THE ASTROPHYSICAL JOURNAL, 422:L83–L86, 1994 February 20

ON THE SPIN-DOWN OF PSR B1509−58

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Received 1993 September 24; accepted accepted 1993 December 7

ABSTRACT

The pulsar PSR B1509−58 is associated with the supernova remnant G320.4−1.2 (MSH 15−52) and has the largest pulse period derivative and the second smallest characteristic age after the Crab pulsar. Although PSR B1509−58 is the second youngest known pulsar, it has not glitched during an 11 yr data span and shows little timing noise, permitting an accurate study of its slowdown. We have measured its braking index to be $n = 2.837 \pm 0.001$ and its frequency third derivative to be $\dddot{\nu} = (-1.02 \pm 0.25) \times 10^{-31}$ s^{-4}. The third derivative is consistent with the value expected for a constant braking index and magnetic moment, although we cannot rule out models in which these quantities vary.

Subject headings: pulsars: individual (PSR B1509−58)

1. INTRODUCTION

Radio pulsars are powered by their rotational kinetic energy and lose energy by emitting electromagnetic radiation at the rotation frequency and by accelerating particle winds, so that their rotation frequency decreases with time. The slowdown may be described by the relation

$$\dot{\nu} = -K\nu^n \, , \tag{1}$$

where n is the first deceleration parameter or braking index, K is a positive constant that depends on the magnetic dipole moment and moment of inertia of the rotating neutron star, and ν is the rotation frequency. For the standard model in which the spin-down torque results from particle acceleration in a dipole magnetic field or dipole radiation at the rotation frequency, $n = 3$ (Manchester & Taylor 1977). The braking index may be obtained in terms of observables by differentiating equation (1):

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2} \, . \tag{2}$$

Differentiating equation (1) again results in an expression for the expected frequency third derivative,

$$\dddot{\nu} = \frac{n(2n-1)\dot{\nu}^3}{\nu^2} \, . \tag{3}$$

This can be expressed differently: a second deceleration parameter m can be defined in analogy with n to be

$$m = \frac{\nu^2\dddot{\nu}}{\dot{\nu}^3} \, . \tag{4}$$

A measurement of m provides a check on the spin-down law since, according to equation (3), $m = n(2n-1)$. Thus, the measurement of the third derivative is useful because it constrains the nature of possible deviations from the simple spin-down law (Blandford & Romani 1988).

The spin-down model predicts that the magnitude of the frequency derivative decreases with time. A stable value for the frequency second derivative has been measured for only the three youngest pulsars, and the implied braking indexes are all somewhat less than the expected value of 3. Lyne, Pritchard, & Smith (1988) measured 2.509 ± 0.001 for the Crab pulsar; Manchester, Durdin, & Newton (1985) measured 2.83 ± 0.03 for PSR B1509−58; and Manchester & Peterson (1989), as well as Nagase et al. (1990), measured 2.02 ± 0.01 for PSR B0540−69.

Stable braking indexes for the vast majority of pulsars are impossible to measure because random variations in pulse arrival times ("timing noise"), sudden increases in rotation frequency ("glitches"), and measurement uncertainties usually dominate the relatively small values of the second derivative due to slowdown. Indeed, most frequency second derivatives reported in the literature were shown to be manifestations of long-term timing noise rather than systematic behavior expected from the simple dipole braking (Cordes & Helfand 1980). Symptoms of measurements of random processes are the following: the magnitude of the second derivative depends on the length of the data span; the ephemeris including the second derivative does not predict arrival times accurately; the magnitude of the rms phase residual decreases only slightly when the second derivative is fitted; the resulting second derivative does not necessarily have the expected sign; and sizes of the resulting braking indexes can be orders of magnitude larger than those predicted by theory.

Frequency third derivatives are evidently likely to be measurable for only the very youngest pulsars. For constant K and n, the predicted $\dddot{\nu}$ for the Crab pulsar is -6.15×10^{-31} s^{-4}. Lyne, Pritchard, & Smith (1993) showed that their timing observations were consistent with that value, although several glitches during their data span precluded a measurement from absolute pulse numbering. In fact, glitches and timing noise in the rotation of the Crab pulsar may never allow a precise measurement of its frequency third derivative. By contrast, no evidence for glitches or significant timing noise has been seen for PSR B1509−58 (Manchester et al. 1985), and so it is an excellent candidate for measurement of a stable third derivative to compare with the predicted value of -0.9338×10^{-31} s^{-4} given by equation (3).

PSR B1509−58 was initially detected at X-ray energies (Seward & Harnden 1982) and subsequently at radio fre-

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1994ApJ...422L..83K

quencies (Manchester, Tuohy, & D'Amico 1982). It is thought to be associated with the supernova remnant G320.4−1.2 (MSH 15−52), although the estimated age of the remnant is much greater than the characteristic age of the pulsar and the association has been considered somewhat controversial (Seward et al. 1983; van den Bergh & Kamper 1984). Recently, Thorsett (1992) suggested that PSR B1509−58 and G320.4−1.2 are the remnants of a supernova witnessed by Chinese astronomers in AD 185. Such a young pulsar provides an opportunity to study the physics of the slowdown process, which is critical in assessing its age and hence determining its origin.

2. OBSERVATIONS AND RESULTS

From 1982 June 24 through 1988 June 23, PSR B1509−58 was observed at the Molonglo Radio Observatory using the Molonglo synthesis telescope (MOST) in total-power mode, at an observing frequency of 843 MHz. Details of the observing system used for the observations are given in Manchester et al. (1985). The detected signal was sampled at 2 ms intervals and integrated synchronously with the apparent pulse period, resulting in a pulse profile that was subsequently cross-correlated with a template to yield a topocentric arrival time for each observation. A total of 176 such observations were made in 78 separate sessions, with integration times in the range of 3000 to 4000 s. The resulting profiles had typical signal-to-noise ratios of 10.

More recent observations of PSR B1509−58 were made using the Parkes 64 m radio telescope at a central observing frequency of 1520 MHz. A total of 72 observations in 35 sessions were made from 1990 March 15 through 1993 June 21, using a cryogenically cooled dual-channel system that received orthogonal linear polarizations. After down-conversion to an intermediate frequency, the two polarization channels were filtered in a 2 × 64 × 5 MHz filter bank and detected. After the polarizations were summed, the 64 signals were integrated and one-bit sampled every 1.2 ms and recorded on magnetic tape. The typical observing time was 1200 s. The data were folded at the apparent pulse period, yielding profiles having signal-to-noise ratios of ~20. In addition, the Parkes data include two observations at 2480 MHz made on 1990 March 16 during a session in which 1520 MHz data were also obtained. As with the Molonglo data, each profile provided a single effective arrival time by cross-correlation with a template. The Parkes observations are part of a larger, continuing project to provide up-to-date parameters for approximately 150 pulsars to the users of the *Compton Gamma-Ray Observatory* (Kaspi 1993; Johnston et al. 1993). These data have recently made possible the detection of PSR B1509−58 at low gamma-ray energies (Ulmer et al. 1993).

The topocentric arrival times for both sets of data were combined and fitted using the TEMPO software package (Taylor & Weisberg 1989) in conjunction with the DE200 planetary ephemeris (Standish 1982). We allowed for a constant time offset between the two data sets, but found it to be consistent with zero; this is as expected since the MOST and Parkes pulse templates were essentially identical. We determined the pulsar dispersion measure using only the dual-frequency data taken during the 1990 March observing session at Parkes. The value is consistent with that used by Kawai et al. (1991), which was obtained from the same data, and was held fixed for the remainder of the timing analysis. We determined the pulsar position by simultaneously fitting for many higher frequency derivatives ("prewhitening") to render the residuals random. Once determined in this way, the position was not varied during the subsequent fit for the spin parameters. The fitted values are given in Table 1, in which numbers in brackets represent the uncertainties in the last digit quoted. The pulsar position is consistent with that determined by Manchester et al. (1985), and there is no indication of a significant pulsar proper motion, with 3 σ upper limits of $\mu_\alpha < 110$ mas yr^{-1} and $\mu_\delta < 190$ mas yr^{-1}.

TABLE 1

TIMING PARAMETERS FOR PSR B1509−58

Right Ascension, α (J2000)	15h 13m 55.62s ± 0.09s
Declination, δ (J2000)	−59° 08′ 09.0″ ± 1.0″
Right Ascension, α (B1950)	15h 09m 59.10s ± 0.09s
Declination, δ (B1950)	−58° 56′ 58.2″ ± 1.0″
Frequency, ν	6.6375697328(8) s^{-1}
First derivative, $\dot{\nu}$	$-6.7695374(4)\times10^{-11}$ s^{-2}
Second derivative, $\ddot{\nu}$	$1.9587(9)\times10^{-21}$ s^{-3}
Third derivative, $\dddot{\nu}$	$-1.02(25)\times10^{-31}$ s^{-4}
First deceleration parameter, n	2.837 ± 0.001
Second deceleration parameter, m	14.5 ± 3.6
Epoch (Modified Julian Day)	48355.0000
Dispersion measure	253.2 ± 1.9 pc cm^{-3}
R.M.S. residual	5.3 ms

The upper portion of Figure 1 shows the timing residuals obtained by fitting for ν, $\dot{\nu}$, and $\ddot{\nu}$, but with $\dddot{\nu}$ fixed at zero; the quartic term arising from the frequency third derivative is evident. The lower portion of the figure shows the residuals after $\dddot{\nu}$ has been removed; these show definite evidence of timing noise, as expected for a young pulsar. The existence of timing noise almost certainly contaminates our measurement of $\dddot{\nu}$, as well as the other frequency derivatives, by amounts greater than the formal fit uncertainties suggest. To estimate the true spin-parameter uncertainties, we fit a fourth frequency derivative to the data (the fitted value, though not consistent with zero, is two orders of magnitude greater than that predicted by eq. [1] and is almost certainly dominated by random processes). The uncertainties in the third and lower frequency derivatives were then chosen so that the values given in Table 1 are consistent with those found when fitting for the fourth frequency derivative. We believe that the uncertainties determined in this way reasonably reflect the true range of possible values, even though the estimation method is admittedly nonrigorous. The length and quality of the data set, together with the unknown nature of the underlying random process, render more rigorous estimation methods of dubious value. Our measured braking index is $n = 2.837 \pm 0.001$, in agreement with the value obtained by Manchester et al. (1985), which was based on a small subset of our present data. The measured value $\dddot{\nu} = (-1.02 \pm 0.25) \times 10^{-31}$ s^{-4} is consistent with the predicted value of $(-0.9338 \pm 0.0002) \times 10^{-31}$ s^{-4} within the estimated uncertainties. Thus, the most straightforward conclusion is that our data are consistent with the simple expression for spin-down given in equation (1) with both n and K constant.

Symptoms similar to those indicative of a nonstationary second derivative might equally well imply a third derivative dominated by random processes. However, none of the usual symptoms characterize our results for PSR B1509−58: the values of the third derivatives obtained independently from

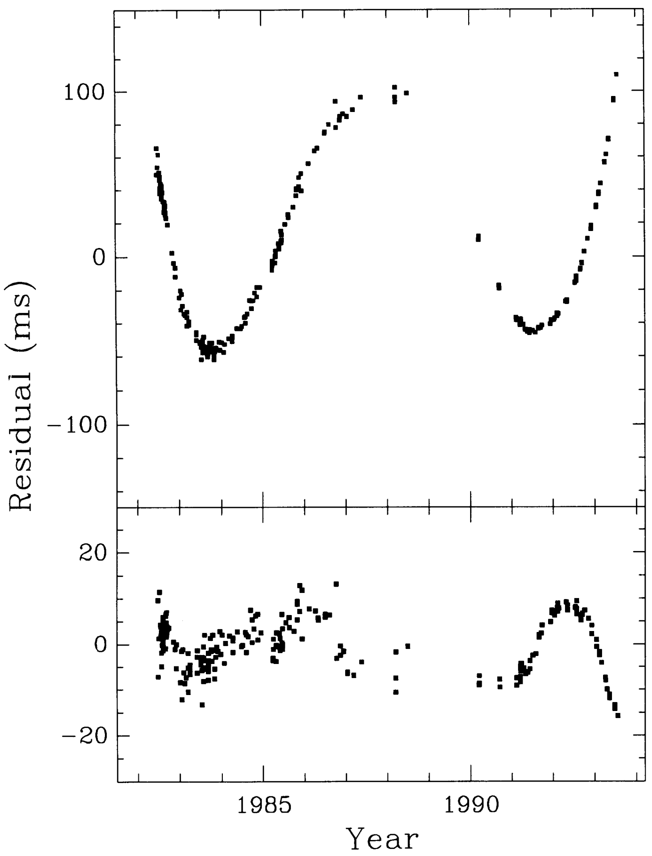

FIG. 1.—Residuals vs. time for PSR B1509−58 after a fit for position, dispersion measure, and spin parameters ν, $\dot\nu$, and $\ddot\nu$ has been removed (*upper panel*) and after $\dddot\nu$ has been removed as well (*lower panel*). The noticeably smaller scatter in the latter half of the data is a result of the better quality Parkes data.

only the MOST and only the Parkes data agree within their respective uncertainties and are consistent with that obtained from both data sets combined; the ephemeris including the third derivative has been predicting arrival times well for nearly a year; the rms residual decreases by a factor of 6 when the third derivative is removed; the measured third derivative has the expected sign; and finally, the measured value is close to the predicted value. We therefore conclude that the quartic signal of Figure 1 is not dominated by random processes and that we have measured the deterministic frequency third derivative of the neutron star's spin-down.

3. DISCUSSION

The measured braking index, like those of the other young pulsars, is significantly different from the value predicted by the simple model in which the braking torque is caused by electromagnetic radiation from a rotating magnetic dipole, or particle acceleration in a dipole field. Several explanations have been proposed to account for observed braking indexes less than 3. Distortion of the magnetic field lines in the radial direction from that of a pure dipole, by strong magnetospheric currents for example, results in $1 \leq n \leq 3$ (Manchester & Taylor 1977). A pulsar wind, in which particles having angular momentum are accelerated away from the pulsar, can also result in $1 \leq n \leq 3$. There is considerable evidence for the existence of pulsar winds (e.g., Kulkarni & Hester 1988; Bell, Bailes, & Bessell 1993; Cordes, Romani, & Lundgren 1993), and the implications of such mass loss on the braking index of PSR B1509−58 were considered by Manchester et al. (1985), who showed that if mass loss was indeed responsible for the deviation of n from 3, a large fraction of the energy and angular momentum loss is in the form of particles. They also pointed out that both the Crab Pulsar and PSR B1509−58 are surrounded by X-ray nebulae, which are presumably powered by injected high-energy particles.

Blandford & Romani (1988) pointed out that another way to have $n < 3$ is to have a time-variable effective magnetic moment M, since the braking torque varies as M^2. This may arise either through a change in the magnitude of the magnetic field or of the alignment of M with the rotation axis. In this case, K in equation (1) is replaced by $K(t)$, and it is straightforward to show that

$$\frac{\dot K \nu}{K \dot\nu} = n - n_0 , \tag{5}$$

where n is the observed braking index as defined in equation (2), and n_0 is the true braking index. Thus, if some value is assumed for n_0, a timescale for torque variations can be calculated. The measurement of $\dddot\nu$, or equivalently of m, in principle provides a check on the variable magnetic moment hypothesis, if a functional form for the time-variability is assumed, since

$$\frac{\ddot K \nu^2}{K \dot\nu^2} = m - n_0(3n - n_0 - 1) . \tag{6}$$

At this stage, the observed value of m rules out exponential growth in K on timescales less than $\sim$1500 yr for $n_0 \geq 3$. For $n_0 = 3$, the timescale implied by equation (5) is 1.9×10^4 yr; shorter timescales would require $n_0 > 3$. Similarly, for constant K but variable n, we can rule out variation on timescales smaller than $\sim$2000 yr. We cannot rule out a brief period of rapid change in K or n sometime in the past.

Growth of the magnetic field in the past $\sim 10^3$ yr was suggested as a possible explanation for the discrepancy between the age of the pulsar and the estimated age of the supernova remnant G320.4−1.2 (MSH 15−5*2*), in which the pulsar is thought to reside (Blandford & Romani 1988). The age τ_c of the pulsar can be obtained by integrating equation (1), assuming K and n are constant:

$$\tau_c = -\frac{\nu}{(n-1)\dot\nu}\left[1 - \left(\frac{\nu}{\nu_0}\right)^{n-1}\right] , \tag{7}$$

where ν_0 was the rotation frequency of the neutron star at birth. For $\nu_0 \gg \nu$, $\tau_c = -\nu/(n-1)\dot\nu = 1691$ yr for PSR B1509−58. For smaller ν_0, this age is an upper limit only, while if the braking index increases with time, the pulsar may be older (Manchester & Taylor 1977). The age of the supernova remnant was estimated by Seward et al. (1983) to be 10^4 yr. However, they also noted that if the explosion had been of unusually high energy and had proceeded adiabatically into an underdense region such as one evacuated by the progenitor's wind, an age of only 2100 yr would be plausible. Since our observations are consistent with the simple spin-down model, we find no reason to doubt the pulsar's youth, and the controversy over the age of G320.4−1.2 remains unsettled.

Thorsett (1992) proposed that PSR B1509−58 is the neutron star remnant of the supernova explosion witnessed by Chinese astronomers in AD 185, which implies that the

G320.4 − 1.2 and pulsar ages are both 1808 yr. If the pulsar were associated with the AD 185 supernova, from equation (7) and assuming $\nu_0 \gg \nu$, the braking index would be $n = 2.718$, significantly different from our measured value. The braking index would be even smaller for smaller initial frequencies. It is extremely unlikely that our measurement has been sufficiently corrupted by low-frequency timing noise to account for such a discrepancy, and, therefore, if the AD 185 association is to be plausible, a time-variable braking index, or some other deviation from the simple spin-down law of equation (1), must be invoked. By contrast, the characteristic age of the Crab pulsar is greater than its true age; hence, no time-variable braking index, or other spin-down law deviation, need be considered.

No glitches have occurred during the 11 yr of PSR B1509 − 58 observations. According to the model of Ruderman (1991), glitches occur when the accumulated difference between the angular velocities of the neutron star crustal lattice and the neutron superfluid force the crust beyond its elastic yield limit. Vortex lines in the rotating superfluid normally migrate outward as the star spins down; however, stress develops because of vortex-pinning to nuclei in the crust. When sufficient stress is place on the crust, sudden cracking can occur together with catastrophic vortex unpinning. When this happens, the angular velocity differential is suddenly removed, and the result is observed as a sudden spin-up of the pulsar. Glitches are observed to be most prevalent in "adolescent" pulsars where the spin-down is rapid (e.g., Kaspi et al. 1992, 1993; McKenna & Lyne 1990). The Crab pulsar glitch activity is significantly lower than those of other glitching pulsars (Lyne et al. 1993). This is probably because the younger Crab pulsar has had less time to cool and responds to the stress of the outward moving vortex lines with a more plastic flow, rather than with a brittle, cracking reponse (Ruderman 1991; Alpar et al. 1981; Ruderman 1976). The absence of glitches in PSR B1509 − 58 provides strong evidence to support the plastic flow hypothesis and implies that PSR B1509 − 58 has a higher internal temperature than the Crab pulsar, even though it is nearly a factor of two older.

We will continue to monitor PSR B1509 − 58 on a regular basis. The measurement of the frequency third derivative will improve approximately as the fourth power of the length of the data span in the absence of strong systematic effects like glitches and timing noise.

We thank R. Blandford, J. Taylor, and an anonymous referee for helpful comments as well as our colleagues at both Molonglo and Parkes for assistance with the timing observations. Molonglo Radio Observatory is operated by the University of Sydney with support from the Australian Research Council. 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.

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