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PERIOD EVOLUTION OF PSR B1259−63: EVIDENCE FOR PROPELLER-TORQUE SPINDOWN

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ABSTRACT

PSR B1259−63 has a pulse period of 47.7 ms and is in a highly eccentric 3.5 yr orbit around the Be star SS 2883. Timing observations of this pulsar, made over a 4.8 yr interval using the Parkes radio telescope, cover two periastron passages, in 1990 August, and 1994 January. The timing data cannot be fitted by the normal pulsar and Keplerian binary parameters but are well fitted by a model which includes pulsar spin-down episodes at each periastron. The most likely explanation is that the pulsar is interacting with the circumstellar disk of SS 2883 via the propeller mechanism.

Subject headings: accretion — astrometry — binaries: eclipsing — pulsars: individual (PSR B1259−63)

1. INTRODUCTION

The binary pulsar PSR B1259−63 is a unique system. Discovered at Parkes in a survey of the Galactic plane at 1.5 GHz (Johnston et al. 1992a), it was shown by Johnston et al. (1992b) to be in a highly eccentric 3.5 yr orbit around a 10th magnitude Be star, SS 2883. The pulsar period P is relatively short, 47.7 ms, and the measured period derivative gives a pulsar characteristic age, $\tau_c = P/(2\dot{P})$, of 3.3×10^5 yr and a surface magnetic field, $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$, of 3.3×10^{11} G. This therefore is a young system, which may evolve through an accretion phase to form a single or binary millisecond pulsar. Rapidly spinning neutron stars can only accrete matter if the co-rotation velocity at the Alfvén radius is less than the Keplerian velocity at the same radius (Bhattacharya & van den Heuvel 1991). Equality of these velocities defines the "spin-up line." At present, PSR B1259−63 lies well to the left of the spin-up line, so that accretion onto the neutron star is not possible until either the pulsar slows down or the pulsar magnetic field decays. The pulsar has a highly polarized double-peaked pulse profile with the two peaks separated by ~140° of longitude (Manchester & Johnston 1995).

Timing observations of PSR B1259−63, made over a 3.4 yr interval and covering the 1990 August periastron, were reported by Johnston et al. (1994). A phase-connected fit to these data gave accurate parameters for the pulsar and its orbit, and showed that the next periastron would occur on 1994 January 9. This paper also reported optical observations which indicate that the companion star is of spectral type B2e, with a mass of $M_* \sim 10\ M_\odot$ and radius $R_* \sim 6\ R_\odot$. This mass implies an orbital inclination $i \sim 35°$. The orbital eccentricity is very high, 0.87, and for sin $i \sim 0.5$, the pulsar approaches within 25 R_* of the companion star at periastron, passing through the circumstellar disk. Observations at the first observed periastron showed that the pulsar was eclipsed at radio frequencies ~1.5 GHz (Johnston et al. 1992b). Interactions at periastron between the pulsar and the emission-line disk were discussed by Kochanek (1993). In particular, "propeller" torques may result in spin-down of the pulsar during the periastron passage (Illarionov & Sunyaev 1975; Ghosh & Lamb 1979; Ghosh 1995).

In this Letter we report timing observations made using the Parkes radio telescope over a 4.8 yr interval covering both the 1990 and 1994 periastron passages and discuss their interpretation. Extensive observations of the pulsar were made at several radio frequencies before and after the 1994 January periastron, in order to probe the circumstellar environment of SS 2883. These observations and their interpretation are discussed by Johnston et al. (1995) and Melatos, Johnston, & Melrose (1995).

2. OBSERVATIONS AND ANALYSIS

A total of 259 pulse times of arrival (TOAs) were measured in 58 separate sessions at the Parkes radio telescope between 1990 January and 1994 October. Most of the observations were at frequencies around 1.5 GHz, but observations at 0.43, 0.66, 4.7, and 8.3 GHz are also included. At all frequencies, dual-channel cryogenically cooled systems receiving orthogonal linear polarizations were used. After conversion to an intermediate frequency, signals for each polarization were split into subbands using filterbanks with channel widths of 0.125 or 0.25 MHz for frequencies below 1 GHz, and 5 MHz for higher frequencies. Signals from corresponding filter polarization pairs were detected, summed, high-pass filtered and one-bit digitized, usually with a sampling interval of 0.6 ms. Further details of the observing systems are given by Johnston et al. (1995).

The data were folded at the topocentric period to form mean pulse profiles which were then convolved with a template to give TOAs. Integration times for each TOA were typically 10 minutes at 1.5 GHz, and 20–30 minutes at other frequencies, giving TOA uncertainties of $\lesssim 100\ \mu$s. Pulsar and binary parameters were obtained using the least-squares fitting program TEMPO (Taylor & Weisberg 1989) with the Jet Propulsion Laboratory solar-system ephemeris DE200. To investigate possible spin-up or spin-down of the pulsar at periastron, TEMPO was enhanced to include period-step terms in the least-squares fit. As discussed by Johnston et al. (1995), significant dispersion and scattering changes were observed around

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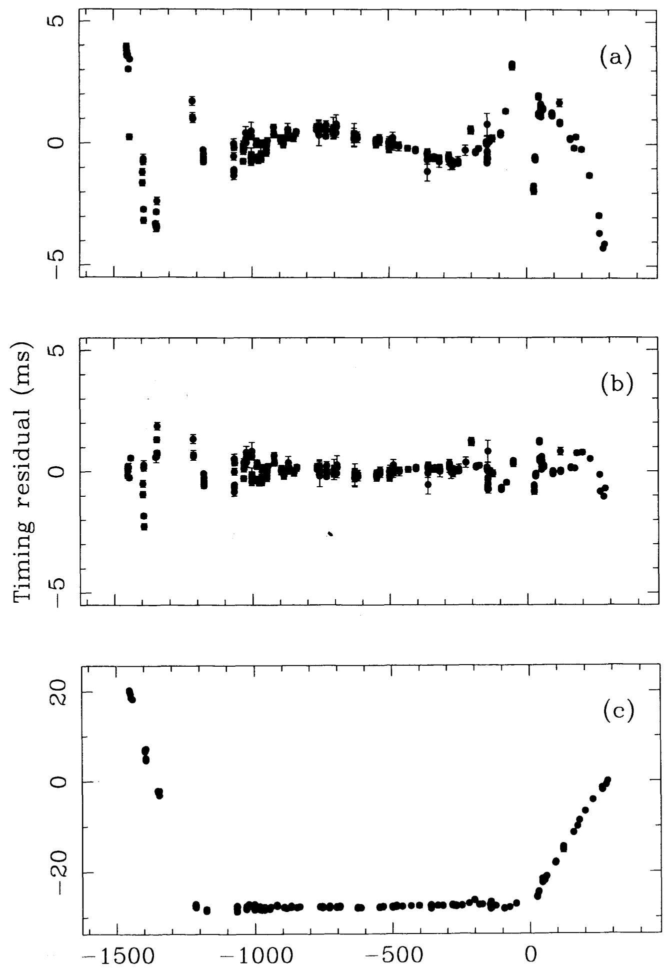

FIG. 1.—Timing residuals for PSR B1259−63. (*a*) Postfit residuals after solving for pulsar and binary parameters but not changes in pulsar period at periastron. (*b*) Postfit residuals after solving for pulsar and binary parameters including period steps at the two periastrons. (*c*) Prefit residuals corresponding to solution (*b*) showing the effect of the steps in period at periastron.

TABLE 1

TIMING PARAMETERS FOR PSR B1259−63

Parameter	Value
Right ascension (J2000)	$13^h02^m47^s.68$
Declination (J2000)	$-63°50'08''.6$
Pulsar Period, P	47.762053542 (8) ms
Period derivative	$2.27579\ (16) \times 10^{-15}$
Epoch of period	MJD 48053.440
Dispersion measure	146.72 (3) cm^{-3} pc
Data span	MJD 47909–49643
Root mean square residual	0.47 ms
Orbital period, P_b	1236.72359 (5) days
Projected semimajor axis, $a \sin i$	1296.580 (2) light s
Longitude of periastron, ω	$138°.6782$ (2)
Eccentricity, e	0.869931 (1)
Epoch of Periastron, T_0	MJD 48124.3448 (1)
$\Delta P/P$ at MJD 48124.3	$(+2.6 \pm 0.3) \times 10^{-9}$
$\Delta P/P$ at MJD 49361.2	$(+1.1 \pm 0.3) \times 10^{-9}$

periastron. Because of this, data from 1990 July and 1993 December were omitted from the analysis. The pulsar was eclipsed during 1994 January.

3. RESULTS

The data were first fitted for pulsar period, period derivative, dispersion measure, and the five Keplerian orbital parameters giving the postfit residuals shown in Figure 1*a*. The pulsar position derived by Johnston et al. (1994), which coincides with the optical position, was assumed. Systematic variations in residuals are observed at all orbital phases, showing that this set of parameters does not satisfactorily model the timing behavior of the system.

Figure 1*b* shows postfit residuals after inclusion in the model of step changes in the pulsar period at the two periastrons. This model produces a much better fit to the data. Near the first periastron (day −1237), residuals are somewhat larger than average, probably owing to unmodeled dispersion or scattering changes. It is not possible to quantify these since the few available observations were at a single frequency, 1.5 GHz. Overall, though, the fit is excellent. Inserting ± 1 turns of residual phase at either periastron passage and repeating the fitting process increases the rms postfit residual by more than a factor of 3. Furthermore, the solution predicts well. A fit to all data up to 1994 August predicted the phases for data taken in 1994 September and October to better than 0.05 periods. We are therefore confident that there are no pulse-counting errors and that this solution is a good representation of the timing behavior. To illustrate the effect of the period steps, Figure 1*c* shows prefit residuals with the steps omitted from the model. Parameters from the final solution are listed in Table 1. Figures in parentheses are errors in the last quoted digit, being twice the rms values given by TEMPO. For epochs after a period step, ΔP should be added to the period given in Table 1.

Inclusion of data from 1993 August to 1994 October and the period steps in the model has changed the pulsar and binary parameters from those quoted by Johnston et al. (1994) by several times the uncertainties quoted in that paper. The new values have substantially smaller uncertainties because of the longer data span and better fit. However, the final rms residual remains significantly higher than the estimated TOA uncertainty. This may be due in part to dispersion or scattering changes as mentioned above, but period irregularities are expected in a young pulsar such as this (Cordes & Downs 1985), and these probably account for the excess rms residual.

4. DISCUSSION

There are two possible origins of the apparent pulsar period changes at periastron—perturbations to the orbital parameters or perturbations to the pulsar period. Orbital perturbations could arise from frictional drag as the pulsar passes through the circumstellar disk, quadrupolar effects resulting from the oblateness of the Be star, or tidal effects on the Be star. A fit to dispersion measure changes around the 1994 January periastron (Johnston et al. 1995) suggests that the radial dependence of the electron density in the circumstellar disk of SS 2883 has the form

$$n_e(r) \sim 4.5 \times 10^{12} (r/R_*)^{-4.2}\ \mathrm{cm}^{-3}\ . \qquad (1)$$

Assuming a hydrogen plasma, this corresponds to a mass density $\rho_p \sim 10^{-17}$ g cm^{-3} at the periastron distance $r_p \sim 25R_*$. Following Kochanek (1993), we assume that the radius within which matter is captured by the pulsar is given by the

Bondi (1952) relation

$$r_{\rm acc} = GM/v^2 , \qquad (2)$$

where M is the mass of the pulsar and v is its velocity relative to the surrounding medium. The pulsar has an orbital velocity at periastron of ~ 75 km s^{-1} but the radial velocity of the wind at this radius is not well determined. If we take $v = 500$ km s^{-1} as a representative terminal velocity (Waters 1986), then $r_{\rm acc} \sim 8 \times 10^{10}$ cm. The effective interaction time is uncertain, not least because of possible misallignment between the pulsar orbit and the disk. However, the pulsar is close to the periastron distance for ~ 20 days, and in this time it could accrete $\Delta M \sim 2 \times 10^{19}$ g. The frictional drag due to this accretion produces a fractional change in orbital energy of order $\Delta M/M \sim 10^{-14}$ which is negligible.

The periastron advance per orbit due to the oblateness of the Be star is given by

$$\Delta\omega = \frac{k_2(q+1)P_b^2\Omega_*^2}{2\pi(1-e^2)^2}\left(\frac{R_*}{a}\right)^5 , \qquad (3)$$

where k_2 is the apsidal constant, $q = M_p/M_*$, and Ω_* is the angular rotation frequency of the Be star (Will 1993). For a 10 $M_\odot$ star, $k_2 \sim 0.002$ (Claret & Gimenez 1991). Even if we take $\Omega_* R_*$ equal to the Keplerian velocity at the surface of the star, $\Delta\omega \sim 0\overset{\circ}{.}001$, two orders of magnitude too small to account for the observed perturbation. Furthermore, simulation of the effect using TEMPO shows that it produces a phase drift of sign opposite to that observed.

Orbital perturbations due to tidal effects are not very well understood, especially in the present case of a very eccentric and long-period system. One possibility is that orbital energy is transferred into non-radial oscillations of the star (Press & Teukolsky 1977). This gives fractional changes in orbital period

$$\frac{\Delta P_b}{P_b} \sim \frac{3}{2}\frac{\Delta a}{a} \sim 3\,\frac{a}{R_*}\frac{M}{M_*}\left(\frac{R_*}{r}\right)^6 T_2(\eta) , \qquad (4)$$

where T_2 is a dimensionless variable describing energy transfer into the second-order oscillation mode and

$$\eta^2 = \frac{M_*}{M + M_*}\left(\frac{r}{R_*}\right)^3 \qquad (5)$$

(Kochanek 1993). For $r = r_p$, we find that $\eta \sim 120$, $T_2 \sim 6 \times 10^{-6}$ and $\Delta P_b/P_b \sim 2 \times 10^{-12}$. Other processes (e.g., Zahn 1977; Tassoul 1990) predict comparable or smaller perturbations.

TEMPO simulations show that phase changes such as those shown in Figure 1*c* require changes in orbital parameters at periastron of order 10^{-5}, much larger than those predicted above. Furthermore, such changes have phase signatures which show significant curvature over 200 days or so, in contrast to the essentially linear changes shown in Figure 1*c*. Changes of this magnitude would also lead to rapid evolution of the system, which cannot be ruled out, but is unlikely.

Accreted matter cannot reach the neutron star, but can interact with the pulsar at the Alfvén radius, slowing the pulsar down via the so-called "propeller" effect (Illarionov & Sunyaev 1975; King & Cominsky 1994). To estimate the magnitude of this slowdown, we assume that the infalling matter carries no angular momentum. Since the wind density is relatively low, the effective Alfvén surface is at the light cylinder. For the accretion mass derived above (2×10^{19} g), the fractional change in pulse period $\Delta P/P$ is found to be $\sim 10^{-9}$, very close to the changes observed at the two periastron passages (Table 1). We conclude, therefore, that the observed phase changes following each periastron are due to propeller spin-down, the first such observation for a radio pulsar.

The accretion luminosity of this material, assuming that it falls to the light cylinder over 20 days or so, is $\lesssim 10^{31}$ ergs s^{-1}, too low to be detected by current X-ray observatories.

As Table 1 shows, the fractional spindown in 1990 August was about twice as large as that in 1994 January. This shows that the wind density and/or velocity at the periastron distance varied between 1990 and 1994. It is worth mentioning that, over timescales much greater than the orbital period, these spin-down episodes result in an effective period derivative about four orders of magnitude smaller than the period derivative due to electromagnetic torques.

For propeller spin-down to occur, the bow shock at the interface between the pulsar and stellar winds must occur inside the accretion radius (Kochanek 1993; Tavani, Arons, & Kaspi 1994). The standoff distance of the bow shock from the pulsar, r_s, is given by

$$r_s^2 = \frac{\epsilon_c \dot{E}}{4\pi c \rho_p v^2} , \qquad (6)$$

where ϵ_c is the conversion efficiency of spin-down luminosity $\dot{E}$ to wind luminosity (Kulkarni & Hester 1988). Taking the values given above for ρ_p and v, and $\dot{E} = 8 \times 10^{35}$ ergs s^{-1} (Taylor, Manchester, & Lyne 1993), we get $r_s \sim 10^{13}\epsilon_c^{1/2}$ cm. For $r_s < r_{\rm acc}$, we require $\epsilon_c \lesssim 10^{-4}$. Studies of bow-shock nebulae around other pulsars (Kulkarni & Hester 1988; Cordes, Romani, & Lundgren 1993) give results consistent with $\epsilon_c \sim 1$. If the expansion velocity of the emission-line gas is less than we have assumed, the relative velocity of the pulsar with respect to the gas could be quite small at periastron, thereby increasing $r_{\rm acc}$. Furthermore, the gas density has a strong radial gradient (eq. [1]), so the bow shock would be significantly deformed, which may allow accretion to occur. Detailed modeling of the interaction is necessary to establish realistic limits on ϵ_c.

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