

A SIX YEAR TIMING SOLUTION FOR PSR B1951+32

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ABSTRACT

Six years of pulse time-of-arrival measurements have been collected from observations of the young, fast pulsar PSR B1951+32 in the CTB 80 supernova remnant using the Jodrell Bank and Arecibo radio telescopes. The combined data allow for the determination of a phase connected solution between 1987 August 21 and 1993 September 21. This solution provides an accurate rotational ephemeris for high energy x-ray and gamma-ray observations of this source made during the six years of radio timing observations to an accuracy of better than one tenth of a pulse period (4 ms). The pulsar has an activity parameter comparable with the value seen in the Crab pulsar.

1. INTRODUCTION

Initial radio timing observations collected between 1987 August and 1989 March showed after nineteen months that the rotational behavior of the pulsar PSR B1951+32 was clearly erratic (Foster *et al.* 1990). The pulsar's spin-parameters imply an age of 10^5 years and a magnetic field strength of 5×10^{11} Gauss, making it the weakest known magnetic field for a pulsar so young. An analysis of the early timing data supplemented by data collected through 1993 September indicates that the pulsar has continued to show erratic timing behavior which appears to be characterized by a low frequency rotational drift. An updated solution for the entire time interval is presented.

High energy photons from neutron stars are associated with young pulsars. To date pulsed emission has been detected with instruments on board the *Compton Gamma Ray Observatory* (CGRO) from only six pulsars: the Crab (Ulmer *et al.* 1992), Vela (Strickman *et al.* 1992), PSR B1706-44 (Kniffen *et al.* 1992), PSR B1509-58 (Wilson *et al.* 1992), Geminga (Mattox *et al.* 1992), and PSR B1055-52 (Fierro *et al.* 1993).

The discovery of a young, fast radio pulsar PSR B1951+32 in the CTB 80 supernova remnant (Kulkarni *et al.* 1988 and Fruchter *et al.* 1988) has motivated several efforts to search for pulsed emission from this source at energies ranging from infrared to gamma-ray. An early infrared search resulted in a 6σ upper-limit to the pulsed infrared flux corresponding to $4 \mu\text{Jy}$ flux limit averaged over the pulse period (Clifton *et al.* 1988). Recent x-ray data collected with *Röntgen Satellite* (ROSAT) indicate the possible presence of pulsed emission in the x-ray band (Sarfi-Harb *et al.* 1994). The pulsar has also been observed at gamma-ray energies by

instruments on board the CGRO on at least three occasions, 1991 June, August, and December, with each observation lasting for a duration of approximately two weeks. This pulsar's erratic rotational rate has made old timing solutions particularly unreliable for predicting future pulse arrival times. Luminosity upper limits (2σ) from the CGRO Oriented Scintillation Spectrometer Experiment (OSSE) over the 0.1 MeV to 1 GeV range are $2.36 \times 10^{34} \text{ erg s}^{-1}$ toward PSR B1951+32 (Ulmer & Schroeder 1994). Perhaps with longer phase connected integrations high energy observations will be able to detect non-radio pulsed emission from PSR B1951+32.

In this paper we report the latest radio pulsar timing solutions over the entire observation span between 1987 and 1993. This will aid long-term phase connected timing solutions using high-energy data sets corresponding to different time periods when PSR B1951+32 was observed.

2. OBSERVATIONS

The pulsar PSR B1951+32 has been timed since shortly after its discovery in 1987 July using the 305 m spherical antenna at Arecibo, Puerto Rico and the 76 m Lovell antenna at Jodrell Bank in the United Kingdom. The Arecibo observations have been made at both 430 and 1400 MHz with total bandwidths of 5 and 40 MHz, respectively. The data were gathered using a 40 MHz autocorrelator (Perillat 1987) and synchronously averaged at the expected pulse period for integration intervals ranging from two to five minutes. The data processing follows that described in Foster *et al.* (1990). Observations were made at thirty-two different epochs between 1987 July and 1989 February at approximately three week intervals. Between 1989 April and 1993 July a total of

TABLE 1. Timing solution for PSR B1951+32 1987 August–1993 September one derivative fit.

Parameter	Value
Right Ascension (J2000)	19 ^h 52 ^m 58 ^s .399±0.096
Declination (J2000)	32°52′39″.87±1.17
Epoch (Julian Date)	2447005.6880
Frequency (Hz)	25.2973973377±0.0000000035
Frequency derivative (Hz s ⁻¹)	-3.742528±0.000042×10 ⁻¹²
Dispersion measure (pc cm ⁻³)	45.15±0.18
rms post-fit residuals (ms)	19.50

17 observations were collected at approximately three month intervals at both 430 and 1400 MHz. The Jodrell Bank measurements were made with dedispersing receivers centered on radio frequencies between 234 and 1642 MHz. Observations were made on 165 days between 1987 August 21 and 1993 September 21 with an average interval between observations of two weeks.

All of the data were time tagged using local atomic time standards at the observatories and referred back to UTC by using the Global Positioning System of satellites. The topocentric arrival times were converted to barycentric arrival times by using the DE200 planetary ephemeris (Standish 1982). A chi-square minimization procedure was applied to the data to determine the best-fit solution to the pulsar's frequency, frequency derivatives, epoch, position, and dispersion measure. The data reduction package used for this purpose is TEMPO (e.g., Taylor & Weisberg 1989).

3. RESULTS

Combining the Arecibo and Jodrell-Bank data permitted a better determination of a long-term timing solution for PSR 1951+32 by filling observational gaps in each of the programs. The observed pulse arrival times from the two data sets were corrected so that the reference phase offsets referred to the center of individual pulses. The resulting systematic difference between the two data sets is less than the random measurement error of the data which is about 250 μ s. A six parameter fit was performed on the data fitting for the rotational frequency, frequency first derivative, epoch, right ascension, declination, and total electron column density or dispersion measure. In Table 1 the resulting spin-down and astrometric parameters are given with 3 σ uncertainties. The residuals relative to the fitted model shown in Fig. 1(a) wander by approximately two full periods peak-to-peak.

Due to the presence of low-frequency “timing noise” in the residuals we also fitted for additional high order derivatives of the rotational frequency in order to describe the data by a Taylor series of the form:

$$\phi = \phi_0 + f(t-t_0) + \frac{\dot{f}}{2}(t-t_0)^2 + \frac{\ddot{f}}{6}(t-t_0)^3 + \dots,$$

where ϕ is the pulse phase at time t , ϕ_0 is the initial phase at time t_0 , and $f, \dot{f}, \ddot{f}, \dots$ are the frequency and its time derivatives. We continued to fit for successively higher frequency derivatives until we no longer obtained a significant im-

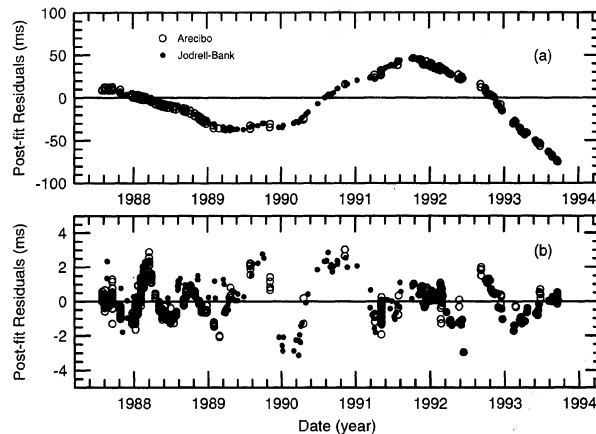


FIG. 1. Residuals between the measured pulsar arrival times and a spin-down model calculated in Barycentric Dynamical Time (TDB) over six years from data collected at Arecibo and Jodrell Bank are plotted for the pulsar PSR B1951+32. The open circles represent data collected from Arecibo and the solid circles represent data collected from Jodrell Bank. The data sets from both observatories have been simultaneously fitted. (a) shows the residuals for a fit that includes only the first frequency derivative, while the data in (b) were fitted for six frequency derivatives.

provement in the chi squared per number of degrees of freedom. The minimum number of derivative required to flatten the data to a point where the χ^2/N no longer improved was six. The result of this fit solving for the rotational frequency of the pulsar and the first six derivatives, as well as the right ascension, declination, and dispersion measure is given in Table 2 and the corresponding residuals are presented in Fig. 1(b). A six derivative fit was applied to the data in order to flatten the residuals sufficiently so that a single phase connected solution could be applied over the duration of the entire data-set. We offer no physical interpretation to this, other than the obvious implication that the timing behavior is erratic, indicative of a large activity parameter. Systematic trends can be seen in the latter, indicating that further, shorter-term “timing noise” exists in the data. However, this solution maintains phase to better than one tenth of a rotational period with root mean squared (rms) of 0.9 ms over the entire six year data set.

An interferometric position for this pulsar was obtained

TABLE 2. Timing solution for PSR B1951+32 1987 August–1993 September six derivatives fit.

Parameter	Value
Right Ascension (J2000)	19 ^h 52 ^m 58 ^s .3076±0.0051
Declination (J2000)	32°52′40″.569±0.085
Epoch (Julian Date)	2447005.6880
Frequency (Hz)	25.2973973463±0.0000000024
Frequency derivative (Hz s ⁻¹)	-3.74329±0.00036×10 ⁻¹²
Frequency 2nd derivative (Hz s ⁻²)	2.69±0.34×10 ⁻²²
Frequency 3rd derivative (Hz s ⁻³)	-2.42±0.20×10 ⁻²⁹
Frequency 4th derivative (Hz s ⁻⁴)	1.054±0.078×10 ⁻³⁶
Frequency 5th derivative (Hz s ⁻⁵)	-2.43±0.18×10 ⁻⁴⁴
Frequency 6th derivative (Hz s ⁻⁶)	2.42±0.18×10 ⁻⁵²
Dispersion measure (pc cm ⁻³)	44.989±0.008
rms post-fit residuals (ms)	0.93

TABLE 3. Timing solution for PSR B1951+32 1991 April–1993 September.

Parameter	First and second derivative fit	UTC at Earth's geocenter fit
Right Ascension (J2000)	19 ^h 52 ^m 58 ^s 298±0.009	19 ^h 52 ^m 58 ^s 298±0.009
Declination (J2000)	32°52′40″48±0.16	32°52′40″48±0.16
Epoch (Julian Date)	2447005.6880	2448799.500000346
Frequency (Hz)	25.29739673±0.00000003	25.29681734±0.00000003
Frequency derivative (Hz s ⁻¹)	−3.73571±0.00043×10 ⁻¹²	−3.74093±0.00043×10 ⁻¹²
Frequency 2nd derivative (Hz s ⁻²)	−3.37±0.28×10 ⁻²³	−3.37±0.28×10 ⁻²³
Dispersion measure (pc cm ⁻³)	44.975±0.018	44.975
rms post-fit residuals (ms)	0.71	0.71

using the Very Large Array (VLA) in the A-configuration on 1989 January 13 by Foster *et al.* (1990), with a measured position in J2000 coordinates of 19^h52^m58^s 191±0.038 and 32° 52′ 40″22±0.56. The timing position obtained from the fit given in Table 2 differs from the interferometric position by 0.21±0.11 seconds of time in right ascension and 0.4±0.6 seconds of arc. This apparent discrepancy probably arises from the residual “timing noise” which is likely to give rise to an underestimate of the errors in the fitted parameters.

In order to provide an up to date ephemeris for the duration of the CGRO mission, a fit including only the first and second frequency derivatives is required to describe the data collected between 1991 April and 1993 September. The best fit solution is given in Table 3 and results in residuals having an rms value of 0.7 ms. This is about 3 times the expected noise from the intrinsic uncertainty in the individual data points because of the remaining “timing noise.” The same solution is converted to the CGRO format using the TEMPO software package and is shown also in Table 3. The timing solution has been converted to a solution at the standard epoch Julian date 2448799.5 (or MJD 48799.0). The actual reference epoch is given for an infinite frequency arrival time in UTC at the Earth's geocenter to an accuracy of 100 μ s.

We can use the measured value of the frequency second derivative to compute a formal braking index

$$n = \frac{f\ddot{f}}{\dot{f}^2},$$

giving $n = +486 \pm 20$. Several young pulsars have measured braking indices between 2.0 and 2.8, where a value of 3 is expected from spin-down by magnetic dipole radiation when the pulsar magnetosphere extends to the light cylinder radius (e.g., Lyne & Graham-Smith 1990). The measured braking index for PSR B1951+32 obtained from the data collected between 1987 September and 1989 February was -50 ± 30 (Foster *et al.* 1990). The large values are almost certainly due to the rotational noise (as defined below) observed in the timing data from this pulsar.

The “timing noise” of the post-fit residuals can be compared to the “timing noise” seen in other pulsars by using the activity parameter A , defined as

$$A = \log[\hat{\sigma}_{\text{TN}}(m, T) / \hat{\sigma}_{\text{TN}}(m, T)_{\text{Crab}}]_{m=2},$$

where T is the total observing duration in days, m is the order of the polynomial fit used to estimate the rms “timing noise” level, and $\hat{\sigma}_{\text{TN}}(m, T)_{\text{Crab}}$ is the rms “timing noise”

observed for the Crab pulsar over a corresponding time interval (Cordes & Downs 1985; Cordes & Helfand 1980). We use a second-order polynomial fit ($m=2$) to remove a constant frequency and frequency derivative term from the timing data to compare with data from other pulsars in a uniform manner. The rms “timing noise” in the residuals relative to the fit over the entire 6 year data set described in Table 1 is 19.5 ms. This gives an activity parameter over the same interval of 0.03, nearly identical to the Crab pulsar's value, which is zero, by definition.

PSR B1951+32 appears to show an erratic timing behavior characterized by low frequency rotational drift in the pulse phase similar to that reported in the Crab pulsar (Lyne *et al.* 1988). The low frequency drift seen in the Crab pulsar timing from 1982 through 1987 was attributed to 20 month period oscillations of the bulk neutron superfluid in the rotating neutron star. At present the data from PSR B1951+32 do not show any similar oscillatory behavior for time-spans shorter than three years.

4. CONCLUSIONS

During the six years that timing observations have been conducted on this source it has shown “timing noise” of amplitude similar to that seen in the Crab pulsar. The rotational noise is independent of radio frequency and therefore must be intrinsic to the rotation of the star itself. The data of the entire observation span are reasonably well described by a model which includes six frequency derivatives. The high order fit has reduced the rms “timing noise” to below 1 ms, but systematic irregularities still exist in the residuals. Strong “timing noise” can affect the observed pulsar spin and astrometric parameters. The result is a discrepancy between data collected at different epochs by more than the measured statistical errors. The determined timing solution for PSR B1951+32 is accurate to better than one tenth of the pulse period over the six year interval between 1987 and 1993, but will probably not remain stable for longer than a few months beyond 1993 September. The timing activity observed in the rotational phase of this pulsar will make a timing proper motion difficult to determine from timing measurements alone. Interferometric observations of the pulsar's proper motion will be needed to obtain the pulsar's distance and space velocity relative to the CTB 80 supernova remnant.

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