association with the SMC is assured by its dispersion measure DM≈105 pc cm$^{-3}$, since models of the galactic electron distribution account for no more than $\sim$25 pc cm$^{-3}$ along that line of sight (Taylor & Cordes 1993).
296 A Radio Pulsar-B Star Binary

Fig. 1. (a) Period and (b) flux density at 430 MHz vs. orbital phase.

2. OBSERVATIONS AND RESULTS

We have monitored PSR J0045−7319 on a regular basis from 1991 February through 1993 July using the 64-m radio telescope at Parkes. Of the 103 successful observations, 101 were obtained at 430 MHz, with the other two at 660 MHz. Barycentric periods derived from the individual observations are shown in Figure 1a as a function of orbital phase; the curve shown is for the binary orbit parameters given in Table 1. The mass function is given by

$$f(M_p) = \frac{(M_c \sin i)^3}{(M_p + M_c)^2} = \frac{4\pi^2 (a_p \sin i)^3}{GP_b^2} = 2.17 M_\odot,$$

where $M_p$ and $M_c$ are the pulsar and companion masses, $i$ is the orbital inclination angle, and the other quantities are defined in Table 1. This is the largest mass function known for a binary radio pulsar. Assuming $M_p = 1.4 M_\odot$, the minimum companion mass, corresponding to $i = 90^\circ$, is $3.97 M_\odot$.

We obtained CCD images of the PSR J0045−7319 field using the Australian National University 2.3-m telescope which reveal a star at the J2000 position $\alpha = 00^h 45^m 35.3^s \pm 0.4^s$, $\delta = -73^\circ 19' 01.9'' \pm 1.1''$, consistent within uncertainties with that of the pulsar, having V magnitude 16.19 and B magnitude 16.03. Allowing for the range of possible reddening of the SMC, we obtain $-0.28 < (B-V)_o < -0.22$ for the intrinsic color. At the distance of the SMC, the star has an absolute V-magnitude of $-3.2 < M_V < -2.6$. We also obtained a low-resolution optical spectrum of the candidate under the service spectroscopy program of the Anglo-Australian Telescope and with the ANU 2.3-m. The observed Balmer jump and weak helium lines show that the star is a main sequence star of spectral class B1. Combined with the photometry, this implies a mass for the companion of $10.0 - 12.5 M_\odot$. No emission lines are evident in the spectrum. Since the probability of chance occurrence of such a star at the pulsar position is small, we conclude that this star is the companion to PSR J0045−7319.
Right Ascension, \( \alpha \) (J2000) & 00^h 45^m 34.9^s \pm 0.2^s \\
Declination, \( \delta \) (J2000) & -73° 19' 03.2" \pm 0.8" \\
Dispersion Measure, DM & 105.4(7) pc cm\(^{-3}\) \\
R.M.S. timing residual & 7.4 ms \\
Mean flux density at 400 MHz & 0.8 mJy \\
Luminosity at 400 MHz & 2800 mJy kpc\(^2\) \\
Period, \( P \) & 0.926758349(1) s \\
Period Derivative, \( \dot{P} \) & 4.465(7) \times 10^{-15} \\
Epoch of Period & MJD 48964.2000 \\
Orbital Period, \( P_o \) & 51.16926(2) days \\
Projected semi-major axis, \( a_s \sin i \) & 174.235(2) lt s \\
Longitude of periastron, \( \omega \) & 115.236(2)° \\
Eccentricity, \( \epsilon \) & 0.80798(1) \\
Epoch of Periastron & MJD 49220.3817(1) \\
Magnetic field strength, \( B \) & 2.1 \times 10^{12} G \\
Characteristic age, \( \tau_c \) & 3.3 \times 10^6 yr \\

Table 1. Observed and Derived Parameters for PSR J0045–7319.

3. DISCUSSION

At periastron, the distance between the pulsar and the companion is \( a_p(1-e)(1+M_p/M_c) < 19/\sin i R_\odot \), for \( M_p = 1.4M_\odot \). For a 10\( M_\odot \) companion, the inclination angle \( i = 41° \), so that at periastron the pulsar approaches to within \( \sim 6 \) stellar radii of the companion. The radio signal from the pulsar might be expected to be dispersed, scattered, or absorbed by the companion’s ionized mass outflow, effects that would vary with orbital phase. However, thus far, we have observed no systematic variations in dispersion measure within our measurement uncertainty; our \( 3\sigma \) upper limit is 3.2 pc cm\(^{-3}\). This limit implies that the mass-loss rate is \( < 8 \times 10^{-12} v_0 M_\odot \) yr\(^{-1}\), where \( v_0 \) is the stellar surface wind velocity in units of 100 km s\(^{-1}\). This is somewhat lower than expected for an isolated B star (de Jager et al 1988).

We observe no obvious systematic variation in the intensity of the pulsed emission with orbital phase (Figure 1b). The pulsar’s signal was detected at periastron and at superior conjunction. During several observations, the pulsar was not detected at all; the corresponding orbital phases are indicated by crosses in Figure 1. The absence of regular radio eclipses implies that the neutron star does not accrete matter at periastron. The non-detections may indicate occasional B-star mass outflow enhancements on time scales of a few days. Much of the observed variation is likely to be due to scintillation in the inhomogeneous interstellar plasma.

The proximity of the pulsar to the companion at periastron is expected to result in an advance of the line of apsides. We observe a marginally significant value for the advance: \( \dot{\omega} = 0.010 \pm 0.003 \) yr\(^{-1}\). From standard expressions for the precession and for apsidal constants (Claret & Gimenez 1991; Will 1993) and using standard assumptions, our observed \( 3\sigma \) upper limit of 0.019° yr\(^{-1}\) to \( \dot{\omega} \) implies that the B star must have mass of less than \( \sim 8M_\odot \). This is somewhat less than the mass estimated from the spectral type; this requires further
A Radio Pulsar-B Star Binary

investigation.

The characteristic age of the pulsar, given by $P/2\dot{P} = 3.3 \times 10^6$ yr, suggests that it has not been spun up by accretion. The system likely formed with the initially more massive star evolving first and explosively collapsing to form the neutron star (van den Heuvel 1992). If we assume the explosion was symmetric and that less than half the total mass was ejected, the pulsar progenitor mass is given by

$$M_{\text{pre}} = (1 + c)(M_c + M_p) - M_c$$

(Gott 1972). Equation 2 implies $M_{\text{pre}} \approx M_c$, which is large for a pre-supernova mass. If the pre-supernova mass were smaller than this, then the system may have remained bound in spite of mass ejection because of an asymmetric explosion having imparted a velocity kick.

The PSR J0045-7319 system represents the second eccentric radio pulsar—non-degenerate companion binary system after the PSR B1259-63 system, and together, they constitute a new class of young binary radio pulsar systems. These systems are likely X-ray binary progenitors since, as the companion evolves, it will expand and overflow its Roche lobe, transferring matter onto the neutron star. As the mass transfer continues, a common envelope will form, and frictional drag will shrink the orbit. If it becomes sufficiently small, complete spiral-in and a "Thornc-Żytkow" object (Thornc & Żytkow 1977), a red supergiant with a neutron-star core, may be formed. Alternatively, the envelope may be ejected before spiral-in is complete. In that case, the companion will evolve either to a massive white dwarf, or to a second neutron star.

A measurement of orbital Doppler shifts in the B-star's absorption lines would verify the association, and determine the mass ratio of the system components. A velocity curve for the companion to a radio pulsar has never before been detectable.

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REFERENCES