The Astrophysical Journal, 567:L141–L144, 2002 March 10
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PROPER-MOTION MEASUREMENTS OF PULSAR B1951+32 IN THE SUPERNOVA REMNANT CTB 80

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Received 2001 December 6; accepted 2002 January 31; published 2002 February 14

ABSTRACT

Using the Very Large Array and the Pie Town antenna, we have measured the position of the radio pulsar B1951+32 relative to nearby background radio sources at four epochs between 1989 and 2000. These data show a clear motion for the pulsar of 25 ± 4 mas yr^{-1} at a position angle 252° ± 7° (north through east), corresponding to a transverse velocity 240 ± 40 km s^{-1} for a distance to the source of 2 kpc. The measured direction of motion confirms that the pulsar is moving away from the center of its associated supernova remnant, the first time that such a result has been demonstrated. Independent of assumptions made about the pulsar birthplace, we show that the measured proper motion implies an age for the pulsar of 64 ± 18 kyr, somewhat less than its characteristic age of 107 kyr. This discrepancy can be explained if the initial spin period of the pulsar was $P_0 = 27 \pm 6$ ms.

Subject headings: ISM: individual (CTB 80) — pulsars: individual (PSR B1951+32) — radio continuum: ISM — stars: neutron — supernova remnants

1. INTRODUCTION

Associations between pulsars and supernova remnants (SNRs) allow measurements that would not be possible on either population of object alone. Since the center of an SNR marks the presumed pulsar birth site, the pulsar's characteristic age, combined with the offset of the pulsar from the center of the SNR, lets us estimate the pulsar's transverse velocity (Frail, Goss, & Whiteoak 1994). A more difficult measurement is to actually measure such a pulsar's proper motion. The direction of motion can confirm (or refute) the association with the SNR, while the magnitude of the motion gives an independent estimate of the pulsar's age (Gaensler & Frail 2000).

PSR B1951+32 is a rapidly spinning ($P = 39.5$ ms) radio, X-ray, and γ-ray pulsar, located on the edge of the unusual SNR CTB 80 (G69.0+2.7; Strom 1987; Kulkarni et al. 1988). While B1951+32 is spinning only slightly slower than the Crab pulsar, its low period derivative implies a much larger characteristic age, $\tau_c \equiv P/2\dot{P} = 107$ kyr, and a much lower surface magnetic field, $B \approx 5 \times 10^{11}$ G (Fruchter et al. 1988).

The distance to the pulsar of 2.4 ± 0.2 kpc, as estimated from its dispersion measure, is consistent with the SNR's distance of 2 kpc as measured with H I absorption (Strom & Stappers 2000), suggesting that the two sources are physically associated. However, this system appears quite different from more typical pulsar/SNR associations, in which a young ($\tau_c \lesssim 20$ kyr) pulsar sits near the center of an approximately circular shell. This difference can be understood if one invokes an evolutionary scenario in which the pulsar was originally interior to the SNR but, as a result of its high space velocity, has caught up with and begun to penetrate its SNR (Fesen, Shull, & Saken 1988; Hester & Kulkarni 1988; Koo et al. 1990). The pulsar's relativistic wind then interacts with the SNR shell, reenergizing and distorting it (Shull, Fesen, & Saken 1989). This sequence can explain both the strange appearance of CTB 80 and the large age for B1951+32 compared with most pulsar/SNR associations.

While this evolutionary picture is aesthetically pleasing, it is imperative that it be verified by observations. Specifically, the model proposed for CTB 80 can be tested by measurement of the proper motion of PSR B1951+32. If the two sources are associated, then the pulsar should be moving away from the center of the SNR, as defined by the shell seen in infrared and H I (Fesen et al. 1988; Koo et al. 1990). The separation between the pulsar and the shell's center, when combined with the pulsar's characteristic age, lets one predict a proper motion for the pulsar of $\mu \approx 15$ mas yr^{-1} at a position angle (P.A.) of ≈250° (north through east), independent of the distance to the system.

PSR B1951+32 shows significant timing noise, which prevents measurement of its proper motion through time-of-arrival analysis (Foster et al. 1994). Thus, only via interferometric measurements can this prediction be tested. In this Letter, we report on measurements of the motion of PSR B1951+32 over an 11 yr baseline. In § 2 we describe our observations, while in § 3 we explain the method used to make our measurements and present our results. In § 4 we discuss the implications of these results for the pulsar and SNR.

2. OBSERVATIONS

Observations of PSR B1951+32 were made with the Very Large Array (VLA) at epochs 1989.04, 1991.55, 1993.02, and 2000.90. Each observation was 8 hr in duration and used the VLA's A configuration. In the 1989, 1991, and 1993 observations, data were recorded at two simultaneous frequencies, 1385 and 1652 MHz, within the 20 cm band. Each frequency consisted of 15 channels spread across a 23.5 MHz bandwidth with a sampling time of 10 s, resulting in a usable field of view of radius ∼10′ centered on the pulsar. For the 2000 epoch observations, we also incorporated data from the Pie Town antenna of the Very Long Baseline Array, which doubled the resolution of the array primarily in one dimension. The observations for that epoch were conducted at 1385 and 1516 MHz and consisted of 15 channels across a 12.5 MHz bandwidth with 5 s sampling, again resulting in a 10′ field of view. The flux density scale of

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TABLE 1
Positions of Sources at Epoch 2000.90

Source	Position (J2000) R.A.	Position (J2000) Decl.	Distance from Pulsar (arcmin)
PSR B1951+32	19 52 58.2(1)	+32 52 41(1)	...
1	19 53 17.80(1)	+32 52 09.6(1)	4.1
2	19 53 16.36(1)	+32 48 46.4(1)	5.5
3	19 53 15.63(1)	+32 59 38.1(1)	7.9
4	19 53 25.41(1)	+32 58 12.5(1)	8.0
5	19 53 13.41(1)	+33 01 21.8(1)	9.3
6	19 52 15.79(1)	+32 49 35.7(1)	9.4
7	19 52 15.64(1)	+32 49 39.2(1)	9.4

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The values in parentheses indicate the uncertainty in the last digit.

our observations was determined using observations of 3C 286, while the time-varying gains for each antenna were measured using regular observations of PKS B1923+210 or TXS 2013+370.

After standard editing and calibration, we produced images of the pulsar field for each epoch and frequency, using multifrequency synthesis to mitigate bandwidth smearing and discarding all baselines shorter than 10 km (corresponding to spatial scales larger than 4″). By removing these shorter baselines, we ensured that emission from SNR CTB 80 and from the compact wind-driven nebula surrounding the pulsar were not detected. The only emission seen in our images was the pulsar itself, the "hot spot" seen immediately adjacent (Strom 1987), and various other point sources spread throughout the field.

We have identified seven such sources within 10′ of the pulsar, as listed in Table 1. After deconvolving each image using the CLEAN algorithm, we applied a Gaussian fit to the pulsar and to each of these seven sources to measure their position and extent at each epoch and frequency.

3. MEASUREMENT OF THE PULSAR PROPER MOTION

In order to accurately measure the pulsar proper motion, we adopted six of the field sources as reference sources, reserving the nearest source to the pulsar (source 1 in Table 1) as a check on our measurements. The reference sources are approximately evenly distributed throughout the field. The quality of each source as an astrometric reference was determined by measuring the vector separation between all possible pairs of sources and then verifying that no source showed trends or significant changes in the magnitude and direction of these vectors. We also verified that in all cases, the dimensions of the fitted Gaussian matched those of the synthesized beam, confirming that scatter broadening and bandwidth smearing (in the case of background sources) or scintillation (in the case of the pulsar) were not affecting our positional determinations.

The ionosphere can potentially distort the measured positions, producing a frequency-dependent angular displacement $\Delta\theta = k\theta\lambda^2$, where θ is the angular separation between a source and the field center, λ is the observing wavelength, and k is a constant. By measuring θ for each source and each frequency, we found that k had a value consistent with zero, demonstrating that any ionospheric effects were dominated by other uncertainties in our measurements.

McGary et al. (2001) used the VLA to measure pulsar proper motions an order of magnitude smaller than that expected here, and they found a variety of other ways in which the positions

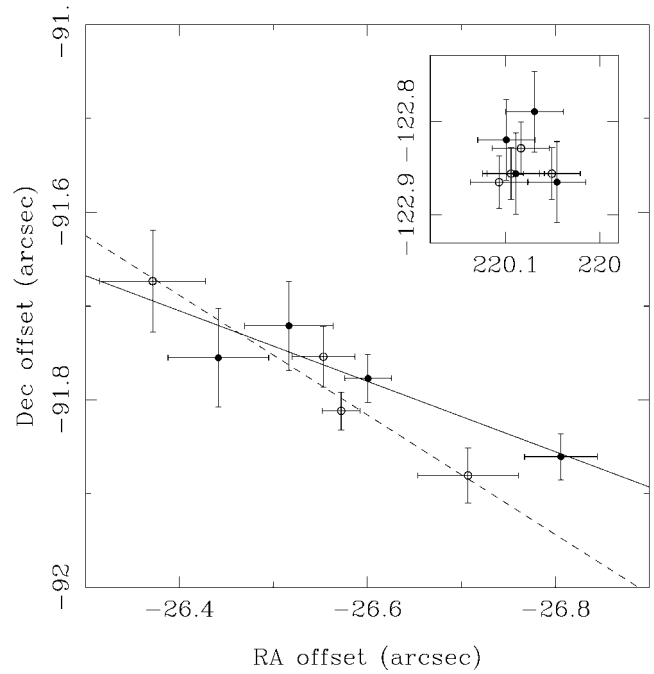

Fig. 1.—Proper-motion measurements of PSR B1951+32. The data points show the offset of the pulsar from the mean reference position at four epochs, and the lines show the weighted best fit to these data. The filled circles and solid line correspond to 1385 MHz data, while the open circles and dashed line represent 1516/1652 MHz data. From left to right, the data points correspond to observations at epochs 1989.04, 1991.55, 1993.02, and 2000.90. The inset shows the position of source 1 at each epoch, plotted on the same scale and determined via the same process.

of reference sources can be distorted, including relativistic effects due to the Earth's motion, errors introduced by the VLA correlator, and additional empirical corrections that had no simple explanation. At the lower precision required here, we have accounted for all these effects simply by measuring the scatter in the position of each reference source between epochs.

We began by determining the vector distances between all possible pairings of the six reference sources. The standard deviations of the components of each vector in right ascension and declination were computed for the four epochs; these were taken as the uncertainty for a particular pairing. This uncertainty was then decomposed between the two sources in that pair, the relative contributions of the two sources to the joint error being weighted inversely by each source's signal-to-noise ratio. We were thus able to derive an uncertainty in the position of each source for each pairing; these uncertainties were averaged over the five possible pairings to determine the best measurement of the true uncertainty in each coordinate for each source. This analysis was performed separately for observations at 1385 MHz and at 1516/1652 MHz. A mean reference position for each epoch and frequency was then determined by averaging together the positions of the six reference sources, weighting the contribution from each source inversely by its distance from the field center.

The separation between the pulsar's position and this mean reference position was then measured for each epoch and frequency, combining in quadrature the calculated uncertainties in the pulsar position with those determined for the reference position. The results of these measurements are plotted in Figure 1 and show a clear motion of the pulsar to the southwest. The flux density of the pulsar was higher during the 1993 observations than at other epochs, resulting in smaller uncer-

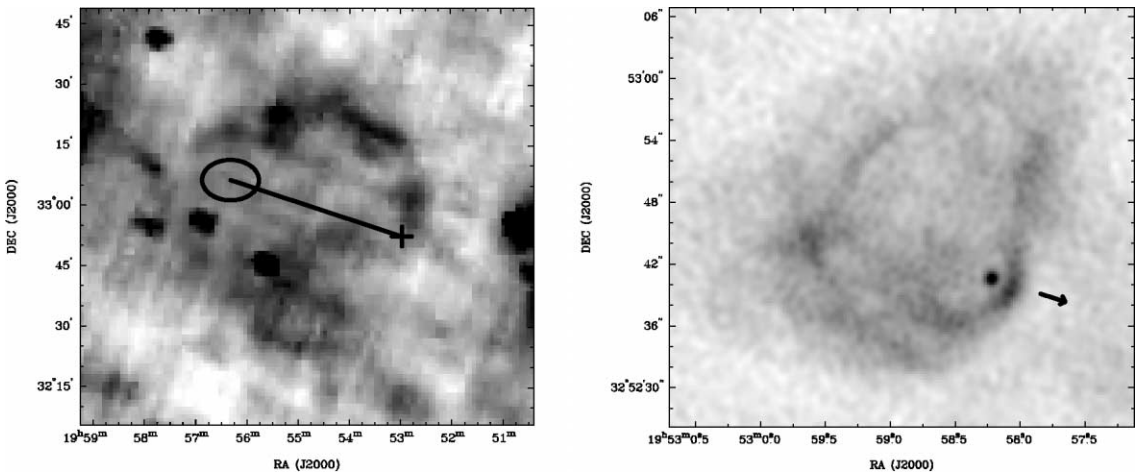

FIG. 2.—SNR CTB 80 and PSR B1951+32. The left panel presents an image of the *IRAS* 60 μm/100 μm ratio in the region, showing the shell of CTB 80. The current position of PSR B1951+32 is marked by the plus sign, the direction along which it has traveled is indicated by the solid line, and its projected birthplace for an age of 107 kyr is marked by the 1 σ ellipse. In the right panel, we show a 1.5 GHz VLA image of the immediate vicinity of the pulsar, made from all baselines of our 1993 epoch data. PSR B1951+32 is the point source to the southwest of center. The arrow indicates the pulsar's measured direction of motion, the length of the arrow corresponding to the distance traveled by the pulsar over 100 yr.

tainties in the pulsar position for this measurement. Note that the position of the pulsar listed in Table 1 is consistent with previous determinations (Foster et al. 1994), but with larger errors due to the systematic errors discussed above. Such uncertainties in the absolute astrometry do not affect our proper-motion measurement, which has been determined based on astrometry relative to nearby background sources.

As an independent test of our approach, we have similarly measured the proper motion for source 1. As is shown in Figure 1, no change in position is seen for this source, demonstrating that the motion measured for the pulsar is real and that the uncertainties have been realistically assessed.

By applying a weighted least-squares fit to the pulsar's position at each epoch, we find a proper motion at 1385 MHz of $\mu = 31 \pm 5$ mas yr^{-1} at P.A. $= 250° \pm 7°$ and at 1516/1652 MHz of $\mu = 26 \pm 6$ mas yr^{-1} at P.A. $= 240° \pm 10°$. These two measurements are consistent with each other within their uncertainties. After taking into account the apparent motion of the pulsar at the level of 5 mas yr^{-1} due to differential Galactic rotation,[7] the combination of our two measurements yields a motion $\mu = 25 \pm 4$ mas yr^{-1} at P.A. $= 252° \pm 7°$. The corresponding projected velocity is $V_t = (240 \pm 40)d_2$ km s^{-1} for a distance $2d_2$ kpc.

4. DISCUSSION

The transverse velocity that we have inferred for PSR B1951+32 is in agreement with the value $V_t \sim 300$ km s^{-1} implied by scintillation in its dynamic spectrum (Fruchter et al. 1988). Furthermore, as shown in Figure 2, the measured position angle of the proper motion agrees closely with the direction predicted if the adjacent hot spot is interpreted as a bow shock driven ahead of the pulsar (Strom 1987). It can also be seen in Figure 2 that the pulsar is clearly traveling directly away from the center of its SNR. While this result is not unexpected given the already strong evidence for an association between the pulsar and the SNR, it is surprising to realize that this is the first time such an effect has actually been observed. Such measurements for other young pulsars in SNRs have failed to demonstrate such motion and have either required specific models of SNR and pulsar evolution to maintain the association (Bailes et al. 1989; Gaensler & Frail 2000) or caused the association to be abandoned (Thompson & Córdova 1994).

While the direction in which the pulsar is moving is as predicted, the magnitude of the pulsar's motion is not in agreement with the simplest expectations. By projecting the pulsar's position back by $\tau_c = 107$ kyr to its inferred birth site, it can be seen from Figure 2 that if the pulsar was born near the center of its SNR, then the pulsar's true age, t_p, must be less than τ_c.

We can make an initial estimate of t_p by simply identifying the offset, Θ, of the pulsar from the SNR's center. We estimate from the morphology of the infrared shell shown in Figure 2 that $\Theta \sim 27'$, so that $t_p = \Theta/\mu \sim 64$ kyr. However, a high-velocity progenitor and/or asymmetric SNR expansion can produce a significant offset between the pulsar birth site and the geometric center of the SNR (Różyczka et al. 1993; Dohm-Palmer & Jones 1996; Hnatyk & Petruk 1999). Given the complicated evolutionary history of CTB 80, it is perhaps overly optimistic to define a precise geometrical center and simply assume that the pulsar was born there.

If the birth site is not at the SNR's geometric center, there is no reason to expect the pulsar to be traveling away from this position (Gvaramadze 2000). However, the farther the birth site from the center of the SNR, the less likely the pulsar should be moving in this direction by chance. We can therefore quantify the uncertainty in the pulsar's birthplace as follows. We assume that for a given angular separation ϕ from the SNR's geometric center, it is equally likely that the pulsar was born at any position on a circle concentric with the SNR and of radius ϕ. Thus, for a particular value of ϕ, we can compute the fraction of possible birth sites that are consistent with the pulsar's direction of proper motion, P.A. $= 252° \pm 7°$. By considering the full range of values $0 \leq \phi \leq \Theta$, we can build up a probability distribution of possible pulsar ages, from the integral of which we can determine the 1 σ confidence limits on ϕ. Using this approach, we find that the pulsar was born within $\pm 8'$ of the SNR's center and that the age implied by our proper-motion measurement is $t_p = 64 \pm 18$ kyr. These estimates are independent of the distance to the system and the site of the

[7] To make this calculation, we have used the rotation curve of Fich, Blitz, & Stark (1989) and have assumed a 10% uncertainty in the systemic velocity of the pulsar.

supernova explosion; they depend only on the assumptions that an approximate geometric center can be defined for the SNR and that the pulsar is moving away from its birthplace. The age that we have derived is consistent with the estimate of 77 kyr, derived from the expansion velocity of the H I shell coincident with the SNR (Koo et al. 1990).

It is not surprising that this system's true age is less than the pulsar's characteristic age. For a pulsar of constant moment of inertia and magnetic dipole moment, it is straightforward to show that (Manchester & Taylor 1977)

$$t_p = \frac{2\tau_c}{n-1}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right], \quad (1)$$

where n is the pulsar's "braking index" and P_0 is its initial spin period. For $n = 3$ and $P_0 \ll P$, equation (1) reduces to $t_p = \tau_c$, but in general neither such condition will be satisfied. While n has not been measured for PSR B1951+32, we find $1.5 \lesssim n \lesssim 3$ for the five pulsars that have had their braking indices measured (Zhang et al. 2001 and references therein). For $n = 3$, the range in t_p determined above implies $P_0 = 25 \pm 5$ ms for PSR B1951+32, while for $n = 1.5$ we find $P_0 = 29 \pm 3$ ms. Combining these estimates, we find that the initial period most likely falls in the range $P_0 = 27 \pm 6$ ms. Again, this estimate does not depend on the assumed distance to the source.

As listed in Table 2, PSR B1951+32 joins a rapidly growing list of pulsars whose initial periods have been determined from their associations with either SNRs or historical supernovae. While these measurements span a reasonable range of initial periods, the data provide good evidence that radio pulsars are born as rapid rotators, with no evidence for a population of longer initial periods as has been sometimes proposed (Vivekanand & Narayan 1981; Chevalier & Emmering 1986). On the other hand, it is becoming abundantly clear that τ_c can be an unreliable estimator of a young pulsar's age, with corresponding implications for associations with SNRs, pulsar velocities, and models for neutron star cooling. With many new pulsar/SNR associations now being identified at both radio and X-ray wavelengths, a statistically useful sample of pulsar initial spin periods should soon emerge.

TABLE 2

INITIAL PERIOD ESTIMATES FOR YOUNG PULSARS

Pulsar	Associated SNR or Nebula	Initial Period (ms)	References
J0537−6910	N157B	<14	1
B0531+21	Crab Nebula	19	2
B1951+32	CTB 80	27 ± 6	3
B0540−69	0540−69.3	30 ± 8	4
J0205+6449	3C 58	60	5
J1811−1925	G11.2−0.3	62	6, 7
J1124−5916	G292.0+1.8	90	8

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We are grateful to Roger Foster for initiating this project and to Dale Frail for making us aware of these archival data. We thank Robin McGary and Glen Monnelly for useful advice. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. J. M. M. acknowledges the support of MIT through a Presidential Fellowship for graduate studies in physics. B. M. G. acknowledges the support of a Clay Fellowship awarded by the Harvard-Smithsonian Center for Astrophysics. E. v. d. S. is currently supported by the European Commission under the TMR programme, contract ERB-FMRX-CT98-0168.

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