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DISCOVERY OF A YOUNG, 267 MILLISECOND PULSAR IN THE SUPERNOVA REMNANT W44

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ABSTRACT

We report the discovery of a 267 ms pulsar, PSR 1853+01, in the supernova remnant W44 (G34.7−0.4). The pulsar is located south of the center of W44, well within its radio shell and at the southern edge of the X-ray emission region which fills the interior of the remnant. The period derivative $\dot{P} \approx 208 \times 10^{-15}$ s s^{-1} leads to a characteristic age of ∼20,000 yr for the pulsar, which agrees well with the estimated age of W44 (≥10,000 yr). Similarly, the dispersion measure derived distance of the pulsar, ∼3.2 kpc, is almost identical with the kinematic distance of the remnant, 3.1 kpc. As expected in the case of a young pulsar, PSR 1853+01 exhibits large timing activity. These data clearly indicate that the two objects are physically related and form the sixth known pulsar-supernova remnant association. We also discuss the possibility that PSR 1853+01 and a nearby older pulsar PSR 1854+00 may have a common origin in a binary system disrupted by the explosion that produced W44.

Subject headings: nebulae: supernova remnants — pulsars

1. INTRODUCTION

The supernova remnant W44 with its shell-like radio structure (Clark, Green, & Caswell 1975) shows no compelling indirect evidence of harboring an active neutron star. It has been classified as an older remnant, in which the X-rays emitted from its central part are most likely to be of thermal origin (Smith et al. 1985). Furthermore, W44 does not show the flat-spectrum, polarized central radio component characteristic of composite remnants powered by compact objects (Weiler 1983; Helfand & Becker 1987; Seward 1987).

Mohanty (1983) discovered a pulsar, PSR 1854+00, just outside the southern edge of the radio shell of W44, but the pulsar's old age (∼10^8 yr) makes its direct association with the remnant unlikely. In this *Letter*, we report the discovery (Wolszczan et al. 1988) and the follow-up timing observations of a 267 ms pulsar, PSR 1853+01, located within the radio shell of W44. Observations of W44 were part of a larger, sensitive search for young pulsars in supernova remnants with the 305 m Arecibo radiotelescope. The results of this survey will be described elsewhere. The unusual proximity of PSR 1853+01 to the older pulsar PSR 1854+00 (20′ separation) has motivated us to conduct timing observations of the latter object along with the W44 pulsar and to consider a possible relationship between the two objects.

2. OBSERVATIONS

Observations were made between 1988 November 17 and 26, at 1418 MHz using the Arecibo 3-level correlation spectrometer as a multichannel receiver. The W44 supernova remnant was sampled at 3′ intervals (3′ is the 1400 MHz FWHM of the telescope beam) in right ascension and declination. The 128-lag autocorrelation functions of 40 MHz bandwidth, dual-polarization input signals were sampled at 1.0 ms intervals and written to magnetic tape for further processing. The integration time at each search position was 8.8 minutes, which corresponds to 0.5 million data points per frequency channel.

The data were processed at the Cornell National Supercomputer Facility. Each data set was first dedispersed at 128 trial dispersion measures ranging from 0 to 1100 pc cm^{-3}, at 8.5 pc cm^{-3} intervals. Then, the dedispersed time series were Fourier transformed, and the resulting power spectra were searched for harmonically related spikes. For each pulsar candidate, a pulse profile shape was synthesized from its complex harmonics. In the case of W44, observed at high zenith angles, and with significant continuum emission from the remnant, the 8 σ sensitivity of this analysis was about 0.3 mJy for pulsar periods down to ∼8 ms.

A periodic signal from the W44 pulsar was detected in the data acquired on 1988 November 23 and 25 at two adjacent telescope beam positions. Subsequent observations made at Arecibo on 1988 December 18 confirmed the discovery of a 267 ms pulsar within the radio confines of the supernova remnant (Fig. 1). Parameters of the new pulsar, PSR 1853+01, based on 18 months of timing observations are listed in Table 1. In addition, we have been observing PSR 1854+00, located only 20′ southwest of PSR 1853+01, just outside the southern rim of W44. Our derived parameters for this pulsar, which significantly improve upon the initial timing model of Mohanty (1983), are also included in Table 1. Integrated profiles of the two pulsars obtained at 1418 MHz are shown in Figure 2. At this frequency, both pulsars are characterized by single-component pulse morphologies with no evidence of interpulse emission.

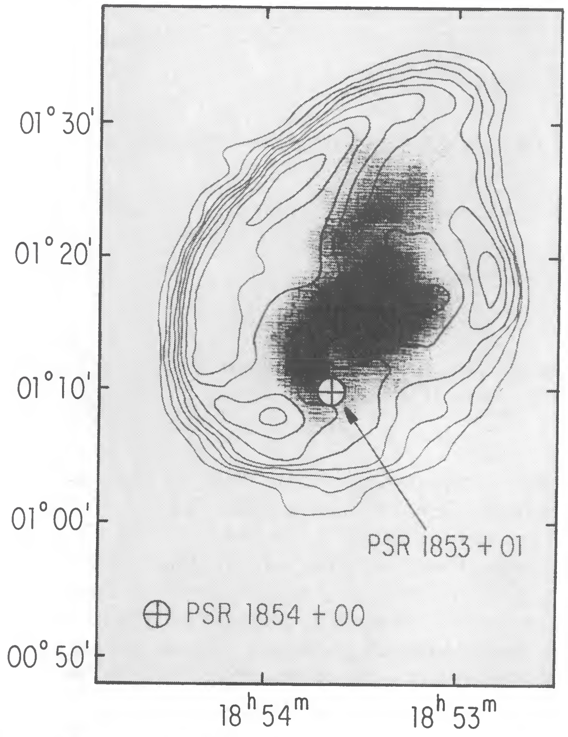

FIG. 1.—Positions of PSR 1853+01 and PSR 1854+00 with respect to the W44 supernova remnant. The combined radio (*contours*) and X-ray (*gray shades*) map of W44 is from Watson et al. (1973).

3. DISCUSSION

3.1. *Association of PSR 1853+01 with W44*

Along with the positional coincidence of PSR 1853+01 with W44, there is other evidence for a physical association of these two objects. The kinematic distance to the remnant is $\sim$3.1 kpc (Caswell et al. 1975). Using the pulsar's dispersion measure (Table 1) and assuming that the electron density along the line of sight to W44 is ~ 0.03 cm^{-3}, as is typical of pulsars lying close to the galactic plane, we obtain 3.2 kpc for the distance to the pulsar. Furthermore, PSR 1853+01 has the fifth largest value of the period derivative ($\dot{P}$) among young pulsars (Table 1; Braun, Goss, & Lyne 1989) and the characteristic age of the pulsar, $\tau = P/2\dot{P} \sim 2 \times 10^4$ yr, agrees well with the estimated age of W44 ($\geq 10^4$ yr) (Smith et al. 1985). Finally, PSR 1853+01 shows large timing activity (Fig. 3 and discussion below), which is characteristic of young pulsars with substantial slowdown rates. These facts unambiguously point to an association between W44 and the pulsar.

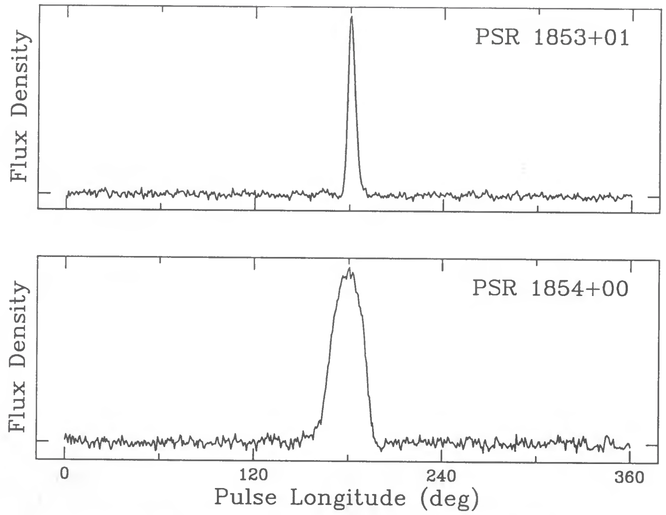

FIG. 2.—Average pulse profiles of PSR 1853+01 and PSR 1854+00 at 1418 MHz. In both cases the effective resolution is 800 μs and the integration time is 1 hr.

The pulsar's present period of 267 ms does not necessarily imply a long (many tens of milliseconds) period at birth. If the Crab pulsar were evolved to the spindown age of 1853+01 (assuming a braking index of 2.5, the Crab's measured value), its period would be 0.22, only 20% smaller than that of 1853+01. It is entirely possible that 1853+01 has followed a spin history very similar to that of the Crab pulsar.

PSR 1853+01 is located at the southern edge of the X-ray emitting interior of the W44 shell. If it was born at the center of the shell, the pulsar would need a projected velocity in excess of 200 km s^{-1} to reach its present position in $\tau \leq 20{,}000$ yr. This prediction will have to be verified by future astrometric observations using the VLA. Attempts to measure a scintillation velocity for the pulsar have not succeeded because of its low flux density. Moreover, the accuracy of timing-based astrometry is limited because of the pulsar's large intrinsic timing noise.

Very young pulsars with high rotational energy-loss rates are known to power the surrounding synchrotron nebulae (e.g., Seward 1987, and references therein). The efficiency of this process in X-rays is described by an empirical relationship $\log L_x = 1.39 \log \dot{E} - 16.6$, where L_x is the X-ray luminosity of the nebula and $\dot{E}$ is the pulsar's rotational energy loss in ergs

TABLE 1

PARAMETERS OF THE PULSARS PSR 1853+01 AND PSR 1854+00

Parameter	PSR 1853+01	PSR 1854+00
P (s)	0.26739884073 ± 0.00000000003	0.35692898802 ± 0.000000003
$\dot{P}$ (s s^{-1})	(208.408 ± 0.003) × 10^{-15}	(0.054 ± 0.002) × 10^{-15}
Epoch (JED)	2447517.1877	2447568.0830
α_{1950}	$18^h53^m38\overset{s}{.}45 \pm 0\overset{s}{.}01$	$18^h54^m28\overset{s}{.}09 \pm 0\overset{s}{.}01$
δ_{1950}	$01°09'22\overset{''}{.}7 \pm 0\overset{''}{.}3$	$00°53'15\overset{''}{.}4 \pm 0\overset{''}{.}4$
DM (pc cm^{-3})	96.7 ± 0.5	83.0 ± 2.0
S_{1400} (mJy)	1.2 ± 0.2	1.5 ± 0.5
	Derived Parameters	
Magnetic field	7 × 10^{12} G	1 × 10^{11} G
Characteristic age	2 × 10^{4} yr	1 × 10^{8} yr

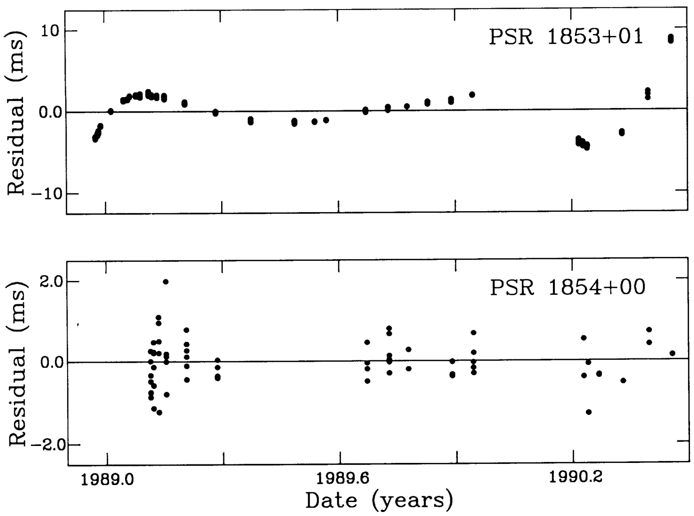

FIG. 3.—Post-fit timing residuals derived from the measurements of pulse arrival times from PSR 1853+01 and PSR 1854+00 at 1418 MHz.

s^{-1} (Seward & Wang 1988). In the case of the W44 pulsar, $\dot{E} \approx 4 \times 10^{35}$ ergs s^{-1}, leading to an estimate of $L_x = 8 \times 10^{32}$ ergs s^{-1} for the X-ray luminosity of the hypothetical synchrotron nebula. This is only a small fraction of the X-ray luminosity of W44 (4×10^{35} ergs s^{-1}) and it is comparable to the upper limit to a point source detection by the *Einstein* HRI (Smith et al. 1985). Consequently, it is not surprising that previous analyses of the X-ray emission from W44 using the *Einstein* data (Watson et al. 1983; Smith et al. 1985) have not found an active neutron star or synchrotron nebula in this remnant. We have reexamined both the IPC and HRI observations of W44 by *Einstein* with a similarly negative result.

Smith et al. (1985) describe the centrally peaked X-ray morphology of W44 in terms of a thermal emission model. This view is further supported by the detection of a thermal X-ray spectrum from the central region of the remnant by Winkler et al. (1982). On the other hand, one cannot rule out the possibility that at least part of the observed X-ray flux may be radiated by "fossil" electrons left over from the pulsar's early life. Adopting the X-ray emitting volume of W44 of 5×10^{59} cm^3 and the observed luminosity (Smith et al. 1985), we obtain a reasonable estimate of the magnetic field in the nebula, $B = 3 \times 10^{-6}$ G. If we further assume that the maximum synchrotron emission occurs at the center of the *Einstein* HRI energy range, $h\nu_c = 1$ keV, the age of low energy electrons becomes ~16,000 yr, comparable to the ages of both W44 and PSR 1853+01.

The W44 remnant and PSR 1853+01 represent a case where the emission from the remnant may derive solely from the interaction of the blast wave with its surroundings. None of the extended radio emission need be associated with the pulsar. In fact, W44 may exemplify the generalization made by Braun et al. (1989) that shell remnants become stronger radio sources after an initial decline due to the supernova blast wave interacting with the stellar wind bubble generated by the presupernova star. The three pulsars studied in detail by Braun et al. (1989) show no supernova remnants though they have spindown ages about equal to that of PSR 1853+01, leading to the conclusion that remnants become invisible after about 20 kyr. W44 may have remained visible longer simply because circumstellar material is located further from the pulsar.

2.2. *Analysis of Timing Data*

The post-fit timing residuals for 1853+01 are dominated by noise that appears in most objects with large $\dot{P}$. Correcting the rms residual for the contribution from measurement errors (~150 μs), the timing noise is $\sigma_{\rm TN}(T = 550d) \approx 2.4$ ms. This corresponds to an activity parameter (Cordes & Helfand 1980) $A \propto \log \sigma_{\rm TN}$ that is identical to that of the Crab pulsar, $A \equiv 0$. For comparison, the Vela pulsar has $A = +0.7$, the CTB80 pulsar (Foster, Backer, & Wolszczan 1990) has $A = -0.7$, and the millisecond pulsar PSR 1937+214 has $A \leq -4.15$. On the other hand, the small $\dot{P}$ pulsar 1854+00 shows no detectable timing noise, as expected, though the limit is not very interesting because of the low signal-to-noise ratio of the data. The timing noise of 1853+01 corroborates the trend seen from other objects, namely that a strong torque on the crust induces substantial noisiness in the interactions of the crust with its enclosed superfluid (e.g., Alpar, Nandkumar, & Pines 1986).

2.3. *Relationship between 1853+01 and 1854+00?*

PSRs 1853+01 and 1854+00 are the closest pair of radio pulsars on the sky (Fig. 1). The angular separation between them is ~20′, while the difference in DM is ~14 pc cm^{-3}. An assumed distance of 3.1 kpc and a nominal electron density of 0.03 cm^{-3}, imply spatial separations of 18 pc and 470 pc in the transverse and radial directions. With the canonical birth rate of neutron stars, it is extremely unlikely that this proximity is coincidental, even taking into account the large spindown age of 1854+00 (Table 1). It is therefore interesting to ask whether the two pulsars might have originated from a now disrupted binary system.

The spin parameters of 1854+00 are suggestive of a possibility that it is a "recycled" pulsar, having undergone accretion induced spin-up during the evolution of the progenitor of 1853+01. The period and period derivative of 1854+00 (Table 1) are both smaller than average, and in the $P - \dot{P}$ diagram it lies below the "spinup" line (e.g., van den Heuvel 1987). The fact that 1854+00 does not lie on the spinup line is likely to be due to accretion terminating before the equilibrium period was reached. Significant evolution of the spin parameters since the end of accretion is unlikely, because its time scale ($10^{7.7}$ yr) is long compared to the lifetime of the progenitor of 1853+01. Consequently, it is plausible that the binary was disrupted by the explosion that formed 1853+01, having survived the explosion that formed 1854+00. In this scenario the two pulsars have been moving apart for ~20,000 yr, the characteristic age of 1853+01; to have reached their present transverse separation in that time their relative velocity must be ~900 km s^{-1}. Such a relative speed would result from the disruption of a binary with semi-major axis ~1 $R_\odot$ and an orbital period of about an hour (Radhakrishnan & Shukre 1985), orbital parameters not unlike the progenitor of the binary pulsar 1913+16 (Taylor & Weisberg 1989). In this case, the difference in the pulsars' dispersion measures must be explained by the inhomogeneity of the interstellar plasma, rather than a difference in radial distance. Over a 20 pc depth (assuming that the true radial separation is about equal to the transverse separation), the required density enhancement is only 0.7 cm^{-3}, similar to the density thought necessary to account for the thermal X-ray emission in the interior and the shell radio source (Smith et al. 1985). The location of both pulsars on the same side of the remnant (Fig. 1) may be the result of an asymmetric explosion of the progenitor of 1853+01, but it can also be derived from orbital dynamics without invoking such an asymmetry.

Although the possibility that 1853+01 and 1854+00 were formed in a binary that disrupted when the younger of the two pulsars was formed is appealing, there are two other alternatives. One is that they were both originally members of a binary system that disrupted when the older pulsar was formed. Such a situation is often invoked to explain the proximity of the Crab pulsar and the nearby pulsar 0525+21 (Gott, Gunn, & Ostriker 1970). For this case, the required relative velocities of the two pulsars are much smaller, since they have been separating for ≥ 15 Myr, rather than 20,000 yr, and 1854+00 is not a recycled pulsar. The second possibility is that the two pulsars were formed from unrelated stars—perhaps members of the same OB association. The W44 region is not near any known OB association but does appear to be in or near a star-forming region, as evidenced by the limb brightening of the radio shell by molecular material. However, the absence of other supernova activity in the region would argue against this.

2.4. *Concluding Remarks*

Though it is generally accepted that pulsars are formed in supernova explosions, the observed associations of pulsars and supernova remnants are few. Where such associations are found they provide much useful information about the early evolution of pulsars and their interaction with the surrounding nebula. In this paper we have shown that the newly discovered pulsar PSR 1853+01 is unambiguously associated with the supernova remnant W44, and that the observed characteristics of the system are compatible with standard models of pulsar and SNR evolution.

We have also discussed the possibility that PSR 1853+01 was formed in a binary system with PSR 1854+00, a much older object. Future work to determine the proper motions of 1853+01 and 1854+00 will help resolve this point. For a transverse speed of 500 km s^{-1} at a distance of 3 kpc, the proper motion would be ~ 30 mas yr^{-1}, a value we expect to be measurable with a series of observations at the VLA.

We also take this opportunity to point out that pulsar searches should continue to focus on supernova remnants. The presence of a pulsar in W44, despite predictions to the contrary, serves as a reminder that morphology and age are not yet good predictors of whether the remnant harbors a pulsar.

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REFERENCES

Alpar, A., Nandkumar, R., & Pines, D. 1986, ApJ, 311, 197
Braun, R., Goss, W. M., & Lyne, A. G. 1989, ApJ, 340, 355
Caswell, J. L., Murray, J. D., Roger, R. S., Cole, D. J. & Cooke, D. J. 1975, A&A, 45, 239
Clark, D. A., Green, A. J., & Caswell, J. L. 1975, Australian J. Phys., Ap. Suppl., No. 37, 75
Cordes, J. M., & Helfand, D. J. 1980, ApJ, 239, 640
Foster, R. S., Backer, D. C., & Wolszczan, A. 1990, ApJ, 356, 243
Gott, J. R., Gunn, J. E., & Ostriker, J. P. 1970, ApJ, 160, L91
Helfand, D. J., & Becker, R. H. 1987, ApJ, 314, 203
Mohanty, D. K. 1983, in IAU Symposium 101, Supernova Remnants and Their X-ray Emission, ed. J. Danziger & P. Gorenstein (Dordrecht: Reidel), p. 503
Radhakrishnan, V., & Shukre, C. 1985, in Supernovae, Their Progenitors and Remnants, ed. G. Srinivasan & V. Radhakrishnan (Bangalore: Indian Academy of Sciences), p. 155
Seward, F. D. 1987, in IAU Symposium 125, The Origin and Evolution of Neutron Stars, ed. D. J. Helfand & J.-H.Huang (Dordrecht: Kluwer), p. 99
Seward, F. D., & Wang, Z.-R. 1988, ApJ, 332, 199
Smith, A., Jones, L. R., Watson, M. G., Willingale, R., Wood, N., & Seward, F. D. 1985, MNRAS, 217, 99
van den Heuvel, E. P. J. 1987, in IAU Symposium 125, The Origin and Evolution of Neutron Stars, ed. D. Helfand & J. Huang (Dordrecht: Reidel), p. 393
Watson, M. G., Willingale, R., Pye, J. P., Rolf, D. P., Wood, N., & Thomas, N. 1983, in IAU Symposium No. 101, Supernova Remnants and Their X-Ray Emission, ed. J. Danziger & P. Gorenstein (Dordrecht: Reidel), p. 273
Weiler, K. W. 1983, Observatory, 103, 85
Winkler, P. F., Canizares, C. R., Markert, T. H., & Szymkowiak, A. 1982, in Supernovae: A Survey of Current Research, ed. M. Rees & M. Stoneham (Dordrecht: Reidel), p. 501
Wolszczan, A., Cordes, J. M., Dewey, R. J., & Blaskiewicz, M. 1988, IAU Circ., No. 4694