A Search for Optical Pulsations from Two Young Southern Pulsars

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ABSTRACT

We report on high-speed optical photometry of the radio positions of two young rotation-powered pulsars. No pulsations were detected from the optical counterpart proposed by Caraveo et al. (1994) for PSR B1509–58, with a 2\(\sigma\) upper limit on the pulsed fraction of < 12\%, significantly lower than that measured in the five known optical pulsars. Given its low pulsed fraction, high optical luminosity, and significant (8\%) chance coincidence probability, we suggest that this candidate is not associated with the pulsar. We also find that the still-unidentified optical counterpart of PSR B1706–44 must have either \(R > 18\) or \(R > 21\), depending upon the pulsar’s (unknown) angular proximity to a nearby bright star.

Subject headings: pulsars: individual (PSR B1509–58) — pulsars: individual (PSR B1706–44) — stars: neutron

1. INTRODUCTION

Nearly 800 isolated rotation-powered neutron stars are currently known, most of them discovered through their radio pulsations (Taylor, Manchester, & Lyne 1993; Taylor et al. 1995). A small fraction of these pulsars has also been detected in the optical, X-ray, and

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gamma-ray bands; in some cases, this emission is also pulsed. The radiation from these objects is believed to arise from three distinct processes. In the youngest pulsars (as estimated by their spindown age, $\tau \equiv P / 2 \dot{P} \lesssim 10^4$ yr, where $P$ and $\dot{P}$ are the pulsar’s spin period and period derivative), non-thermal emission arising from the relativistic acceleration of $e^+e^-$ pairs in the corotating magnetosphere dominates at all wavelengths (see Romani 1996). In young and middle-aged pulsars ($10^4 \lesssim \tau \lesssim 10^6$ yr), thermal soft X-ray emission arising from the initial cooling of the neutron star surface has been detected, in addition to non-thermal magnetospheric emission (see Ögelman 1993). In two nearby older pulsars ($10^6 \lesssim \tau \lesssim 10^7$ yr), thermal soft X-ray emission is detected and is thought to arise from heating of the polar caps by returning $e^+e^-$ pairs accelerated in the outer magnetosphere (Yancopoulos, Hamilton, & Helfand 1994; Manning & Wilmore 1994). The other known rotation-powered pulsars are thus far detected only through their non-thermal radio emission. Optical/ultraviolet emission of young and middle-aged pulsars probes both the non-thermal and thermal components and thus may provide significant constraints on theoretical models when combined with X-ray data.

Optical emission has been reported from directions of nine pulsars. Pulsations were detected from all five pulsars for which time-resolved data are available, most recently from PSR B0656+14 and Geminga (Shearer et al. 1997a, 1997b). In most cases, the optical pulsed fraction is $\sim 100\%$. Because the intrinsically faint optical emission expected from pulsars leads to non-negligible probabilities of chance coincidence with the radio position, the detection of optical pulsations is a crucial test of a proposed counterpart.

In this paper, we report negative results of a search for optical pulsations near the radio positions of two young pulsars in the Southern sky. These non-detections call into question the counterpart proposed by Caraveo, Mereghetti, & Bignami (1994, hereafter CMB94) for the very young PSR B1509–58 ($P = 150$ ms, $\dot{P} = 1.6 \times 10^{-12}$, $\tau = 1600$ yr) and set the first limits on an optical counterpart for the relatively young PSR B1706–44 ($P = 102$ ms, $\dot{P} = 9.3 \times 10^{-14}$, $\tau = 17400$ yr). In the course of completing this work, we learned of two independent non-detections of pulsations from the proposed optical counterpart of PSR B1509–58 (R. N. Manchester 1997, private communication; Mignani et al. 1998).

2. OBSERVATIONS AND ANALYSIS

We obtained high-speed photoelectric photometry of the radio coordinates of the two young pulsars on UT 1995 May 26–29 (MJD 49863–49866) with the 4-m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) in La Serena, Chile. The details of the observational setup and the photometric and timing calibrations are described by
Chakrabarty (1998). The night of May 26 was photometric, but sky conditions gradually deteriorated over the next several nights, with many high, thin clouds present on May 29.

Our observations were made with the Automated Single Channel Aperture Photometer (ASCAP) and a dry-ice-cooled Varian VPM-159A photomultiplier tube at the f/7.5 Ritchey-Chretien focus. The Varian phototube, which has an InGaAsP photocathode, is sensitive over a wide wavelength range, with a quantum efficiency of 15% at 4000 Å and 5% at 9000 Å. Most of the observations used the R filter from the UBVRI filter set described by Graham (1982). Two of the observations used a longpass RG-610 filter, which blocks optical wavelengths shortward of 6100 Å. Most of the observations were made through a 6.6 arcsec circular aperture, although one observation (run 45R) was made through a 9.2 arcsec aperture. The data were recorded at 1 ms resolution and rebinned to 10 ms resolution for timing analysis. One of the observations (run 45R) contained an instrumental signal at 60 Hz and its higher harmonics along with another at 1.75 Hz and its higher harmonics. These contaminants were restricted to a discrete set of frequencies and were easily identified. Table 1 gives a log of our observations.

We used the published radio coordinates of the two pulsars to position our aperture (see Table 2). For PSR B1509–58, we observed the optical counterpart proposed by CMB94, which is coincident with the radio timing position of Kaspi et al. (1994) within 1 arcsec. For PSR B1706–44, the two published radio interferometric positions differ by 3.7 arcsec (McAdam, Osborne, & Parkinson 1993; Frail, Goss, & Whiteoak 1994). This discrepancy is larger than the reported measurement uncertainty and may be due to confusion effects caused by nearby extended non-thermal radio emission. A new radio timing position lies between the two interferometric positions (Wang et al. 1998). The mean of the three radio positions is close to a relatively bright optical star, which we designate as star 1. This and several other stars, along with the two radio positions, are shown in Figure 1, which is a 2-min R-band exposure of the field taken from the CTIO 1.5-m telescope on 1995 May 28. We computed an astrometric solution for this image using stellar coordinates derived from a 1987 V-band plate of the region, obtained from the STScI Digitized Sky Survey. We observed three different positions in this field, indicated by the circles on Figure 1. The first two positions were centered on stars 1 and 2, respectively, and used a 6.6 arcsec aperture.

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3CMB94 used the radio timing position of Manchester, Durdin, & Newton (1985), as quoted in the catalog of Taylor et al. (1993). The Kaspi et al. (1994) position supersedes this but has a somewhat larger uncertainty owing to the inclusion of systematic errors due to timing noise.

4Based on photographic data obtained using the UK Schmidt Telescope, operated by the Royal Observatory, Edinburgh with funding from the UK SERC. The Digitized Sky Survey was produced at STScI under NASA grant NAGW-2166.
The third position was centered near stars 4 and 5, and used a 9.2 arcsec aperture.

3. RESULTS

For each observation, the data were transformed to the solar system barycenter frame using the Jet Propulsion Laboratory DE200 solar system ephemeris (Standish et al. 1992), and the time series was flattened by subtracting a low-order polynomial. The pulse phases for the binned arrival times were computed according to a contemporaneous radio timing model of the form

$$\phi(t) = \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}_0(t - t_0)^2 + \frac{1}{6}\ddot{\nu}_0(t - t_0)^3,$$

where $\phi$ is the pulse phase as a function of the barycentric time $t$; $t_0$ is the epoch for the timing model; and $\nu_0$, $\dot{\nu}_0$, and $\ddot{\nu}_0$ are the pulse frequency and its derivatives at $t = t_0$. The radio timing parameters for PSRs B1509–58 and B1706–44 are regularly monitored at Parkes Observatory in Australia and are available in an electronic database maintained at Princeton University.

The resulting pulse phase distributions were searched for evidence of periodicity using the $H$-test, a sensitive statistical test for weak periodic signals of unknown pulse shape (de Jager, Swanepoel, & Raubenheimer 1989). The chief advantages of the $H$-test are that it is independent of binning and that it is sensitive to a wide range of pulse shapes. We found no convincing evidence for pulsations in any of our observations. The computed probabilities for a uniform (unpulsed) distribution of phases are included in Table 1. We also used the background-subtracted unpulsed (“DC”) intensity to estimate a 95%-confidence upper limit on the pulsed fraction (see de Jager 1994, Chakrabarty et al. 1995, and Chakrabarty 1996 for a discussion of this problem). These upper limits are included in Table 1.

4. DISCUSSION

Based on its radio dispersion measure and the distance model of Taylor & Cordes (1993), PSR B1509–58 is estimated to be 4.4 kpc distant. Assuming a rough $V$ extinction law of $\sim 1$ mag kpc$^{-1}$ (e.g., Spitzer 1978), this implies an absolute magnitude of $M_V = 4.4$ for the CMB94 candidate counterpart. As CMB94 pointed out, this optical luminosity far exceeds the prediction of the $B^4P^{-10}$ law derived by assuming synchrotron emission near the light

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5 Available on the web at http://pulsar.princeton.edu/ftp/gro. The parameters for these two pulsars are based on observations at the Parkes radio telescope by R. N. Manchester, M. Bailes, and collaborators.
cylinder and scaling the surface dipole magnetic field and spin period of the Crab pulsar (Pacini 1971). It also far exceeds an extrapolation of the pulsar’s non-thermal power-law X-ray spectrum into the optical. The Pacini scaling law is able to account for the optical luminosity of the other young pulsars where non-thermal emission dominates (Pacini & Salvati 1987), but it cannot account for the older pulsars, whose optical emission is probably thermal in origin (e.g., Shearer et al. 1997a). However, since non-thermal emission should dominate in PSR B1509–58, one would expect the scaling law to apply.

Our 2σ upper limit of < 12% on the optical pulsed fraction of the CMB94 candidate contrasts with the ~ 100% optical pulsed fraction observed in 4 of the 5 known optical pulsars (see Table 3). Only PSR B0540–69 has a lower pulsed fraction of 16% (Boyd et al. 1995). However, this value must be regarded as a lower limit due to the uncertain contribution from the synchrotron nebula enshrouding the pulsar. At the distance of the LMC, the 0.65 arcsec aperture used in the Hubble Space Telescope (HST) observation covered a 0.16 pc region around PSR B0540–69 (Boyd et al. 1995). By comparison, the 1 arcsec aperture used in an HST observation of the much closer Crab pulsar covered only 0.01 pc around the neutron star and still included a ~ 5% nebular contribution (Percival et al. 1993). Therefore, the optical pulsed fraction of PSR B0540–69 is probably considerably higher than 16%. Thus the CMB94 candidate, if it were the true pulsar counterpart, would be remarkable both for its high optical efficiency and its low optical pulsed fraction.

It is instructive to compute the probability of a chance optical coincidence with the radio position of PSR B1509–58. The density of stars with $V < 22$ in the Galactic plane is $\sim 10^{5.5}$ stars deg$^{-2}$ (Allen 1973). Poisson statistics then give a probability of $\sim 8\%$ for finding an unrelated $V \leq 22$ star within 1 arcsec of the pulsar. Given its high optical luminosity, small pulsed fraction, and significant chance coincidence probability, we suggest that the CMB94 candidate is not associated with PSR B1509–58. Deep optical spectroscopy should eventually settle the question. If it is not the true counterpart, then identification of the actual $V \geq 22$ counterpart at such a necessarily small angular separation from the CMB94 candidate is likely impossible with ground-based observations.

We can use our non-detection of pulsations from the observed stars in the PSR B1706–44 field to place the first limits on this pulsar’s optical flux. Our photoelectric photometry of star 1 on May 26 yielded the following magnitude and colors: $V = 17.3$, $U - B = 1.0$, $B - V = 1.1$, $V - R = 0.7$, and $R - I = 0.4$. Based on differential photometry using our $R$-band image of the field, we conclude that $R \geq 21$ (unless the pulsar lies within $\sim 2$ arcsec of star 1, in which case $R \geq 18$). Given the nearby presence of star 1 and the discrepancy in the radio positions, ground-based identification of this optical counterpart will also be difficult. The present optical limits are not constraining for the Pacini (1971) relation, which
predicts a dereddened magnitude of $R \sim 28$ for PSR B1706-44.

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REFERENCES

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McAdam, W. B., Osborne, J. L., & Parkinson, M. L. 1993, Nature, 361, 516
Spitzer, L. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)

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Table 1. Log of Observations

<table>
<thead>
<tr>
<th>Target</th>
<th>Run ID</th>
<th>MJD&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Duration (min)</th>
<th>Filter</th>
<th>Chance probability&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Pulsed fraction&lt;sup&gt;c&lt;/sup&gt;</th>
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<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CMB94 candidate</td>
<td>33R</td>
<td>49865.145</td>
<td>49</td>
<td>R</td>
<td>40.1%</td>
<td>&lt; 12%</td>
</tr>
<tr>
<td>CMB94 candidate</td>
<td>41R</td>
<td>49866.010</td>
<td>60</td>
<td>R</td>
<td>4.6%</td>
<td>&lt; 17%</td>
</tr>
<tr>
<td><strong>PSR B1706–44</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Star 1</td>
<td>26RG</td>
<td>49864.306</td>
<td>60</td>
<td>RG-610</td>
<td>38.9%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Star 1</td>
<td>34RG</td>
<td>49865.207</td>
<td>108</td>
<td>RG-610</td>
<td>10.2%</td>
<td>&lt; 0.2%</td>
</tr>
<tr>
<td>Star 2</td>
<td>44R</td>
<td>49866.124</td>
<td>30</td>
<td>R</td>
<td>29.1%</td>
<td>&lt; 3%</td>
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<tr>
<td>Stars 4 and 5</td>
<td>45R</td>
<td>49866.152</td>
<td>120</td>
<td>R</td>
<td>9.0%</td>
<td>&lt; 6%</td>
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<sup>a</sup>Modified Julian date = JD – 2,400,000.5. MJD 49864 = 1995 May 27.

<sup>b</sup>H-test probability of a uniform distribution.

<sup>c</sup>95%-confidence upper limits.
Table 2. J2000.0 Positions

<table>
<thead>
<tr>
<th>Object</th>
<th>RA (h m s)</th>
<th>Decl. (° ′ ″)</th>
<th>Ref.</th>
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<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio timing position</td>
<td>15 13 55.62(9)</td>
<td>-59 08 09(1)</td>
<td>1</td>
</tr>
<tr>
<td>CMB94 optical candidate(^a)</td>
<td>15 13 55.52</td>
<td>-59 08 08.8</td>
<td>2</td>
</tr>
<tr>
<td>PSR B1706–44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio interferometry(^b)</td>
<td>17 09 42.86</td>
<td>-44 29 06.1</td>
<td>3</td>
</tr>
<tr>
<td>Radio interferometry</td>
<td>17 09 42.71(3)</td>
<td>-44 29 09.4(3)</td>
<td>4</td>
</tr>
<tr>
<td>Radio timing position</td>
<td>17 09 42.73(2)</td>
<td>-44 29 07.7(6)</td>
<td>5</td>
</tr>
<tr>
<td>Star 1</td>
<td>17 09 42.80(6)</td>
<td>-44 29 10.3(7)</td>
<td>6</td>
</tr>
</tbody>
</table>

\(^a\)0.5 arcsec (1σ) error radius.
\(^b\)Positional uncertainty not specified.

References. — (1) Kaspi et al. 1994; (2) CMB94; (3) McAdam et al. 1993; (4) Frail et al. 1994; (5) Wang et al. 1998; (6) This work.
Table 3. Optical and X-Ray Pulsed Fractions

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>log $\tau$ (yr)</th>
<th>Pulsed fraction$^a$</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Optical</td>
<td>X-ray$^b$</td>
</tr>
<tr>
<td>Very young pulsars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crab pulsar</td>
<td>3.1</td>
<td>100%</td>
<td>$\gtrsim$75%</td>
</tr>
<tr>
<td>PSR B0540–69</td>
<td>3.2</td>
<td>$&gt;16%$</td>
<td>15%</td>
</tr>
<tr>
<td>PSR B1509–58</td>
<td>3.2</td>
<td>$\cdots$</td>
<td>65%</td>
</tr>
<tr>
<td>Young pulsars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vela pulsar</td>
<td>4.1</td>
<td>$\sim100%$</td>
<td>11%</td>
</tr>
<tr>
<td>PSR B1706–44</td>
<td>4.2</td>
<td>$\cdots$</td>
<td>$\lesssim18%$</td>
</tr>
<tr>
<td>Middle-aged pulsars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSR B0656+14</td>
<td>5.0</td>
<td>$\sim100%$</td>
<td>18%</td>
</tr>
<tr>
<td>Geminga</td>
<td>5.5</td>
<td>$\sim100%$</td>
<td>33%</td>
</tr>
<tr>
<td>PSR B1055–52</td>
<td>5.7</td>
<td>?</td>
<td>17%</td>
</tr>
<tr>
<td>Old pulsars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSR B1929+10</td>
<td>6.5</td>
<td>?</td>
<td>30%</td>
</tr>
<tr>
<td>PSR B0950+08</td>
<td>7.2</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

$^a$A question mark indicates an integrated detection with no pulsation search. A blank entry indicates lack of a counterpart.

$^b$As measured in the 0.1–2.4 keV band by ROSAT.

FIGURE CAPTION

FIGURE 1: $R$-band image of the PSR B1706–44 field. North is up, and east is to the left. From north to the south, the crosses indicate the interferometric position of McAdam et al. (1993), the timing position of Wang et al. (1998), and the interferometric position of Frail et al. (1994). The crosses are drawn 2 arcsec across, which is larger than the quoted measurement uncertainties (where quoted). The three circles indicate the aperture positions and sizes used in our observations. Star 1 has $R = 16.6$ and star 5 has $R \approx 20.9$. The brightest star in the field is HD 329564, with $R \lesssim 13.4$. 
Figure 1

PSR B1706-44