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RADIO DETECTION OF PSR B0540 – 69

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ABSTRACT

Using the Parkes radio telescope at an observing frequency of 640 MHz, we have detected radio pulses from the 50 ms pulsar, PSR B0540 – 69, which is associated with the supernova remnant 0540 – 693 in the Large Magellanic Cloud. This pulsar was discovered at X-ray wavelengths and subsequently detected in the optical band. It has a mean flux density of only 0.4 mJy and a broad pulse profile, similar to that at optical and X-ray wavelengths. The dispersion measure of 146 cm^{-3} pc is somewhat higher than, but not inconsistent with, that for other pulsars located in the Magellanic Clouds.

Subject headings: pulsars: individual (PSR B0540 – 69) — Magellanic Clouds — supernova remnants

1. INTRODUCTION

The pulsar PSR B0540 – 69 was discovered at the position of the supernova remnant 0540 – 693 in the Large Magellanic Cloud (LMC) by Seward, Harnden, & Helfand (1984) using data from the *Einstein X-Ray Observatory*. This remnant had been shown previously to have a nonthermal X-ray spectrum (Clark et al. 1982) and hence it was likely that it contained a young pulsar. The short period of the pulsar, 50 ms, and its rapid slowdown rate confirmed its association with the supernova remnant. Optical pulses were detected by Middleditch & Pennypacker (1985) with a mean pulsed magnitude of about 23. At both X-ray and optical wavelengths, the pulse shape is broad, almost sinusoidal, but with a slight bifurcation at the pulse peak.

Pulse timing measurements at optical and X-ray wavelengths show that the pulsar braking index $n = 2.01 \pm 0.02$ (Manchester & Peterson 1989; Nagase et al. 1990; Gouiffes, Finley, & Ögelman 1992). If this index has remained constant, it implies an initial period of 38 ms when combined with the age of 760 yr, estimated from the size and expansion velocity of the [O III] emission-line region (Mathewson et al. 1980; Reynolds 1985; Kirshner et al. 1989).

Prior to the identification of the gamma-ray source Geminga as a 237 ms pulsar (Halpern & Holt 1992), PSR B0540 – 69 was the only known rotation-powered pulsar not detected at radio wavelengths. Previous searches (e.g., Manchester, D'Amico, & Tuohy 1985) failed to detect any radio pulses from this pulsar. In view of its particular interest, both as a pulsar in the LMC and as one associated with a supernova remnant, we have made an extended series of observations to improve on the sensitivity of previous radio searches. These observations reveal the presence of radio pulses with a mean pulse shape similar to that at X-ray and optical wavelengths and a dispersion measure somewhat larger than other LMC pulsars (McConnell et al. 1991).

2. OBSERVATIONS AND ANALYSIS

The observations were made in two main sessions, 1989 November 27 to December 3 and 1990 January 19–30, using the Parkes 64 m radio telescope of the Australia Telescope National Facility. Two orthogonal linear polarizations, each with a bandwidth of 32 MHz and a central radio frequency of 640 MHz, were fed into a receiver system having a system equivalent flux density of 85 Jy on cold sky. Following conversion to intermediate frequency, each polarization was split into 128 adjacent frequency channels of 0.25 MHz bandwidth, which were then detected, low-pass–filtered, and pairwise summed. The resultant 128 total-power outputs were then high-pass–filtered to remove baseline drifts, one-bit sampled at 1.2 ms intervals, and recorded on magnetic tape. The pulsar was observed a total of 35 times, 11 in the first session and 24 in the second, giving a total observation time of 33.5 hr.

The data from each observation were folded at the expected topocentric pulse period in off-line analysis to form 128 mean pulse profiles, one for each frequency channel. Data from different observations were then summed by computing the effective start time at the solar system barycenter and then using the barycentric pulsar parameters from Gouiffes et al. (1992) (solution 1) to compute the required phase shift for each observation. The X-ray position (Seward et al. 1984) was assumed. The final pulse profile was then obtained by summing over frequency with delays appropriate for the assumed dispersion measure. The data from the two sessions were each searched over a range of 0.1 μs in period about the nominal value and dispersion measures from 0 to 250 m^{-3} pc, using the nominal period derivative. Also, the data combined from the two sessions were searched over ranges of 0.02 μs in period and 4×10^{-15} in period derivative about the nominal values at a dispersion measure of 147 cm^{-3} pc, and separately, over a range of 100 cm^{-3} pc about 145 cm^{-3} pc at the nominal period derivative.

The pulsar was also observed in two sessions at 1.5 GHz, using a dual-channel receiver with 2 × 64 × 5 MHz frequency channels, in a third session at 436 MHz using a 2 × 256 × 0.125 MHz system, and then at 660 MHz using the filterbank system described above. The 1.5 GHz observations were made on 1988 May 14–29 and 1988 December 16–18 with a total duration 7.6 and 4.3 hr, respectively, the 436 MHz observations were made on 1992 May 1–2 for 9.7 hr, and the 660 MHz observations made on 1992 July 22 for 10.1 hr. The data from these four sessions were analyzed in a similar way to that described above, and the 436 and 660 MHz data were additionally searched within each day's set over a period range of 0.8 μs and a dispersion measure range of 25 cm^{-3} pc around the nominal values.

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TABLE 1

Barycentric Periods for PSR B0540 − 69

Observation/Prediction	Period (s)	Epoch (MJD)	Observed minus Predicted (ns)
Observed: 1989 Nov–Dec	0.0503607149(4)	47860.0	…
Predicted: Gouiffes et al. 1992	0.05036071604(7)	47860.0	− 1.14 ± 0.41
Predicted: Nagase et al. 1990	0.05036071673(2)	47860.0	− 1.83 ± 0.40
Observed: 1990 Jan	0.0503629928(2)	47915.0	…
Predicted: Gouiffes et al. 1992	0.05036299255(7)	47915.0	− 0.25 ± 0.21
Predicted: Nagase et al. 1990	0.05036299330(2)	47915.0	+ 0.50 ± 0.20
Observed: 1992 July	0.050400694(8)	48825.8	…
Predicted: Gouifes et al. 1992	0.05040069108(12)	48825.8	+ 2.9 ± 8.0
Predicted: Nagase et al. 1990	0.05040069299(25)	48825.8	+ 1.0 ± 8.0

3. RESULTS AND DISCUSSION

Analysis of the 1989 November–December data at 640 MHz revealed a broad pulse with signal-to-noise ratio 7.4 at a barycentric period of 0.0503607149(4) s at a dispersion measure of 143 cm^{-3} pc, where the number in parentheses after the period is the estimated uncertainty in the least significant digit. Similarly, the January data showed a maximum signal-to-noise ratio of 8.1 at a barycentric period of 0.0503629928(2) s and a dispersion measure of 149 cm^{-3} pc. Table 1 gives these periods in relation to periods predicted from the fits to the *EXOSAT* (Gouiffes et al. 1992) and *Ginga* (Nagase et al. 1990) X-ray data. The observed periods are very close to those predicted by both the *EXOSAT* and *Ginga* fits. It is now recognized that the period and period derivative derived by Manchester & Peterson (1989) were incorrect because of pulse counting errors between the relatively widely spaced optical observations (cf. Nagase et al. 1990).

The search of the combined data set gave a best signal-to-noise ratio of 10.1 with the parameters listed in Table 2. The period derivative was calculated in two ways: by stepping the value used in computing the phases in the search procedure and by simply differencing the observed periods given in Table 1. The derivative obtained from the search process is not very precise since only the end points of the phase are well constrained; however, the two methods give consistent results.

PSR B0540 − 69 was detected again in the 1992 July observations at 660 MHz with a signal-to-noise ratio of 6.8. Observed and predicted periods are given in Table 1. The excellent agreement between the expected and observed periods, despite the wide period range (0.8 μs) searched, gives us confidence in this detection. Furthermore, the best dispersion measure, 140 ± 12 cm^{-3} pc, while not very precise, is consistent with the earlier measurements and the profile has the same mean flux density and broad shape as before.

The period derivative obtained by differencing the 1992 and 1990 periods is given in Table 2. This value is closer to the values derived by Nagase et al. (1990), 479.082(2) × 10^{-15}, and by Gouiffes et al. (1992), 479.059(4) × 10^{-15}, than the values derived from the 1989–1990 observations alone.

TABLE 2

Parameters for PSR B0540 − 69

Parameter	Value
R.A. (J2000) (assumed)	$05^{\mathrm{h}}40^{\mathrm{m}}11\overset{\mathrm{s}}{.}1$
Decl. (J2000) (assumed)	$-69°19'57\overset{''}{.}5$
Barycentric period	0.05036196145(5) s
Period Derivative (search)	479.50(30) × 10^{-15}
Period Derivative (1989–1990)	479.35(10) × 10^{-15}
Period Derivative (1990–1992)	479.04(10) × 10^{-15}
Epoch (MJD)	47890.0
Dispersion Measure	146(4) cm^{-3} pc
Mean Flux Density at 640 MHz	0.4 mJy

The derived dispersion measure is greater than the values obtained for Magellanic Cloud pulsars by McConnell et al. (1991), 65–107 cm^{-3} pc, but not inconsistent with them. PSR B0540 − 69 is close to the large H II region complex DEM 269 (Davies et al. 1976), and it is probable that this contributes to its dispersion measure.

Figure 1 shows the mean pulse profile derived from the combined observations. The broad profile is unusual but not unprecedented for pulsar radio profiles. There is a hint of bifurcation of the peak around phase 0.4. Clearly this is of marginal significance, but it persists in profiles formed from the two sessions separately. Within the uncertainties, the radio profile is very similar to both the X-ray pulse profile (Seward et al. 1984) and the optical pulse profile (Middleditch & Pennypacker 1985). These results suggest that the broad profile is intrinsic. As is discussed further below, it is also possible that interstellar scattering contributes to the observed pulse width.

The mean flux density at 640 MHz, S_{640}, 0.4 mJy, is very low by pulsar standards which, together with the broad profile, accounts for the difficulty in detecting the object. Defining luminosity as $L = S_{640} d^2$, where d is the distance to the pulsar, assumed to be 55 kpc, PSR B0540 − 69 has a luminosity of about 1200 mJy kpc^2. This is higher than average for known pulsars (Lyne, Manchester, & Taylor 1985) and approximately equal to the corresponding value for the Crab pulsar, but is

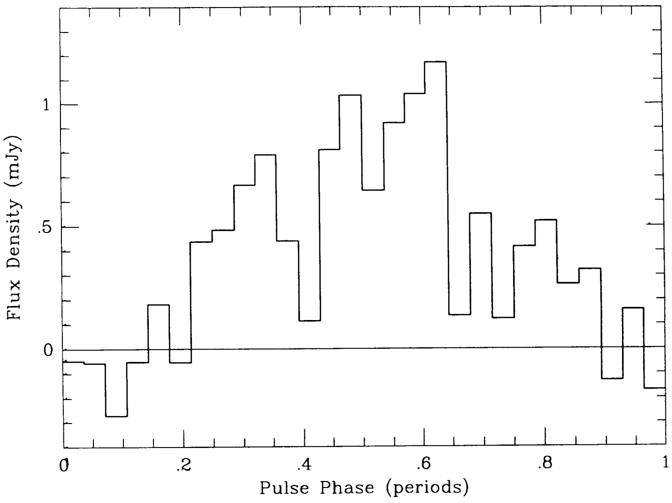

Fig. 1.—Mean pulse profile for PSR B0540 − 69 at a radio frequency of 640 MHz.

about a factor of 10 weaker than the luminosity of the other known Magellanic Cloud pulsars.

Analyses of the 1.5 GHz and 436 MHz data revealed no significant pulsations, with upper limits of 0.1 and 0.5 mJy, respectively. The higher frequency limit corresponds to an upper limit on the spectral index of −1.6; many pulsars have spectral indices steeper than this, and the Crab pulsar in particular has a spectral index of −3.3 at high radio frequencies (Manchester 1971). The spectrum of the pulsed emission from the Crab pulsar turns over at low radio frequencies owing to the effects of interstellar scattering (Rankin et al. 1970). The failure to detect PSR B0540−69 at 430 MHz could be attributed to a large scattering time, which is about 5 times greater at 436 MHz than at 640 MHz. Thus a scattering time as small as 10 ms at 640 MHz, which would only contribute a small fraction to the observed pulse width at that frequency, could reduce the 436 MHz pulsed flux below our detection limit.

Although the differences between the observed and predicted period parameters are small, they are, in most cases, not within the estimated errors. Furthermore, the two X-ray determinations do not agree to within their estimated errors. These small differences are almost certainly due to irregular fluctuations in the pulsar period. Such irregularities are common in young pulsars and it would be surprising if they were not present in PSR B0540−69. However, no large glitches, such as those observed in the Vela pulsar (Cordes, Downs & Krause-Polstorff 1988), have occurred in the period of PSR B0540−69 over the 6 year interval from the start of the optical timing observations (Manchester & Peterson 1989) in 1986 July, to the end of the present observations in 1992 July.

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