Searching for a Pulsar in SN1987A

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Abstract. SN 1987A offered a unique opportunity to detect a pulsar at the very beginning of its life and to study its early evolution. Despite many searches at radio and optical wavelengths, no pulsar has yet been detected. Details of a recent search using the Parkes radio telescope are given. Limits on the X-ray, optical and radio luminosity of a point source at the centre of SN 1987A place limits on the properties of a central neutron star. However, neither these nor the pulsar limits preclude the presence of a relatively slowly rotating neutron star ($P \gtrsim 100$ ms) with a moderate surface dipole magnetic field in SN 1987A. Galactic studies suggest that a significant fraction of pulsars are born with parameters in this range. In view of this, continued searches for a pulsar in SN 1987A are certainly justified.

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INTRODUCTION

As by far the nearest supernova to be observed in the modern era, SN 1987A offered a unique opportunity to search for a pulsar at the very beginning of its life. The detection of a neutrino burst at the time of the SN [1, 2] was good evidence that a neutron star was formed at the time of the explosion. If such a pulsar were found, it would of course be of immense interest to study its properties at such an early stage of its life.

The Crab pulsar remains the youngest known radio pulsar, with a characteristic age, $\tau_c = P/(2\dot{P})$, where $\dot{P}$ is the first time derivative of the period, of 1240 years and a true age of about 950 years.\(^1\) Three apparently younger pulsars are known, all detected only at X-ray or $\gamma$-ray wavelengths: PSRs J1808$-2024$, J1846$-0258$ and J1907+0919. The first and third are “soft gamma-ray repeaters”, with long periods but very large spin-down rates, giving them characteristic ages of just 280 years and 1050 years respectively. PSR J1846$-0258$ is an X-ray pulsar lying at the center of the supernova remnant (SNR) Kes 75 with a characteristic age of about 720 years.

Fig. 1 shows the observed distribution of pulsars in the $P - \dot{P}$ plane. Anomalous X-ray pulsars (AXPs) and SGRs are located in the top-right corner of the diagram with strong implied surface dipole magnetic fields, $B_S \propto (P\dot{P})^{1/2}$, and long periods. There are about 35 plausible, or at least possible, associations of pulsars with supernova remnants and these are all relatively young pulsars, mostly with $\tau_c < 10^5$ years. Non-thermal pulsations in the optical, X-ray or $\gamma$-ray bands are observed from about 45 pulsars and,

\(^1\) Pulsar parameters quoted in this paper have been obtained from the ATNF Pulsar Catalogue http://www.atnf.csiro.au/research/pulsar/psrcat. Original references are given in the catalogue.
FIGURE 1. Observed distribution of pulsars in the period – period derivative plane. Lines of constant characteristic age and surface-dipole magnetic field strength are marked as is the limiting period for spin-up by accretion from a binary companion. Pulsars for which there is a plausible association with a supernova remnant and which emit at optical and higher frequencies are indicated.

apart from a few millisecond pulsars, these pulsars are relatively young. Of the 35 pulsars in the catalogue with characteristic age less than 20,000 years, 21 are detected in one or more of the high-energy bands. Only four or five pulsars have detectable non-thermal pulsations at optical wavelengths [3], but these include two of the youngest known pulsars, the Crab pulsar and PSR B0540–69. Furthermore, PSR B0540–69 is located in the Large Magellanic Cloud, not far from SN 1987A. One other young pulsar, PSR J0537–6910, which has a period of just 16 ms, is also located in the Large Magellanic Cloud close to SN 1987A. This pulsar is detected only at X-ray wavelengths and is associated with the SNR N157B.

The way pulsars move on the $P – \dot{P}$ diagram is determined by the time-dependence of
the rotational braking torque. For many possible braking mechanisms, the torque can be expressed as a power law

\[ N = -K \nu^n \]  

(1)

where \( K \) is a constant, \( \nu = 1/P \) and \( n \) is known as the braking index. For braking by reaction to emission of magnetic-dipole radiation, \( K \propto B_s^2 \) where \( B_s \) is the dipole magnetic field strength at the surface of the neutron star, and \( n = 3 \). The observed value of \( n \) is dominated by the secular braking in only the youngest known pulsars and values of \( n \) between 1.4 and 3.0 have been measured. If the true age of pulsar, \( \tau \), is known or can be estimated, for example, from an association with a SNR, and the braking index \( n \) is assumed to be constant, the pulse period at birth can be estimated from

\[ P_0 = P \left[ 1 - \frac{(n-1)}{2} \frac{\tau}{\tau_c} \right]^{1/(n-1)} \]  

(2)

where \( P \) is the current period. There are 12 SNR – pulsar associations where a reasonably reliable SNR age can be estimated [4, 5, 6] leading to estimates of birth period which range from < 11 ms for PSR J0538-6910 to about 420 ms for PSR J1210-5226, associated with the large shell SNR G296.5+10.0. For the Crab pulsar, the estimated birth period is about 19 ms.

A statistical study of the pulsars detected in the Parkes Multibeam Pulsar Survey (PMPS) [7] taking into account the survey selection effects [8] suggests that 40% of pulsars are born with periods in the range 100 – 500 ms. From an analysis of pulsars detected in the PMPS and the Swinburne intermediate-latitude pulsar survey, Faucher-Giguère and Kaspi [9] obtained consistent results with a gaussian initial-period distribution centred at 300 ms and with a standard deviation of 150 ms.

The distribution of initial magnetic magnetic fields is not well known. Vranesevic et al. [8] find that pulsars with \( B_s > 2.5 \times 10^{12} \) G account for more than half the pulsar birthrate and an independent analysis by Lorimer et al. [10] confirms these results. On the other hand, Fig. 1 shows many pulsars exist with periods of a few hundred milliseconds and \( B_s \) in the range \( 10^{11} \) to \( 10^{12} \) G. These pulsars have very probably been born close to their present location in the \( P - \dot{P} \) plane. Although their observed number is comparable to the number of high-\( B_s \) pulsars, their birthrate is much lower because they move across the \( P - \dot{P} \) plane much more slowly.

**OPTICAL SEARCHES**

Early searches concentrated on optical wavelengths because X-ray telescopes had insufficient sensitivity and the expectation that the surrounding nebula would be opaque at radio wavelengths. The first Australian attempt was made by Bruce Peterson and the author on 26 February, 1987, just three days after the SN, using the 4-m Anglo-Australian Telescope (AAT) with the dust cover nearly closed and a high-speed photometer system previously used for pulsar timing [11]. In the next few months, several observations were made using an 8-inch Celestron telescope on the ground beside the AAT with the photometer system and then through 1988 at approximately monthly intervals, again using the AAT. These searches gave a limit on the pulsed fraction of the SN light of about \( 10^{-5} \)
corresponding to an I-magnitude limit of about 20 [12]. A similar search was carried out at Las Campanas, Cerro Tololo and Mt Stromlo observatories by Pennypacker et al. [13] with a similar upper limit on any optical pulsations.

Then in March, 1989, Kristian et al. [14] announced the detection of a periodicity at 0.508 ms based on a 7-hour observation with the 4-m Cerro Tololo telescope. The periodicity had a sinusoidal variation with a period of about 8 hours, suggesting the presence of a Jupiter-sized planet around the pulsar. The very short pulse period had major implications for neutron-star models and more than 50 papers were published in the next year or so on the implications of this result. Regrettably, in 1990, it was realised that the periodicity was spurious, due to interference from the TV guider on the telescope [15].

A Brazilian group claimed detection of optical pulsations at 18.4 ms (reported by Murdin [16]) but this was not confirmed [17]. An extensive search using various ESO telescopes between 1988 March and 1990 April was reported by Ögelman et al. [18] with limits of about 22nd magnitude for pulsations at frequencies up to 5000 Hz.

In 1992 John Middleditch began circulating a series of preprints of an extensive paper, ultimately published in 2000 [19], reporting the detection of optical pulsations at a period of 2.14 ms using the Las Campanas 2.5-m Dupont Telescope and other telescopes. Although there were numerous detections of a signal near this period, the significance of each was relatively low and the period and amplitude showed significant and largely unpredictable fluctuations. In particular, a modulation of the signal with a period of $\sim 1000$ s was observed. This modulation was of uncertain origin, sometimes having the appearance of amplitude modulation and sometimes frequency or phase modulation. Fig. 2 shows the observed variations in amplitude of the signal, its fundamental frequency and the frequency of the modulation. The amplitude of the pulsed signal was highly variable with I magnitudes in the range 21 to 25 and a persistent spin-down with $dv/dt \sim 2 \times 10^{-10}$ s$^{-2}$ was observed. Middleditch et al. [19] suggested that the observations were consistent with precession and spin-down due to gravitational radiation from a neutron star with a non-axisymmetric oblateness of $\sim 10^{-6}$. Despite repeated observations by Middleditch et al. [19] and others, no evidence for this pulsation was found after 1996 and its identification with a neutron star in SN 1987A remains doubtful.

An optical search using the High Speed Photometer system on the Hubble Space Telescope was reported by Percival et al. [20]. Four observations in 1992 – 1993 covering the band 160 – 700 nm, each of about 40 min duration and with 100 $\mu$s sampling, were searched with both Fourier and time-domain folding methods. No significant pulsations were observed in the period range 0.2 ms to 10 s with an upper limit for the pulsed emission equivalent to a V magnitude of $\sim 24$. A search with similar parameters was made by Manchester and Peterson [21] using the 3.9-m Anglo-Australian Telescope. Data were obtained on two nights of exceptional seeing and searched for periodicities in the range 0.2 ms to 10 s. No significant pulsations were observed with an upper limit in V of about 24.6 magnitudes.
FIGURE 2. Amplitude (in I magnitude) and frequency dependence of the 2.14 ms pulsations detected by Middleditch et al. [19] over four years from 1992. The third panel from the top shows the variation of pulse frequency, the second panel shows variations of the pulse frequency derivative and the lowest panel shows variations of the modulation period.

TABLE 1. Results of a radio search for a pulsar in SN 1987A

| Band  | Freq. (MHz) | Total/Chan. BW (MHz) | $t_{\text{int}}$ (ms) | $DM_{\text{diag}}$ (cm$^{-3}$ pc) | $DM_{\text{step}}$ (cm$^{-3}$ pc) | DM Range (cm$^{-3}$ pc) | Time (h) | Limit ($\mu$Jy) |
|-------|-------------|----------------------|----------------------|----------------------------------|---------------------------------|------------------------|----------|----------------|
| 20cm  | 1390        | 256/0.5              | 0.25                 | 160                              | 0.60                            | 10–2420                | 2.3      | 115            |
| 20cm  | 1518        | 576/3.0              | 0.50                 | 70                               | 0.68                            | 10–2170                | 4.7      | 54             |
| 10cm  | 3083        | 864/3.0              | 0.25                 | 295                              | 2.0                             | 10–2100                | 4.7      | 90             |
| 3cm   | 8370        | 864/3.0              | 0.25                 | 5850                             | 40                              | 20–6020                | 4.7      | 58             |

RADIO SEARCHES

Most pulsars are detected at radio wavelengths and so, despite the low probability of a detection at least in the first few years, searching for a pulsar in SN 1987A at radio wavelengths was an obvious thing to do. Early searches using the Parkes 64-m radio telescope at frequencies between 400 and 5000 MHz were reported by Manchester [12] with the best upper limit $\sim 0.2$ mJy at 1.5 GHz. Observations have been made every 1 – 2 years since then with similar parameters and upper limits.

A more extensive search was carried out at Parkes in 2006 December 19 – 23 using three different receivers and different filterbank systems. The frequencies and bandwidths used are listed in Table 1. For all observations the sum of the power in the two orthogonal polarisations for each frequency channel was one-bit sampled and recorded on Digital Linear Tapes; see Manchester et al. [7] for details of the data acquisition and recording system.
The diagonal DM (DM_{diag}) is the dispersion measure for which the dispersion delay across one channel is equal to the sampling interval. For higher dispersions the pulse is smeared and the sensitivity is reduced, especially for short-period pulsars; for typical sensitivity curves as a function of period and DM, see Manchester et al. [7]. The DM step (DM_{step}) is the DM increment for a delay of two sample intervals across the full bandwidth. For DMs up to DM_{diag} successive trial DM values are separated by DM_{step}. From DM_{diag} to 3 DM_{diag} the trial DMs are separated by 2 DM_{step} and so on until the maximum DM is reached.

Data were processed using the SIGPROC pulsar search package. Data were first dedispersed at each trial DM and then compensated for the Doppler shifts resulting from motion of the observatory relative to the solar-system barycenter. The resulting time series was then Fourier-transformed, harmonics summed and the power spectra searched for candidates above a threshold of 7σ. DM ranges searched and observation times on SN 1987A are given in Table 1. Transform lengths were 2^{24} samples and the pulse period range searched was between the inverse Nyquist frequency and 5 s. Observations of 2.3-h duration were also made with each system at a position 30 arcmin south of the SN position to assist with identifying spurious candidates.

No significant candidates with a S/N ratio greater than 9.0 were observed in any system and in no case was there a convincing detection of a genuine candidate in more than one receiver system or in independent observations with the same system. The flux density limits corresponding to a 9σ threshold in each analysis are given in Table 1. In deriving these limits, the pulse duty cycle was assumed to be 0.1.

OTHER LIMITS ON A CENTRAL PULSAR

Many young pulsars drive a pulsar-wind nebula (PWN). The most famous example is of course the Crab Nebula, but it is far from being typical. Even of the known pulsars associated with SNR, only about half have detectable PWN [22]. With just a few exceptions, all of the pulsars with associated PWN have spin-down luminosities greater than 10^{36} erg s^{-1}. Only a minority of SNR have detectable PWN. For example, the Cambridge SNR catalogue [23] contains 265 SNR of which only 39 have evidence for a PWN. Clearly, detectable PWN are only associated with the most energetic young pulsars.

Compact central objects (CCO) have been found in eight or nine SNR [24, 25]. These objects have thermal X-ray spectra consistent with surface emission from a neutron star. Kaplan et al. [26] searched for CCOs in a volume-limited sample of SNRs, placing luminosity limits of \( \sim 10^{31} \) erg s^{-1} on X-ray point sources in four SNRs. Limits an order of magnitude higher are placed on a further six SNR from the sample by Kaplan et al. [27]. These limits are comparable to the lowest detected luminosities from CCOs, for example, RX J0007.0+7302 in W44, which has a luminosity of \( \sim 5 \times 10^{31} \) erg s^{-1} [28]. Hence they do not necessarily rule out the presence of a central neutron star in these SNR.

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2 See http://sigproc.sourceforge.net.
Although SN 1987A, or more accurately, the resulting SNR, is getting brighter at all wavelengths, imaging observations show that the increasing emission is confined to the outer parts of the expanding envelope and, at least in the optical and X-ray bands, primarily to the region of interaction with the inner ring [29, 30, 31]. There is no evidence for a central point (or near-point) source at any wavelength. Shtykovskiy et al. [32] obtain a luminosity limit in the 2 – 10 keV band of $5 \times 10^{34}$ erg s$^{-1}$ using XMM-Newton data and Park et al. [31] obtain a limit of $1.5 \times 10^{34}$ erg s$^{-1}$ using Chandra. In the optical band from 290 to 965 nm Graves et al. [29] give a limit on the luminosity of any point source of $5 \times 10^{33}$ erg s$^{-1}$ using the Hubble Space Telescope.

These limits are well above luminosities of detected CCO in our Galaxy and hence do not preclude the presence of a similar object in SN 1987A. Based on a bolometric luminosity limit of $3 \times 10^{34}$ erg s$^{-1}$ for a central PWN, Ögelman and Alpar [33] find that for a pulsar period of 300 ms, $B_s < 2.5 \times 10^{12}$ G, not a very restrictive limit.

At radio wavelengths, the best limit is obtained from the 9-GHz imaging where the expanding shell is best resolved [34]. However, even at this frequency, the beamwidth is a significant fraction of the nebular diameter and it is difficult to limit the flux density of any central PWN or pulsar. A conservative limit on the flux density of a central source is 1 mJy. If we assume a flat radio spectrum and a radio bandwidth of 20 GHz, then this corresponds to a radio luminosity of $\sim 3 \times 10^{31}$ erg s$^{-1}$. Let us assume that the entire spin-down energy of a central pulsar is converted to luminosity of a surrounding PWN. This is the most conservative assumption in the sense of giving a lower limit to spin-down luminosity of any central pulsar. If we assume a spin period of 200 ms, then for a spin-down luminosity of $3 \times 10^{31}$ erg s$^{-1}$, the required surface dipole magnetic field is $B_s \sim 6 \times 10^{10}$ G. As discussed above, these parameters are within the range of possible birth parameters for pulsars. If we make the more realistic assumption that only a fraction of the spin-down luminosity goes to powering a PWN, then the pulsar period could be shorter and/or the magnetic field stronger.

It is abundantly clear that a central neutron star, if it exists, does not have the high spin-down luminosity typical of pulsars associated with Galactic PWN. However, it is also true that existing limits on the luminosity of a central point source do not rule out the presence of a perfectly plausible young neutron star with $P > 100$ ms and $B_s$ in the range $10^{11}$ to $10^{12}$ G at the centre of SN 1987A.

**IMPLICATIONS OF THE PULSAR NON-DETECTION**

Since the optical non-thermal emission from pulsars is evidently a strong function of pulsar period [35], optical searches are doomed to failure if the central pulsar has a period of 100 ms or more as suggested above.

The flux density limits given in Table 1 correspond to a radio luminosity (assuming an effective radiated bandwidth of 1 GHz and a circular beam of width 36°) of about $10^{21}$ erg s$^{-1}$, much less than the likely spin-down luminosity for a central pulsar. For a more direct comparison with the radio luminosity of known pulsars, we use the psuedo-luminosity $L_r = Sd^2$, where $S$ is the mean flux density at 1400 MHz and $d$ is the pulsar distance. For $S = 50$ µJy, the upper limit on $L_r$ is about 125 mJy kpc$^2$. Fig. 3 shows $L_r$ versus age for known radio pulsars with this limit marked by a horizontal dashed line.
line. Because of the (relatively) large distance to the Magellanic Clouds, the limit is not very restrictive. Even the Crab pulsar is below the line and young but low-luminosity pulsars found in deep searches toward SNR such as J1124-5916 in G292.0+1.8 [36] and J1930+1852 in G54.1+0.3 [37], both of which have $\tau_c \sim 2900$ yrs and $L_r \sim 2$ mJy kpc$^2$, are nearly two orders of magnitude below it. Therefore, these radio searches certainly do not exclude the presence of a low-luminosity pulsar similar to many young pulsars in our Galaxy at the centre of SN 1987A.

Even if a pulsar with a high radio luminosity were present in SN 1987A, there are a number of reasons why we might not be able to detect it. Most obviously, the pulsar may not be beamed toward us. The beaming fraction (fraction of the celestial sphere swept over by the beam as the star rotates) is not very well determined. Beaming fractions are probably larger in the high-energy bands where the emission is incoherent and could be 50% or more. In the radio band, a beaming fraction of 20% is often assumed, but for young pulsars it could be considerably larger. Radio beams are generally quite patchy, so even if the over-all beamwidth is large, there is a finite chance of being missed by the stronger parts of the beam.

It is possible that the pulsar magnetic field takes some time to develop. Most current models assume either that the field a compressed stellar field or that it is generated during the collapse by dynamo action [e.g., 38], but other models exist [39] in which the field growth takes place after the neutron-star formation. If the growth timescale is decades, then even a rapidly spinning neutron star could still be undetectable.

Even though the outer parts of the SN 1987A nebula are now quite transparent in all relevant bands, it is possible that the immediate environment of the central star still has a relatively high gas density which would cause scattering and/or absorption of emission...
from the star. Fryer et al. [40] discuss fallback of stellar ejecta on to the neutron star and show that it will have a very high opacity at early times and will be largely driven off by radiation pressure. However, fallback is possible decades after the SN explosion [41] and this may still form a relatively dense and turbulent nebula surrounding the star.

Finally, there is the possibility that a neutron star formed at the time of the SN accreted so much matter from fallback of ejecta that it exceeded the maximum mass of a neutron star and became a black hole [42, 43]. Fryer et al. [40] argue that this is unlikely, or at least subject to a restrictive range of conditions.

CONCLUSIONS

The enormously exciting prospect of being able to study a pulsar in its earliest years has motivated a large number of searches for a pulsar in SN 1987A. These searches were primarily at optical and radio wavelengths since our experience with other young pulsars shows that these are the most likely bands for a successful detection. Regretably, despite all this effort (and several false alarms) no pulsar has been detected. Furthermore, limits on the luminosity of a central point (or near point) source at the centre of SN 1987A show that any central pulsar is not highly energetic like the Crab pulsar or PSR B0540–69.

However, all of these limits leave open a region of parameter space for a young neutron star in the centre of SN 1987A. Specifically, a neutron star with a rotation period $P \gtrsim 100$ ms and a surface dipole magnetic field strength $B_s$ in the range $10^{11}$ to $10^{12}$ G is not ruled out by any observations so far. There is clear evidence that some neutron stars are born in the Galaxy with parameters in this range.

Therefore, continued searches for a pulsar in SN 1987A are certainly justified. The greatly increased sensitivity of the proposed Square Kilometer Array will be highly beneficial to radio searches since the current luminosity limits are well above typical luminosities of young radio pulsars. If the pulse period is relatively long, detection of non-thermal optical or X-ray pulsations is unlikely, but more sensitive searches in the future may detect thermal emission from the neutron-star surface and possibly modulation due to rotation of the star.

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REFERENCES

1. K. Hirata et al., Phys. Rev. Lett. 58, 1490–1493 (1987).
2. R. M. Bionta et al., Phys. Rev. Lett. 58, 1494–1496 (1987).
3. B. Kern, C. Martin, B. Mazin, and J. P. Halpern, ApJ 597, 1049–1058 (2003).
4. Z.-R. Wang, M. Li, and Y. Zhao, *Chin. J. Astron. Astrophys.* 6, 625–628 (2006).
5. W. W. Tian, and D. A. Leahy, *A&A* 455, 1053–1058 (2006).
6. C.-Y. Ng, and R. W. Romani, *ApJ* (2007), in press, astro-ph/0702180.
7. R. N. Manchester et al., *MNRAS* 328, 17–35 (2001).
8. N. Vranesevic et al., *ApJ* 617, L139–L142 (2004).
9. C.-A. Faucher-Giguère, and V. M. Kaspi, *ApJ* 643, 332–355 (2006).
10. D. R. Lorimer et al., *MNRAS* 372, 17–35 (2001).
11. R. N. Manchester, and B. A. Peterson, *ApJ* 342, L23–L25 (1989).
12. R. N. Manchester, *PASA* 7, 548–549 (1988).
13. C. R. Pennypacker et al., *ApJ* 617, L139–L142 (2004).
14. J. Kristian, and N. Vranesevic et al., *ApJ* 617, L139–L142 (2004).
15. J. Kristian, *Nature* 349, 747 (1991).
16. P. Murdin, *Nature* 347, 511 (1990).
17. F. J. Jablonski, *Revista Mex. de Astron. Astrofis.* 21, 329–330 (1990).
18. H. Ögelman et al., *A&A* 237, L9–L12 (1990).
19. J. Middleditch et al., *New Astron.* 5, 243–283 (2000).
20. J. W. Percival et al., *ApJ* 446, 832–837 (1995).
21. R. N. Manchester, and B. A. Peterson, *ApJ* 456, L107–L109 (1996).
22. V. M. Kaspi, M. S. E. Roberts, and A. K. Harding, in *Compact Stellar X-ray Sources*, edited by W. H. G. Lewin, and M. van der Klis, CUP, Cambridge (2005).
23. D. A. Green, *A Catalogue of Galactic Supernova Remnants (2006 April Version)*, Mullard Radio Astronomy Observatory, Cambridge, 2006, (http://www.mrao.cam.ac.uk/surveys/smrs/).
24. G. G. Pavlov, D. Sanwal, and M. A. Teter, in *Young Neutron Stars and Their Environments*, edited by F. Camilo, and B. M. Gaensler, 2004, *IAU Symposium 218*, pp. 239–246.
25. S. Park et al., *ApJ* 653, L37–L40 (2006).
26. D. L. Kaplan, D. A. Frail, B. M. Gaensler, E. V. Gotthelf, S. R. Kulkarni, P. O. Slane, and A. Nechita, *ApJS* 153, 269–315 (2004).
27. D. L. Kaplan, B. M. Gaensler, S. R. Kulkarni, and P. O. Slane, *ApJS* 163, 344–371 (2006).
28. P. Slane, E. R. Zimmerman, J. P. Hughes, F. D. Seward, B. M. Gaensler, and M. J. Clarke, *ApJ* 601, 1045–1049 (2004).
29. G. J. M. Graves et al., *ApJ* 629, 944–959 (2005).
30. P. Bouchet et al., *ApJ* 650, 212–227 (2006).
31. S. Park, S. A. Zhekov, D. N. Burrows, G. P. Garmire, and R. McCray, *ApJ* 610, 275–284 (2004).
32. K. E. Shlykovskiy, A. A. Lutovinov, M. R. Gilfanov, and R. A. Sunyaev, *Astron. Lett.* 31, 258–262 (2005).
33. H. Ögelman, and M. A. Alpar, *ApJ* 603, L33–L35 (2004).
34. B. M. Gaensler, L. Staveley-Smith, R. N. Manchester, M. J. Kesteven, L. Ball, and A. K. Tzioumis, these proceedings, 2007, in press (astro-ph/0705.0057).
35. F. Pacini, and M. Salvati, *ApJ* 321, 447–449 (1987).
36. F. Camilo, R. N. Manchester, B. M. Gaensler, D. L. Lorimer, and J. Sarkissian, *ApJ* 567, L71–L75 (2002).
37. F. Camilo et al., *ApJ* 574, L71–L74 (2002).
38. A. Bonanno, V. Urpin, and G. Belvedere, *A&A* 440, 199–205 (2005).
39. R. D. Blandford, and R. W. Romani, *MNRAS* 234, 57P–60P (1988).
40. C. L. Fryer, S. A. Colgate, and P. A. Pinto, *ApJ* 511, 885–895 (1999).
41. S. E. Woosley, and T. A. Weaver, *ApJS* 101, 181–235 (1995).
42. H. A. Bethe, and G. E. Brown, *ApJ* 445, L29–L32 (1995).
43. R. A. Chevalier, *ApJ* 459, 322–329 (1996).