THE ASTROPHYSICAL JOURNAL, 423:L43–L45, 1994 March 1

A MASSIVE RADIO PULSAR BINARY IN THE SMALL MAGELLANIC CLOUD

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Received 1993 November 8; accepted 1993 December 13

ABSTRACT

We have discovered regular Doppler shifts of the pulse period of PSR J0045−7319, the only known pulsar in the Small Magellanic Cloud. These indicate that the pulsar is in a highly eccentric 51 day orbit with a companion star of mass greater than 4 $M_\odot$. No regular eclipses of the pulsed signal are observed. Optical observations in the direction of the pulsar reveal a 16th magnitude B star, which we conclude is the pulsar's companion. Timing observations imply that this pulsar has not been spun up by accretion from the companion, suggesting that, like the PSR B1259−63 binary system, the PSR J0045−7319 system is a progenitor of an X-ray binary system.

Subject headings: binaries: general — Magellanic Clouds — pulsars: individual: PSR J0045−7319

1. INTRODUCTION

In some X-ray binary systems, a massive star, evolved to the point of overflowing its Roche lobe, transfers matter onto a neutron star companion, which results in the emission of X-rays. Before such systems enter the mass accretion phase, it seems plausible that the neutron star might be detectable as a radio pulsar. The discovery of PSR B1259−63 (Johnston et al. 1992) provided the first example of a radio pulsar in a binary system with a nondegenerate companion, thereby confirming this hypothesis. The hint of an eclipse near periastron in the PSR B1259−63 system suggested that only the most eccentric systems of its type would be detectable, since otherwise the pulsar's radio signal would be absorbed, scattered, or dispersed by mass outflow from the companion for significant fractions of the orbit.

PSR J0045−7319 (PSR B0042−73) was discovered in a systematic 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, having flux density at 430 MHz of only ~1 mJy, 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 $\simeq$ 105 pc cm^{-3}, since models of the galactic electron distribution account for no more that ~25 pc cm^{-3} along that line of sight (Taylor & Cordes 1993).

As part of a large, continuing radio pulsar timing project undertaken at the 64 m radio telescope at Parkes, Australia, we have made timing observations of PSR J0045−7319, as well as of the three Large Magellanic Cloud pulsars discovered by McConnell et al. (1991). The latter three were found to be isolated and unremarkable, aside from having high intrinsic luminosities (Kaspi 1993). We report here on PSR J0045−7319, which we found to be in a highly eccentric binary orbit with a main-sequence star.

2. OBSERVATIONS AND RESULTS

We have monitored PSR J0045−7319 on a regular basis from 1991 February 8 through 1993 July 17 using the 64 m radio telescope at Parkes. Of the 103 successful observations, 101 were obtained at a radio frequency of 430 MHz using a 2 × 256 × 0.125 MHz filter-bank spectrometer, while two were obtained at 660 MHz using a 2 × 128 × 0.25 MHz spectrometer. The detected signals were sampled at either 1.2 or 4.8 ms and written to magnetic tape. Typical observation times were 30 minutes. The sampled data were folded synchronously at the topocentric pulse period, and the resulting profiles were convolved with a standard template to yield arrival times with uncertainties in the range 1–9 ms.

The timing analysis was carried out using the standard TEMPO software package (Taylor & Weisberg 1989) and the JPL DE200 solar system ephemeris (Standish 1982), giving the pulsar position, dispersion measure, spin, and orbital parameters listed in Table 1, in which the bracketed numbers are the 1 σ uncertainties in the last digit quoted, and i is the angle between the planes of the orbit and the sky. Residual times of arrival after the timing model has been subtracted appear featureless, both as a function of time and orbital phase. Barycentric periods derived from the individual 30 minute observations are shown in Figure 1*a* as a function of orbital phase; the curve shown is for the binary orbit parameters given in Table 1.

For a Keplerian binary orbit, the mass function is a useful quantity which provides information on the mass of the system:

$$f(M_p) = \frac{(M_c \sin i)^3}{(M_p + M_c)^2} = \frac{4\pi^2 (a_p \sin i)^3}{G P_b^2} = 2.17\ M_\odot\ , \qquad (1)$$

where M_p and M_c are the pulsar and companion masses, and the other quantities are defined in Table 1. This is the largest mass function known for a binary radio pulsar. Assuming

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TABLE 1

PARAMETERS FOR PSR J0045 − 7319

Right Ascension, α (J2000)	$00^{h}45^{m}34\overset{s}{.}9 \pm 0\overset{s}{.}2$
Declination, δ (J2000)	$-73^{\circ}19'03\overset{''}{.}2 \pm 0\overset{''}{.}8$
Dispersion measure, DM	105.4(7) pc cm^{-3}
Period, P	0.9262758349(1) s
Period derivative, $\dot{P}$	$4.465(7) \times 10^{-5}$
Epoch of period	MJD 48964.2000
Orbital period, P_b	51.16926(2) days
Projected semimajor axis, $a_p \sin i$	174.235(2) lt s
Longitude of periastron, ω	115.236(2)°
Eccentricity, e	0.80798(1)
Epoch of periastron	MJD 49220.3817(1)
rms timing residual	7.4 ms
Mean flux density at 400 MHz	0.8 mJy
Mass function	2.16905(8) $M_{\odot}$
Magnetic field strength, B	2.1×10^{12} G
Characteristic age, τ_c	3.3×10^{6} yr

$M_p = 1.4\ M_{\odot}$, 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 on 1993 January 20 and 1993 August 20. The images reveal a star at the J2000 position $\alpha = 00^{h}45^{m}35\overset{s}{.}3 \pm 0\overset{s}{.}4$, $\delta = -73^{\circ}19'01\overset{''}{.}9 \pm 1\overset{''}{.}1$, consistent within the 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 $-0.28 < (B-V)_0 < -0.22$ for the intrinsic color. For a distance modulus 18.8 ± 0.3, 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 on 1993 June 21, and with the ANU 2.3 m on 1993 August 20. 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. The radial velocity of 167 ± 40 km s^{-1} agrees with the nominal radial velocity of the SMC of 165 km s^{-1}. Since the probability of chance occurrence of such a star at the pulsar position is small, even in the SMC, we conclude that this star is the companion to PSR J0045 − 7319.

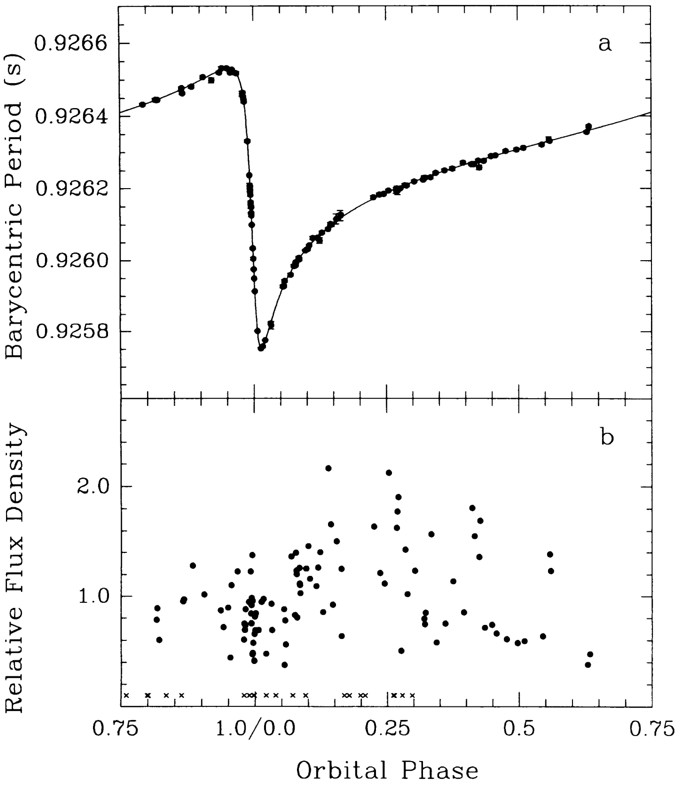

FIG. 1.—(a) Barycentric period and (b) relative flux density at 430 MHz as functions of orbital phase. The period uncertainties are shown but are typically smaller than the points, while the flux uncertainties, ~0.2 on this scale, are omitted for clarity. Periastron is defined to occur at orbital phase 0.0; superior conjunction is at orbital phase 0.995. Orbital phases of nondetections of the pulsar are indicated by crosses.

3. DISCUSSION

At periastron, the distance between the pulsar and the companion is $a_p(1-e)(1+M_p/M_c) \lesssim 19/\sin i\ R_{\odot}$, for $M_p = 1.4\ M_{\odot}$. For a 10 $M_{\odot}$ companion, the inclination angle $i = 41^{\circ}$, so that at periastron the pulsar approaches to within ~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 σ upper limit is 3.2 pc cm^{-3}. Assuming a 10 $M_{\odot}$ companion and mass loss in the form of an ionized wind whose density decreases as the square of the radial distance from the stellar surface, this limit implies that the mass-loss rate is $\lesssim 1 \times 10^{-11} v_0\ M_{\odot}$ 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, Nieuwenhuijzen, & van der Hucht 1988); the presence of the pulsar should, if anything, enhance the outflow.

We also observe no obvious systematic variation in the intensity of the pulsed emission with orbital phase (Fig. 1b). The pulsar's signal was clearly detected at periastron and at superior conjunction, which occurs 5.5 hr before periastron. The flux density around the two epochs of periastron we observed was somewhat lower than average, but it has been even lower at epochs away from periastron. During several observations, the pulsar was not detected at all; the corresponding orbital phases are indicated by crosses in the figure. Although they all fall within the half of the orbit closest to periastron, that is also where most of the observations have been made. The absence of regular radio eclipses implies that the neutron star does not accrete matter at periastron. The nondetections may, however, indicate occasional B-star mass outflow enhancements on timescales of a few days. Much of the observed variation is likely to be due to scintillation in the inhomogeneous interstellar plasma, either in our Galaxy or in the SMC.

The proximity of the pulsar to the companion at periastron is expected to leave a significant dynamical signature, in the form of an apsidal advance. In other words, the longitude of periastron is expected to precess because of the deviation of the companion's gravitational field from the inverse square law because of tidal deformation by the pulsar. Our timing analysis of PSR J0045 − 7319 yields a marginally significant value for the periastron advance: $\dot{\omega} = 0\overset{\circ}{.}010 \pm 0\overset{\circ}{.}003$ yr^{-1}. From standard expressions for the precession and for apsidal constants (Claret & Gimenez 1991; Will 1993), and assuming that the

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companion's angular velocity is synchronized to the orbital motion at periastron and that the spin axis is perpendicular to the orbital plane, our observed 3 σ upper limit of $0\overset{\circ}{.}019\ \mathrm{yr}^{-1}$ to $\dot{\omega}$ implies that the B star must have mass of less than $\sim 8\ M_\odot$. This is somewhat less than the mass estimated from the spectral type. This suggests that the assumption of synchronization may be incorrect, that the angular momentum of the companion may have a finite projection on the orbital plane, or that the apsidal constants are overestimated. More detailed modeling of the system including nonequilibrium effects should prove interesting.

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 from its companion, and so its evolutionary history is clear (van den Heuvel 1992): the initially more massive star in the system evolved first and collapsed to form the neutron star, generating a supernova explosion. If we assume the explosion was symmetric and that less than half the total mass was ejected, the pulsar progenitor mass is given by

$$M_{\mathrm{pre}} = (1 + e)(M_c + M_p) - M_c \qquad (2)$$

(Gott 1972). For a companion mass $M_c = 10\ M_\odot$ and a pulsar mass $M_p = 1.4\ M_\odot$, Equation (2) implies $M_{\mathrm{pre}} \approx M_c$, which is large for a presupernova mass. If the presupernova 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 (Johnston et al. 1992). The system may well have a high runaway velocity (Blaauw 1961), though at the distance of the SMC, even a transverse velocity of 1000 km s^{-1} would result in a proper motion of under 5 mas yr^{-1}, which would be difficult to observe.

The PSR J0045−7319 system represents the second eccentric radio pulsar-nondegenerate companion binary system after the PSR B1259−63 system, and together they constitute a new class of young binary radio pulsar systems. Like PSR B1259−63, the PSR 70045−7319 system is a likely X-ray binary progenitor since, as the companion evolves, it will eventually expand and overflow its Roche lobe, transferring matter onto the neutron star. As the mass transfer continues, a common envelope will form, and the large frictional drag will shrink the orbit. If it becomes sufficiently small, complete spiral-in and a "Thorne-Żytkow" object (Thorne & 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, leaving a system similar to PSR B0655+64, or to a second neutron star, leaving either a bound system like PSR B1913+16, or two isolated neutron stars.

A measurement of orbital Doppler shifts in the B-star's absorption lines would unambiguously 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. For a 10 $M_\odot$ companion and assuming a 1.4 $M_\odot$ pulsar, the maximum fractional wavelength shift is $\sim 10^{-4}$ and should be measurable.

V. M. K. received support from a Natural Sciences and Engineering Research Council of Canada 1967 Fellowship and from an NSF Grant for US-Australia Collaborative Research. J. F. B. acknowledges an Australian Government Postgraduate Research Award and V. M. K. and J. F. B. acknowledge help from the ATNF student program. We thank J. Glowacki, S. Magri, D. Lorimer, and L. Nicastro for help with the radio observations, and the Anglo-Australian Observatory for their help with the optical spectroscopy.

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