THE ASTROPHYSICAL JOURNAL, 409:L57–L60, 1993 June 1

A YOUNG, GLITCHING PULSAR NEAR THE DIRECTION OF W28

V. M. KASPI,[1] A. G. LYNE,[2] R. N. MANCHESTER,[3,1] S. JOHNSTON,[3] N. D'AMICO,[4] AND S. L. SHEMAR[2]
Received 1993 January 20; accepted 1993 March 16

ABSTRACT

Timing observations of PSR B1758−23 (PSR J1801−23) made over a 6 yr period using the 64 m Parkes radio telescope and the 76 m Lovell radio telescope show that this pulsar is young and is located close to the edge of the supernova remnant W28. The pulsar's characteristic age of 58,000 yr is consistent with the estimated remnant age, but the large observed dispersion of the pulsar signal is difficult to reconcile with the independently estimated remnant distance. PSR B1758−23 has glitched three times during our observations, in keeping with the trend of high glitch activity in younger pulsars.

Subject headings: pulsars: individual (PSR B1758−23) — supernova remnants — ISM: individual (W28)

1. INTRODUCTION

PSR B1758−23 was discovered in a search for short-period pulsars directed at various galactic objects including W28 (Manchester, D'Amico, & Tuohy 1985). During the search, a large grid of positions was observed in order to map the error circle of the gamma-ray source 2CG 006−00, which overlaps with W28. The pulsar's dispersion measure (DM) of 1074 pc cm^{-3} is the largest known for any pulsar. Using the Taylor & Cordes (1993) model, the implied distance to the pulsar is ~13.5 kpc, which places it beyond the center of the Galaxy. The large discrepancy between the derived pulsar distance and the previously estimated distance to the remnant of approximately 2 kpc, together with the relatively long pulsar period of 0.42 s, led Manchester et al. (1985) to suspect that PSR B1758−23 is most likely neither particularly young, nor associated with either W28 or 2CG 006−00. The positional coincidence may be due to chance superposition in a region where the surface density of both pulsars and supernova remnants (SNRs) is high.

The radio source W28 lies in a confused region of the Sagittarius spiral arm in the Galactic plane. Among the members of the W28 complex are two extended H II regions commonly known as the Lagoon and Trifid nebulae (M8 and M20), several young star clusters, a molecular cloud, and a prominent 45′ diameter SNR (see Hartl et al. 1983 and references therein). While the various objects may be superposed on the sky by chance, it is likely that they are associated and are interacting with one another, with the SNR expanding and impacting on neighboring clouds (Wooten 1981; Hartl et al. 1983).

Our recent timing observations of PSR 1758−23 reveal that its characteristic age is 58,000 yr. The pulsar has glitched three times in the duration of our observations. We report here on our timing observations and discuss the possibility that the pulsar and the supernova remnant are associated. We also discuss this pulsar's glitch activity in the context of the trend noted by McKenna & Lyne (1990) of actively glitching "adolescent" pulsars.

[1] Joseph Henry Laboratories and Physics Department, Princeton University, Princeton, NJ 08544.

[2] University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, SK11 9DL, UK.

[3] Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 2121, Australia.

[4] Istituto di Fisica dell'Università di Palermo and Istituto di Radioastronomia del CNR, Bologna, Italy.

2. OBSERVATIONS AND RESULTS

Using the 64 m Parkes radio telescope, we have made timing observations of PSR B1758−23 at a central observing frequency of 1520 MHz. A total of 54 observations in 31 separate sessions were made from 1990 January through 1992 December using an observing system and analysis procedure described elsewhere (e.g., Manchester et al. 1991; Kaspi et al. 1992). We also observed PSR B1758−23 at Jodrell Bank using the 76 m Lovell radio telescope at radio frequencies between 1400 and 1660 MHz. At Jodrell Bank, 70 arrival times were obtained in the period from 1986 September through 1992 January.

Data at both observatories were folded at the apparent pulse period, and arrival times were obtained by convolution of the pulses with standard pulse profiles. The two sets of arrival times were combined, and rotation and position parameters were obtained using the program TEMPO with the JPL DE200 barycentric ephemeris. A time offset accounting for differential instrumental delays and different standard templates was removed from the data in the timing analysis.

The pulse profile at 1520 MHz is shown in Figure 1. It is clearly dominated by a truncated exponential, typical of profiles which have suffered heavy multipath scattering in the interstellar medium. Observations of this pulsar at lower radio frequencies are hampered by severe pulse broadening since the truncated exponential decay time varies as $\nu^{-4.4}$, where ν is the observing frequency (Cordes, Weisberg, & Boriakoff 1985).

From the timing data, it is clear that the pulsar has a large period derivative and has suffered three period glitches during our observations. In Table 1 we present spin parameters for four intervals surrounding the three glitches. Uncertainties quoted are twice the formal standard deviations. For the periods, the error is given in units of the last digit quoted. Timing positions and DMs determined from the arrival times in the glitch-free intervals before and after the second and third glitches agree to within the uncertainties reported. We quote the mean values as the pulsar position and DM. There were insufficient data to determine a position from the observations before the first glitch. Spin parameters were obtained for all four glitch-free intervals by using the mean position and DM held fixed. Figure 2 shows the timing position of the pulsar with respect to the SNR. The large uncertainty in declination is due to the proximity of the pulsar to the plane of the ecliptic. The characteristic age τ_c and the surface magnetic field

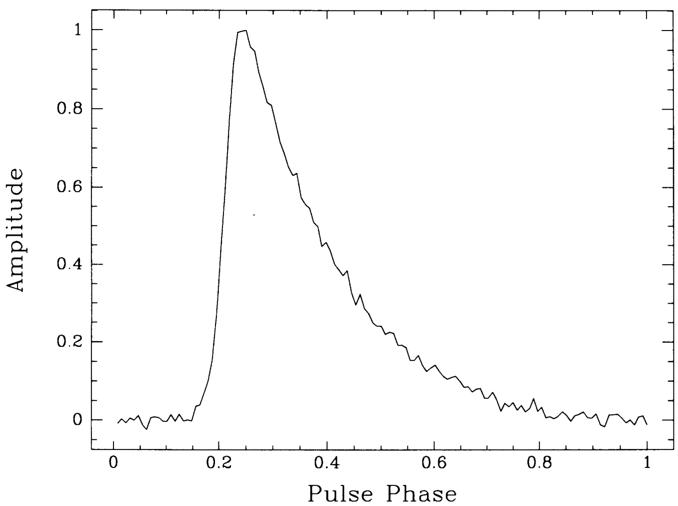

FIG. 1.—Pulse profile of PSR B1758−23 at 1520 MHz

strength B given in Table 1 were obtained using the standard formulae

$$\tau_c = P/2\dot{P} \quad (1)$$

and

$$B = 3.2 \times 10^{19}(P\dot{P})^{1/2}G\,, \quad (2)$$

where P is the pulse period and $\dot{P}$ is the period derivative (Manchester & Taylor 1977).

TABLE 1

SPIN-DOWN AND GLITCH PARAMETERS FOR PSR B1758−23

Parameter	Value
Right ascension (J2000)	$18^h01^m19^s.859 \pm 0^s.058$
Declination (J2000)	$-23°06'17'' \pm 102''$
Right ascension (B1950)	$17^h58^m17^s.592$
Declination (B1950)	$-23°06'16''$
Dispersion measure	1074 ± 6 pc cm^{-3}
Mean flux density at 1520 MHz	6.5 ± 1.8 mJy
Characteristic age	58,000 yr
Surface magnetic field strength	6.9×10^{12} G
MJD range/Number of observations	46693 − 46864/7
Period (s)	0.41575769(1)
Period derivative	$113.1 \pm 0.3 \times 10^{-15}$
Period epoch (MJD)	46800
RMS phase residual (ms)	5.8
Glitch $\Delta P/P$	$(2.0 \pm 0.3) \times 10^{-7}$
MJD range/Number of observations	46950 − 47806/25
Period (s)	0.41576347334(2)
Period derivative	$112.981 \pm 0.002 \times 10^{-15}$
Period epoch (MJD)	47400.00
RMS phase residual (ms)	2.4
Glitch $\Delta P/P$	$(2.312 \pm 0.009) \times 10^{-7}$
MJD range/Number of observations	47904 − 48444/43
Period (s)	0.41577175274(3)
Period derivative	$112.983 \pm 0.004 \times 10^{-15}$
Period epoch (MJD)	48258.00
RMS phase residual (ms)	2.2
Glitch $\Delta P/P$	$(3.4768 \pm 0.0008) \times 10^{-7}$
MJD range/Number of observations	48464 − 48957/49
Period (s)	0.41577551288(2)
Period derivative	$112.983 \pm 0.003 \times 10^{-15}$
Period epoch (MJD)	48658.00
RMS phase residual (ms)	1.7

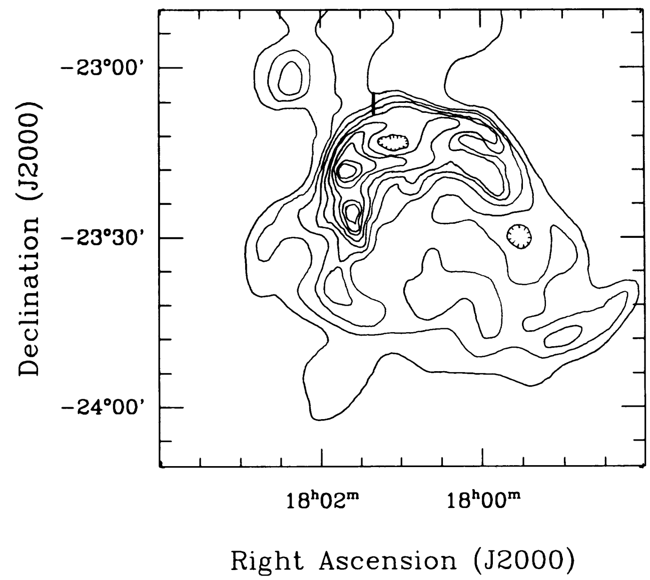

FIG. 2.—Radio image of W28 at 408 MHz (after Shaver & Goss 1970) with the position of PSR B1758−23 indicated. The first contour is at brightness temperature 300 K above absolute zero, and contours are drawn at 200 K intervals.

Also in Table 1 are parameters describing the observed glitches. The three glitches are comparable and moderate in magnitude. Post-glitch relaxation effects may have contaminated the fitted and period derivatives, but they cannot be distinguished because of infrequent sampling. The $\Delta P/P$ values are for the center of the interval between the adjacent sets of preglitch and post-glitch arrival times and were found by extrapolation; the quoted errors include a contribution due to the uncertainty in glitch epoch. From the data reported here, the glitch activity parameter, defined by McKenna & Lyne (1990) to be the mean fractional period change per year, is $\sim 10^{-7}$ yr^{-1}, or about one-eighth that for the Vela pulsar. Such frequent glitches will most likely preclude measurement of the pulsar proper motion from timing observations.

3. DISCUSSION

3.1. *PSR B1758−23 and the W28 Supernova Remnant*

With a young pulsar in near positional coincidence with an SNR of similar age, the possibility that the two objects are associated must be considered. For an association to be plausible once positional coincidence on the sky has been established, it must be shown that the pulsar and SNR are at the same distance, and that their ages are consistent.

First, we consider the pulsar and SNR distances. Distances to pulsars are generally determined using the observed DM, together with a model for the Galactic free electron distribution. For a DM of 1074 pc cm^{-3}, the Taylor & Cordes (1993) electron distribution model yields a distance of 13.5 kpc for PSR B1758−23. In their paper Taylor & Cordes state that typical distance errors are no larger than $\sim 30\%$, with no dependence on Galactic longitude apart from pulsars along the line of sight to the Gum Nebula ($l = 260°$); for a 30% uncertainty, upper and lower bounds on the distance are 9.5 and 16.5 kpc.

The remnant distance has been estimated using a variety of methods. Many authors have used the Σ-D relation to derive distances near ~ 2 kpc (Milne 1970; Clark & Caswell 1976; Goudis 1976; Milne 1979). Green (1991) has shown that this

SNR distance-determination method is extremely uncertain and not reliable as a distance estimator for any one particular remnant, mainly because observational selection effects are responsible for the apparent paucity of small-diameter SNRs with low surface brightness. Indeed, from the scatter in the Σ-D plot in Figure 1 of Green (1991), we find that distances anywhere between 0.6 and 2.8 kpc are consistent with the relation. The upper limit of 2.8 kpc is more reliable, however, since the dearth of high-surface-brightness, large-diameter SNRs cannot be attributed to selection effects. Other distance measurements to the W28 SNR are based on its likely associations with various neighboring objects (Allakhverdiyev et al. 1983; Hartl et al. 1983) and yield estimates that are consistent with ~ 2 kpc. We adopt 2 kpc as the distance to the remnant for the remainder of this *Letter*, but we note that the uncertainty may be as high as 50%. Though the uncertainty is large, there is little possibility that the remnant is at a distance close to the lowest estimates for PSR B1758−23 based on its DM.

We now compare the ages of the pulsar and SNR. The characteristic age τ_c of 58,000 yr is an upper limit to the pulsar's true age (Manchester & Taylor 1977). The age of the remnant, on the other hand, is more difficult to determine. Assuming a distance to the remnant and using an observed expansion velocity, the age t_4 of the remnant (in units of 10^4 yr) can be estimated using theoretical models for SNR evolution in the interstellar medium. The SNR stage of evolution determines the dependence of the age on observed parameters: for the adiabatic expansion phase (also known as the Sedov phase), the radius r of the remnant is given by

$$r = KVt_4 \text{ pc} , \tag{3}$$

where V is the expansion velocity in km s^{-1} and $K = 0.0256$. In the later radiative-cooling stage, the same expression holds, but with $K = 0.0359$ (Shull & Silk 1979 and references therein). The present expansion velocity of the W28 SNR has been measured to be 40–50 km s^{-1} (Lozinskaya 1973). If the SNR is in the Sedov phase, for $V = 45$ km s^{-1}, its age is $\sim 100{,}000$ yr. If it is in the radiative-cooling phase, the age is $\sim 72{,}000$ yr. These ages of course have large uncertainties; for a distance uncertainty of 50%, the range of possible ages for the Sedov case is 50,000–150,000 yr, while for the radiative-cooling phase, it is 35,000–110,000 yr. Further uncertainty in the age results from the unusually cluttered surroundings of the expanding shell. Regardless of the evolutionary stage, therefore, the ages of the pulsar and remnant are consistent within the large uncertainties.

If we assume the pulsar is as old as τ_c and that it was born at the center of the W28 SNR, its transverse velocity must be approximately 200 km s^{-1}, which is typical of the pulsar population. Furthermore, the morphology of the remnant by itself led Shull, Fesen, & Saken (1989) to suggest the association between the W28 remnant and PSR B1758−23. Thus, the association would be quite plausible were it not for the enormous DM-distance discrepancy.

With such complexity and so many H II regions in the neighborhood of the W28 SNR, it might be possible for one to lie along the line of sight to PSR B1758−23 and to account for the large observed DM. The Taylor & Cordes (1993) model of the Galactic electron distribution predicts a DM of approximately 100 pc cm^{-3} for a pulsar in the direction of PSR B1758−23 at a distance of 2 kpc. For $\mathrm{DM_{PSR}} - \mathrm{DM_{ISM}} \approx 970$ pc cm^{-3}, a cloud dimension of a few pc implies an electron density of a few hundred per cm^{-3}. The optical depth due to free-free radiation in the Raleigh-Jeans approximation is given by

$$\tau_\nu = 8.2 \times 10^{-2} T_e^{-1.35} \nu^{-2.1} \int n_e^2 \, dl , \tag{4}$$

where T_e is the electron temperature in K, the frequency ν in GHz, and $\int n_e^2 \, dl$ is in pc cm^{-6} (Altenhoff et al. 1960). The optical depth is 1.4 at 408 MHz, assuming $T_e = 5000$ K, a cloud size of 20 pc, and a clumping factor of 5. Such a cloud would have an angular extent of $\sim 35'$ at 2 kpc, and its observed brightness toward a clump should be ~ 3800 K, which is greater than the observed brightness temperature of 600–1200 K in the direction of the pulsar (Shaver & Goss 1970). Increasing the clumping factor increases the predicted brightness temperature, but increasing the size of the dispersing region or the electron temperature decreases it.

Very energetic electrons associated with the remnant, excited by shock-heating for example, may contribute to the excess DM without adding significantly to the continuum background. However, to be consistent with the Shaver & Goss (1970) map, the dimension of a cloud of electrons with temperature 100,000 K must be greater than ~ 50 pc for a clumping factor of 5. So large a cloud having such high temperature seems implausible, especially since its total energy must be over 10^{51} ergs. A compact or ultracompact H II region of dimension less than ~ 0.5 pc, such as those discussed by Habing & Israel (1979), lying along the line of sight to the pulsar could account for the enormous DM and would not be obvious on the Shaver & Goss map because of beam dilution, since it would be much smaller than their beam. However, the probability of such a chance alignment is small. Compact H II regions, being signatures of star formation, are rarely isolated and are often located near more evolved H II regions, or close to near-IR continuum/OH maser sources. If a compact H II region were the source of the high DM, it might be associated with M20, although the distance from the edge of M20 to the pulsar is at least ~ 5 pc. (Ultra)compact H II regions have been detected in the region of W28, although more than a degree away (Habing & Israel 1979).

We conclude that this association is possible but not probable. Some emission may be hidden by baseline offsets in existing maps. More sensitive maps of the region around the pulsar, especially using short spacings to detect large structures such as an extended foreground H II region, might clarify the situation. Similarly, high-resolution maps in the direction of PSR B1758−23 might detect or rule out a compact H II region. Were this pulsar-SNR association one day proven, it would be among the oldest known.

In principle, it may be possible to use refractive scintillation to verify that the pulsar is indeed at 13.5 kpc rather than closer, since the time scale for flux density variations is proportional to $d^{1/2}$ where d is the distance (Kaspi & Stinebring 1992). Our flux density calibration is not precise enough to enable us to extract anything but rough flux estimates. At 13.5 kpc, the predicted refractive time scale is many years, and well-calibrated flux density measurements at intervals of a few hundred days over a period of several years are likely to be required in order to measure variations.

3.2. *PSR B1758−23 and Glitches*

McKenna & Lyne (1990) noted an apparent trend that "adolescent" pulsars, that is, pulsars with characteristic ages greater than ~ 200 yr but much younger than the average pulsar ($\tau_c \sim 10^6$ yr), have more frequent large glitches than either their younger or older counterparts. PSR B1758−23, along with PSR J1341−6220 which has τ_c = 12,000 yr (Kaspi et al. 1992), are new additions to the list of "adolescent," multiply-glitching pulsars and therefore agree well with this trend. PSR B1758−23 and PSR J1341−6220 are only the third and fourth pulsars known to have suffered more than two large glitches (Lyne 1992).

The observed characteristics of glitches are well described by a vortex pinning model (Alpar et al. 1984). In this model, vortex lines in the neutron superfluid slowly migrate outward as the pulsar cools and spins down. Since they become pinned to nuclei in the neutron star crustal lattice, their attempted expansion is hindered, and the superfluid cannot spin down as rapidly as the crustal lattice. A differential angular velocity from superfluid to crust develops, and stresses on the lattice eventually strain it beyond its elastic yield limit. Sudden crustal cracking may then occur, resulting in an outward motion of that region of crust, including the vortex lines that were previously pinned to the local nuclei. The angular velocity differential is suddenly removed and the crust recoils by spinning up, which is observed as a sudden decrease in the pulse period. In the context of this model, the prevalence of glitches in young pulsars is because of their higher rates of spin-down, and the observed paucity of glitches in the very youngest pulsars (PSRs B0531+21, B1509+58 and B0540−69) is explained by their presumably higher temperatures, which allow a smoother, more plastic reaction to the built-up stresses, rather than a brittle, sudden cracking response.

Ruderman (1991) predicts the glitch activity parameter should vary inversely as the pulsar characteristic age. The observed activity parameter for PSR B1758−23 of $\sim 10^{-7}$ yr^{-1} is approximately consistent with this scaling when compared to other young pulsars for which glitches have been observed (see Table 2 in McKenna & Lyne 1990). However, the activity parameter is strongly dependent on the length of time during which timing observations have been made compared to the time between glitches, and so this agreement is still tentative. The continuing discovery of glitches in pulsars, along with the continued monitoring of pulsars known to have glitched, will help constrain parameters of glitch models, thereby providing important information on the structure of neutron stars.

We thank J. Dickel and T. Phillips for their careful reading of the manuscript and for useful comments. V. M. K. thanks the Natural Sciences and Engineering Research Council of Canada and the NSF for support.

REFERENCES

Allakhverdiyev, A. O., Amnuel, P. R., Guseinov, O. H., & Kasumov, F. K. 1983, Ap&SS, 97, 261
Alpar, M. A., Anderson, P. W., Pines, D., & Shaham, J. 1984, ApJ, 276, 325
Altenhoff, W., Mezger, P. G., Strassl, H., Wendker, H., & Westerhout, G. 1960, Veroff. Sternw., 59, 48
Clark, D. H., & Caswell, J. L. 1976, MNRAS, 174, 267
Cordes, J. M., Weisberg, J. M., & Boriakoff, V. 1985, ApJ, 288, 221
Goudis, C. 1976, Ap&SS, 40, 91
Green, D. A. 1991, PASP, 103, 209
Habing, H. J., & Israel, F. P. 1979, ARA&A, 17, 345
Hartl, H., Malin, D. F., MacGillivray, H. T., & Zealey, W. J. 1983, Ap. Lett., 23, 193
Kaspi, V. M., Manchester, R. N., Johnston, S., Lyne, A. G., & D'Amico, N. 1992, ApJ, 399, L155
Kaspi, V. M., & Stinebring, D. R. 1992, ApJ, 392, 530
Lozinskaya, T. 1973, Soviet Astron., 17, 603
Lyne, A. G. 1992, Phil. Trans. R. Soc. Lond. A, 341, 29
Manchester, R. N., D'Amico, N., & Tuohy, I. R. 1985, MNRAS, 212, 975
Manchester, R. N., Kaspi, V. M., Johnston, S., Lyne, A. G., & D'Amico, N. 1991, MNRAS, 253, 7P
Manchester, R. N., & Taylor, J. H. 1977, Pulsars (San Francisco: Freeman)
McKenna, J., & Lyne, A. G. 1990, Nature, 343, 349
Milne, D. K. 1970, Australian J. Phys., 23, 425
———. 1979, Australian J. Phys., 32, 83
Ruderman, M. 1991, ApJ, 366, 261
Shaver, P. A., & Goss, W. M. 1970, Australian J. Phys. Astr. Supp., 14, 77
Shull, J. M., Fesen, R. A., & Saken, J. M. 1989, ApJ, 346, 860
Shull, J. M., & Silk, J. 1979, ApJ, 234, 427
Taylor, J. H., & Cordes, J. M. 1993, ApJ, in press
Wootten, A. 1981, ApJ, 245, 105