THE 69 MILLISECOND RADIO PULSAR NEAR THE SUPERNOVA REMNANT RCW 103

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ABSTRACT

We report the detection of the radio pulsar counterpart to the 69 ms X-ray pulsar discovered near the supernova remnant RCW 103 (G332.4−0.4). Our detection confirms that the pulsations arise from a rotation-powered neutron star, which we name PSR J1617−5055. The observed barycentric period derivative confirms that the pulsar has a characteristic age of only 8 kyr, the sixth youngest of all known pulsars. The unusual apparent youth of the pulsar and its proximity to a young remnant require that an association be considered. Although the respective ages and distances are consistent within substantial uncertainties, the large inferred pulsar transverse velocity is difficult to explain given the observed pulsar velocity distribution, the absence of evidence for a pulsar wind nebula, and the symmetry of the remnant. Rather, we argue that the objects are likely superposed on the sky; this is reasonable given the complex area. Without an association, the question of where is the supernova remnant left behind following the birth of PSR J1617−5055 remains open. We also discuss a possible association between PSR J1617−5055 and the γ-ray source 2CG 333+01. Although an association is energetically plausible, it is unlikely given that *EGRET* did not detect 2CG 333+01.

Subject headings: gamma rays: observations — pulsars: individual (PSR J1617−5055) — stars: neutron —
supernova remnants — X-rays: stars

1. INTRODUCTION

RCW 103 (G332.4−0.4) is a young shell supernova remnant with a complicated observational history. An X-ray point source near the center of the remnant was discovered by Tuohy & Garmire (1980), who suggested that it is a "radio-quiet" thermally cooling neutron star, the stellar remnant of the supernova explosion. This was supported by Tuohy et al. (1983) and later by Manchester, D'Amico, & Tuohy (1985) and Kaspi et al. (1996), who failed to find evidence for pulsed emission in radio searches. Aoki, Dotani, & Mitsuda (1992) detected 69 ms pulsations from the direction of the remnant using *Ginga*, providing additional evidence for the neutron star identification. However, *Ginga*'s poor spatial resolution (∼1° × 2°) precluded any firm association. Recently, Gotthelf, Petre, & Hwang (1997) detected the central source using the *ASCA* X-ray observatory and argued that its spectrum is harder than that of a cooling neutron star. They found no evidence for pulsations, setting upper limits that were inconsistent with the Aoki et al. claim. This history recently took a dramatic turn with the detection of the 69 ms periodicity in the *ASCA* data from a point source, AXS J161730−505505, located 7′ north of the center of the remnant, outside the 5′ remnant radius (Gotthelf et al. 1997; Torii et al. 1998). Here we report the discovery of pulsed radio emission from this pulsar, which we name PSR J1617−5055.

2. OBSERVATIONS

We observed the X-ray pulsar position reported by Gotthelf et al. (1997) (J2000, R.A. $16^{\rm h}17^{\rm m}30^{\rm s}$, decl. −50°55′05″) at the Parkes Observatory 64 m radio telescope in New South Wales, Australia, on 1998 January 15 and 16, for 2.6 and 4.0 hr, respectively. For these observations, we used the center beam of the Parkes multibeam receiver system at a central radio frequency of 1374 MHz. The cryogenically cooled system receives orthogonal linear polarizations, each of which is downconverted to an intermediate frequency and filtered in a 2 × 96 × 3 MHz analog filter-bank spectrometer. Data were one-bit sampled at 250 μs and recorded onto magnetic tape using a DLT 7000 tape recorder attached to a DEC Alpha workstation. The data acquisition software and hardware are those being used in a major survey of the Galactic plane for pulsars (see Camilo et al. 1997).

In offline processing, the data were dedispersed at dispersion measures (DMs) between 0 and 600 pc cm^{-3}. Each dedispersed time series was folded over a range of topocentric periods $\pm 2\mu$s from that predicted by the ephemeris estimated by Torii et al. (1998). A highly significant detection (signal-to-noise ratio 21) was found at DM = 467 ± 5 pc cm^{-3}, at barycentric period 0.069356847 ± 0.000000003 s (epoch MJD 50829.7). The pulsation was unambiguously confirmed the next day (signal-to-noise ratio 33). The profile obtained by folding the data from the latter observation is shown in Figure 1.

The 1.4 GHz average radio pulse is unexceptional, characterized by a single peak of 50% intensity width 5.8 ± 0.6 ms
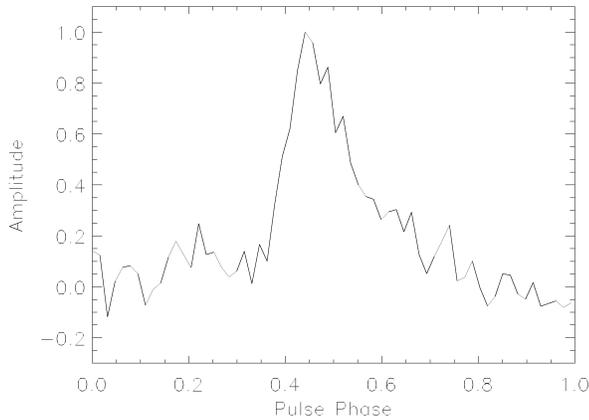
FIG. 1.—Pulse profile of PSR J1617−5055 at 1.4 GHz

(10% intensity width 11 ± 1 ms), convolved with a one-sided exponential of decay time constant 8.7 ± 0.5 ms, probably due to scattering. Although the observations were not carefully calibrated, we estimate the flux density of the source to be ∼0.5 mJy, with an uncertainty of ∼30%. Using archival Australia Telescope Compact Array (ATCA) data taken of the area, but filtering out large-scale structure, seven unresolved sources can be seen within ∼4′ of the pulsar that have 1.4 GHz flux densities between 0.5 and 1.4 mJy. None of these sources is noticeably circularly or linearly polarized, although bandwidth depolarization could easily account for the latter possibility. The source closest to the *ASCA* position has flux density ∼0.5 mJy, consistent with our estimate from Parkes and a flat spectrum similar to other young pulsars; it is at (J2000) R.A. $16^h17^m29^s3$, decl. −50°55′13″2 (uncertainty ∼0″2).

We searched for occurrences of giant radio pulses from PSR J1617−5055 by combining individual dedispersed samples to form a 20 ms resolution time series. Significantly narrower pulses were unlikely to be seen since dispersion smearing and multipath scattering should combine to broaden pulses by ∼10 ms. We found no occurrences of single pulses having amplitude exceeding 9 times the rms noise, corresponding to 54 times the mean pulse energy. For an emission rate and amplitude distribution of giant pulses as observed for the Crab pulsar (Argyle & Gower 1972; Lundgren et al. 1995), we would expect at least five occurrences above this energy threshold in our data. Our analysis thus demonstrates that PSR J1617−5055 is not emitting Crab-like giant radio pulses.

It is straightforward to understand why previous searches for radio pulsations from RCW 103 at Parkes did not detect PSR J1617−5055. They were conducted at radio frequencies near 430, 660, and 1520 MHz: at the two lower frequencies, interstellar scattering is expected to have broadened the pulse beyond detectability. At 1520 MHz, the Parkes telescope beam has FWHM ∼ 13′, so the sensitivity to PSR J1617−5055 is reduced by ≳50% when pointing at the center of RCW 103.

3. DISCUSSION

Using the barycentric period of our radio detection and that found by Torii et al. (1998), we find that $\dot{P} = 1.351(2) \times 10^{-13}$, consistent with the value of 1.4×10^{-13} that Torii et al.

derive using the *Ginga* detection.[1] From the measured $\dot{P}$, we infer a surface magnetic field strength $B \equiv 3.2 \times 10^{19}(P\dot{P})^{1/2} = 3.1 \times 10^{12}$ G and a spin-down luminosity $\dot{E} \equiv 4\pi^2 I\dot{P}/P^3 = 1.6 \times 10^{37}$ ergs s^{-1}, where I is the neutron star moment of inertia, assumed to be 10^{45} g cm^2. The implied characteristic age for PSR J1617−5055 is $\tau_c \equiv P/2\dot{P} = 8.1$ kyr. This is the sixth youngest known pulsar characteristic age after the Crab pulsar, PSR B0540−69, PSR B1509−58, PSR B1610−50, and the recently discovered PSR J0537−6910 (Marshall et al. 1998).

The apparent proximity of so young a pulsar to a young supernova remnant demands that an association be considered. If they are associated, the nature of the well-studied central X-ray source would be unclear, as no tenable interpretations other than its being an isolated cooling neutron star have been put forward (Popov 1998; Heyl & Hernquist 1998). The probability of chance superposition of the pulsar near the remnant is difficult to quantify but is certainly not negligible, particularly in this complex region of the sky: this line of sight traverses the Sagittarius-Carina and Scutum-Crux spiral arms and may extend to the Norma arm. Indeed, the very young radio pulsar PSR B1610−50, only ∼30′ away on the sky from PSR J1617−5055, is also probably superposed only by chance near the supernova remnant Kes 32 (Johnston et al. 1995; Gaensler & Johnston 1995b; but see also Caraveo 1993). We now consider the evidence for an association between PSR J1617−5055 and RCW 103.

3.1. Do Independent Distance Estimates for the Pulsar and Remnant Agree?

First we consider the remnant distance. Westerlund (1969) estimated the distance to RCW 103 to be $d = 3.9$ kpc, by associating it with OB stars nearby on the sky. Caswell et al. (1975) used H I absorption to establish a systemic velocity of −44 km s^{-1} for the remnant, which, using the rotation curve of Fich, Blitz, & Stark (1989) and standard IAU parameters (Kerr & Lynden-Bell 1986), corresponds to a distance of 3.1 ± 0.4 kpc. This has often been taken to be the actual distance to the source (e.g., Dickel et al. 1996; Gotthelf et al. 1997); however, the signal-to-noise ratio in the absorption spectrum is low, and 3.1 kpc should more reasonably be adopted as a lower limit on the distance. Leibowitz & Danziger (1983) and Ruiz (1983) independently estimated the distance to be ∼6.5 kpc from the visual extinction of optical filaments. All observations are thus reconciled if $d \sim 6.5$ kpc, and the remnant is not associated with Westerlund's OB stars.

Next we consider the pulsar distance. Using the standard DM-distance model (Taylor & Cordes 1993), the observed pulsar DM implies a distance of 6.1–6.9 kpc. This close agreement with the RCW 103 distance estimated above could be merely fortuitous. A comparison of pulsar distances from H I absorption and the DM-distance model reveals that the latter may systematically underestimate the electron density for pulsars near PSR J1617−5055. There are two pulsars within 20° of PSR J1617−5055 that have similar DMs and have distance estimates from H I absorption. PSR B1641−45 has DM = 475 pc cm^{-3} and H I absorption lower and upper distance limits of 4.2 ± 0.3 and 5.0 ± 0.3 kpc, respectively (Frail & Weisberg 1990), while the Taylor & Cordes (1993) model predicts

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[1] The uncertainty in $\dot{P}$ derived from the *Ginga* period is at least 0.1×10^{-13} and probably larger. It is dominated by the uncertainty in the *Ginga* period, which was not quoted by Aoki et al. (1992).

5.7–6.4 kpc. Similarly, PSR B1718−35 (DM = 496 pc cm^{-3}) has an H I distance range of 4.4 ± 0.5 to 5.2 ± 0.6 kpc (Weisberg et al. 1995), while the DM-distance model reports 5.8–7.5 kpc. If we adopt the mean electron density for these two pulsars for PSR J1617−5055, its distance may be as low as 4.5 kpc. There is no evidence for any line-of-sight H II region that could significantly contribute to the DM of PSR J1617−5055.

The X-ray luminosity L_x of plerionic nebulae powered by pulsars is correlated with spin-down luminosity $\dot{E}$ (Seward & Wang 1988; Becker & Trümper 1997). Torii et al. (1998) argue that if the unpulsed component of the X-ray emission from the direction of PSR J1617−5055 is from an unresolved synchrotron nebula, then its observed L_x is consistent with the range predicted by empirical $L_x/\dot{E}$ relationships only if the pulsar's distance is much larger than 3.1 kpc. For $d \sim 6.5$ kpc, the observed L_x is still somewhat lower than that predicted by the empirical relationship but is at least within the scatter delimited by other sources.

Thus, distance estimates to PSR J1617−5055 and RCW 103 agree, although both have sufficiently large uncertainty that the agreement is not strong evidence for an association.

3.2. *Do Independent Age Estimates for the Pulsar and Remnant Agree?*

RCW 103 has long been thought to be a very young remnant because of its symmetric shell morphology, which suggests that it has had insufficient time to be distorted by irregularities in the ambient medium. The X-ray structure supports this view, as it is characteristic of the young "double-shock" evolutionary stage (Chevalier 1982). However, the observed correlation of the optical and infrared line emission with the radio filaments suggests that the remnant has reached the Sedov point-blast stage. This is supported by the remnant's polarization structure, which indicates an absence of the radial magnetic field pattern seen in all young double-shock shell remnants (Dickel et al. 1996). On this basis, Dickel et al. suggest that the remnant has just entered the Sedov stage. Assuming a distance of 3.1 kpc, given the observed angular diameter, Dickel et al. argue that the remnant probably has an age of ∼1 kyr. Using the same arguments but taking the distance to be 6.5 kpc (§ 3.1), the age is ∼2 kyr. A larger age has been estimated from X-ray observations. Gotthelf et al. (1997) studied the remnant's X-ray spectrum and, using a nonequilibrium ionization plasma model for Sedov hydrodynamics (Hamilton, Sarazin, & Chevalier 1983), deduced an age of 4 kyr, for a distance of 3.1 kpc. The larger distance would correspondingly increase this age estimate. However, the most direct method of age estimation comes from Carter, Dickel, & Bomans (1997), who have detected the mean expansion rate of the remnant to be 1″.8 ± 0″.2 per 25 yr using optical images taken 25 yr apart. They conclude that the remnant can be no older than ∼3 kyr and is most likely 2 kyr old. These estimates do not depend on the distance to the source.

The unusually low characteristic age $\tau_c = 8$ kyr for the pulsar tends to support an association with RCW 103. However, the characteristic age reflects the true pulsar age only if the braking index $n = 3$, as expected for a simple magnetic-dipole braking, and if the initial spin period P_0 is much less than the current period. Figure 2 summarizes the dependence of the age on these two parameters. P_0, an unknown, is plotted along the x-axis and the true pulsar age τ on the y-axis. The curves show the dependence of the true age on P_0 for several n that span the range of observed values. Note that for $P_0 < 20$ ms and
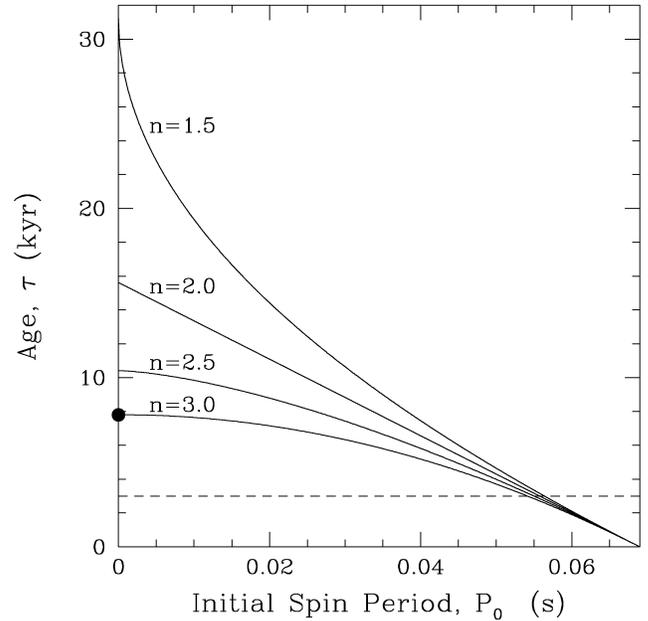

FIG. 2.—The true age τ of PSR J1617−5055 as a function of the assumed initial spin period P_0 for four values of the braking index n. The dashed line represents the estimated upper bound on the age of RCW 103. The filled circle represents the characteristic age $\tau_c \equiv P/2\dot{P}$ (see text).

$n < 3$, as is the case for those pulsars for which these quantities are known with certainty (a particularly low value of n has recently been reported for the Vela pulsar; see Lyne et al. 1996), the true age of PSR J1617−5055 must be considerably greater than that inferred for RCW 103. The horizontal dashed line represents the estimated upper bound on the remnant age, ∼3 kyr. The intersection of the dashed line with each curve gives P_0 for each n. Thus, if the pulsar and remnant are associated, then P_0 is ∼50 ms, independent of n. This value for P_0 would not be surprising given the range implied by the range of current spin periods for the very youngest pulsars (e.g., PSR B1509−58 has $P = 150$ ms).

3.3. *Is the Implied Pulsar Transverse Velocity Reasonable?*

If PSR J1617−5055 and RCW 103 are associated, the pulsar birthplace must be near the remnant center. The symmetry of the shell makes the birthplace easy to identify, in contrast to other proposed associations, such as that of PSR B1509−58. For an association, the implied proper motion of PSR J1617−5055 would be ∼130 (3 kyr/τ) mas yr^{-1}, and the corresponding transverse velocity is ∼4200 (d/6.5 kpc) (3 kyr/τ) km s^{-1}. This velocity would be unusually large given the observed pulsar velocity distribution (Lyne & Lorimer 1994; Hansen & Phinney 1997). Simulations of remnant evolution assuming the Lyne & Lorimer (1994) velocity distribution suggest that fewer than 2% of young pulsars should have left their parent shells (Gaensler & Johnston 1995a). If an association exists, this pulsar would easily rank among the fastest moving stellar objects in the Galaxy and would have important implications for models of supernova explosions (cf. Burrows & Hayes 1996) and binary evolution (e.g., Brandt & Podsiadlowski 1995; Fryer & Kalogera 1997). The large required space motion makes it easy to verify observationally; the proper motion may be detectable from radio timing observations in a few years (although frequent glitches, as expected from this young pulsar, could preclude such a measurement); similarly, gated

radio imaging and high spatial resolution X-ray observations over several years should detect the motion.

3.4. *Is There Evidence for a Pulsar Wind Nebula?*

For an association, the required high pulsar velocity suggests that a pulsar wind nebula might be observable, a result of the confinement of the pulsar's relativistic wind by ram pressure (see Cordes 1996 for a review). The spectacular nebula observed for the young, energetic radio pulsar PSR B1757−24, apparently located just outside the supernova remnant G5.4−1.2, is strong evidence for a high pulsar velocity and hence the association with the remnant (Frail & Kulkarni 1991; Manchester et al. 1991). A similar nebula might be expected near PSR J1617−5055, if indeed it has a high space velocity. Dickel et al. (1996) published high-resolution radio maps of RCW 103 that just fail to include the position of PSR J1617−5055. A reanalysis of their ATCA 1.4 GHz data shows no evidence in the pulsar direction for extended emission on spatial scales between 6″ and 30′, down to a 3 σ limit of 1.2 mJy beam^{-1}. A nebula like that observed for PSR B1757−24 would have been detectable. This provides evidence against a high velocity, particularly because PSR J1617−5055 has spin-down luminosity $\dot{E}$ an order of magnitude larger than that of PSR B1757−24. Brighter nebulae are expected for larger ambient densities, although the latter is estimated to be very small for PSR B1757−24. Furthermore, there is no evidence from the morphology of RCW 103 that an energetic pulsar passed through its shell. The spectacular shell "rejuvenation" interactions observed for PSR B1757−24/G5.4−1.2 and, for example, PSR B1951+32/CTB 80 (Fesen, Shull, & Saken 1988; Shull, Fesen, & Saken 1989; Hester & Kulkarni 1988) are absent in RCW 103. This is evidence against an association, particularly given how recently the pulsar would have to have crossed the shell.

4. PSR J1617−5055: A γ-RAY PULSAR?

High-energy γ-ray emission from rotation-powered pulsars is observed to be well correlated with spin-down luminosity corrected for distance (see Thompson 1996 for a review). Assuming $d \sim 6.5$ kpc for PSR J1617−5055, its $\dot{E}/d^2$ is over 30 times larger than that for PSR B1055−52, a known γ-ray pulsar. PSR J1617−5055 is therefore an excellent candidate for observable γ-ray emission. Indeed, the *ASCA* position of PSR J1617−5055 lies 0°.6 outside the 90% confidence 1° error radius of the high-energy γ-ray source 2CG 333+01 (Swanenburg et al. 1981). If 2CG 333+01 is the counterpart of PSR J1617−5055, then the conversion efficiency of $\dot{E}$ to $E > 100$ MeV γ-rays is ∼0.1$(d/6.5$ kpc$)^2$, assuming 1 sr beaming and a differential γ-ray photon index of 2. This efficiency is comparable to those of other known γ-ray pulsars. However, a counterpart to 2CG 333+01 appears neither in the Second *EGRET* Catalog (Thompson et al. 1995) nor in the Lamb & Macomb (1997) catalog of GeV *EGRET* sources. As γ-ray fluxes of pulsars are observed to be steady (McLaughlin et al. 1996), we conclude that unless PSR J1617−5055 is the first counterexample, or the absence of an *EGRET* counterpart can be explained otherwise, the association of PSR J1617−5055 and 2CG 333+01 is doubtful.

5. CONCLUSIONS

Our discovery of radio pulsations from PSR J1617−5055 confirms that the 69 ms pulsations observed by Torii et al. (1998) come from a young, energetic rotation-powered pulsar in the direction of the young supernova remnant RCW 103. We have considered the possible association between PSR J1617−5055 and RCW 103 and argue that it is unlikely, given the required transverse velocity—which is much higher than that implied by the observed pulsar velocity distribution—and the absence of evidence for a pulsar-powered nebula or any effect on the remnant shell. This same large velocity makes our conclusion easy to test observationally, as the corresponding large proper motion should be easily detectable. In the absence of an association, the interesting question of where is the supernova remnant left behind following the birth of the very young PSR J1617−5055 (similarly for the young PSR B1610−50, also not clearly associated with a remnant) remains open. One possibility is that their braking indexes are smaller than the canonical 3.0, as in the older Vela pulsar, rendering their characteristic ages inappropriately small and giving more time for the remnant to have faded from view. Long-term timing observations can test this hypothesis. Finally, we note that the high $\dot{E}$ for PSR J1617−5055 implies that it should be an observable γ-ray pulsar. The pulsar's coincidence with an unidentified *COS B* source 2CG 333+01 is interesting, but the absence of any counterpart detected by *EGRET* is problematic.

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