A Spin-down Power Threshold for Pulsar Wind Nebula Generation?

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Abstract. A systematic X-ray survey of the most energetic rotation-powered pulsars known, based on spin-down energy loss rate, $\dot{E} = I \dot{\omega}$, shows that all energetic pulsars with $\dot{E} > \dot{E}_c \approx 3.4 \times 10^{36}$ erg s$^{-1}$ are X-ray bright, manifest a distinct pulsar wind nebula (PWN), and are associated with a supernova event, either historically or via a thermal remnant, with over half residing in shell-like supernova remnants. Below $\dot{E}_c$, the $2-10$ keV PWN flux ratio $F_{\text{PWN}}/F_{\text{PSR}}$ decreases by an order-of-magnitude. This threshold is predicted by the lower limit on the spectral slope $\Gamma_{\text{min}} \approx 0.5$ observed for rotation-powered pulsars (Gotthelf 2003). The apparent lack of bright pulsar nebulae below a critical $\dot{E}$ suggests a change in the particle injection spectrum and serves as a constraint on emission models for rotation-powered pulsars. Neither a young age nor a high density environment is found to be a sufficient condition for generating a PWN, as often suggested, instead the spin-down energy loss rate is likely the key parameter in determining the evolution of a rotation-powered pulsar.

1. A Chandra Study of the Most Energetic Pulsars

Table 1 presents the 28 most energetic pulsars from the complete pulsar catalog of Manchester (2003), ordered by spin-down power ($\dot{E} = I \dot{\omega}$, where $I$ is the neutron star moment of inertia and $\omega$ is its angular velocity). These include all known pulsars detected in both the radio and X-ray energy bands with a spin-down power above $\dot{E} = 10^{36}$ erg s$^{-1}$ (but excludes the one millisecond pulsar in this range). Of the full list, 25 out of 28 sample objects are radio pulsars, 21 are X-ray pulsars, of which only 3 are detected in X-rays alone. So far, 5 radio pulsars have no known follow-up yet in any waveband. For each pulsar with available Chandra ACIS X-ray data, and for its PWN, we measured the unabsorbed flux in the $2-10$ keV band using the method described in Gotthelf (2003). Herein, we compared these fluxes with the spin-down energy loss rate and present the flux ratio $F_{\text{PWN}}/F_{\text{PSR}}$, where $F_{\text{PSR}}$ is the sum of the pulsed and unpulsed pulsar emission.

All of the top 13 pulsars in Table 1 have been observed in X-rays; this includes the 9 brightest X-ray PWN used in the initial study of Gotthelf (2003). When ordered by $\dot{E}$ it is apparent that all energetic pulsars with $\dot{E}_c \gtrsim 3.4 \times 10^{36}$ erg s$^{-1}$ are X-ray bright, show a resolved PWN, and are associated with evidence of a supernova event. The jury is still out on PSR J1617−5055, which is highly
absorbed and was observed with Chandra too far off-axis to resolve a nebula, and on J1112−6102, for which no follow-up X-ray observation currently exist.

Table 1: Pulsars Ordered by Spin-down Power\(^a\)

| Pulsar     | Remnant          | \(E^a\) \(\times 10^{36}\) | Dist \(b\) (kpc) | \(\epsilon = F_{PW}/E\) | Code\(^d\) |
|------------|------------------|---------------------------|-----------------|------------------|-----------|
| J0537−6910 | N157B            | 481.6                     | 49              | 0.003            | 15        |
| J0534+2200 | Crab (SN1054)    | 440.6                     | 2.0             | 0.03             | 30        |
| J0540−6919 | SNR 0540−69      | 146.5                     | 49              | 0.05             | 4         |
| J0205+6449 | 3C58 (SN1181)    | 27.0                      | 3.2             | 0.0004           | 60        |
| J2229+6114 | G106.6+2.9       | 22.5                      | 12              | 0.001            | 9         |
| J1513−5908 | MSH 15−52        | 17.7                      | 5.0             | 0.01             | 5         |
| J1617−5055 |                  | 16.2                      | 6.5             | 0.001            | -         |
| J1124−5916 | G292.0+1.8       | 11.9                      | 5.4             | 0.0002           | 10        |
| J1930−1852 | G54.1+0.3        | 11.6                      | 5               | 0.002            | 5         |
| J1420−6048 | Kookaburra       | 10.4                      | 7.7             | 0.004            | 10        |
| J1846−0258 | Kes 75           | 8.3                       | 19              | 0.15             | 23        |
| J0835−4510 | Vela SNR         | 6.9                       | 0.3             | 0.0001           | 9         |
| J1811−1926 | G11.2−0.3 (SN386?) | 6.4                     | 5               | 0.006            | 9         |
| J1112−6103 |                 | 4.5                       | ...             | ...              | -         |
| J1952+3252 | CTB 80           | 3.7                       | 2.5             | 0.0005           | 1.1       |
| J1709−4429 | G343.1−2.3?      | 3.4                       | 2.5             | 0.0001           | -         |
| J2021+3651 |                 | 3.4                       | 10              | ...              | -?        |
| J1524−5025 |                 | 3.2                       | 3.8             | ...              | -?        |
| J1913−1011 |                 | 2.9                       | 4.5             | ...              | -?        |
| J1826−1334 |                 | 2.9                       | 4.1             | 0.0008           | 2.3       |
| J1801−2451 |                 | 2.6                       | 4.6             | 0.0008           | 0.1       |
| J1016−5857 |                 | 2.6                       | 9.3             | ...              | -         |
| J1105−6107 |                 | 2.5                       | 7.1             | ...              | -?        |
| J1119−6127 | G292.2−0.5 (radio) | 2.3                      | 4               | 0.00005          | 0.2       |
| J1803−2137 |                 | 2.2                       | 4.0             | ...              | -?        |
| J1048−5832 |                 | 2.0                       | 3.0             | ...              | -         |
| J1837−0604 |                 | 2.0                       | 6.2             | ...              | -?        |
| J0940−5428 |                 | 1.9                       | 4.3             | ...              | -?        |

\(^a\)Table rank-ordered by spin-down power \(E = I\omega\dot{\omega}\), were \(I \equiv 10^{45}\) gm cm\(^{-2}\).

\(^b\)Best estimate of the pulsar distance \((d\), in kpc\) from the literature.

\(^c\)Efficiency, \(\epsilon\), the ratio of pulsar luminosity \((L_X \equiv F_X/4\pi d^2 = L_{PW} + L_{PSR})\) in the 2–10 keV band measured following the procedure of Gotthelf (2003) and the spin-down power.

\(^d\)Code: \(s = Chandra\) PWN survey object (Gotthelf 2003); \(r = \)Radio source; \(x = \)X-ray source.

In contrast, pulsars whose spin-down energy loss rate falls below \(\dot{E}\) lack both a bright nebula and a supernova association in the X-ray energy regime. For several of these objects Chandra observations detect weak nebulosity. Diffuse X-ray emission is found around PSR J1709−4420 (Gotthelf et al. 2002) and tentatively indicated for PSR J2021+3651, a newly discovered pulsar with a similar \(\dot{E}\) (Roberts, this proceedings). An extremely faint X-ray “tail” is found trailing the “Duck” radio pulsar PSR J1801−2451, but this is interpreted as a ram-pressured confined cometary wind (Kaspi et al. 2001). The Chandra observation of PSR J1826−1334 confirms a faint PWN, barely resolved with the ROSAT HRI (Finley et al. 1996). Finally, arcsecond localization of J1105−6107, previously associated with X-ray emission (Gotthelf & Kaspi 1998), shows that
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Figure 1. *Left panel:* A comparison between the $2-10$ keV spectral slope of the nine brightest known pulsars ($\Gamma_{PSR}$) and the inverse square root of their spin-down power, $\dot{E}_{40}^{-1/2}$, in units of $10^{40}$ erg s$^{-1}$. The dashed-line indicates the best-fit model. *Right panel:* Relationship between the above pulsars’ spectral slope ($\Gamma_{PSR}$) and that of their wind nebulae ($\Gamma_{PWN}$), assuming a simple power-law spectral model. The dashed line indicates the best-fit. The physical origin of this relationship has yet to be determined. From Gotthelf (2003).

Evidently all pulsars with $\dot{E} > \dot{E}_c$ display bright PWNe while for the less energetic pulsars the nebula emission is vestigial, at best, when resolved from the background. This fact is quantified by the flux ratio $F_{PWN}/F_{PSR}$ given in Table 1 which shows that the PWNe of the less energetic pulsars are genuinely subluminous relative to their PSR flux. This comparison is best done statistically since the distance estimates are mostly uncertain (factor $\sim 2$). Above $\dot{E}_c$, the mean flux ratio for these pulsars is of order $\sim 14$, while the less energetic pulsars have a ratio of order $\sim 1.5$. This factor of ten change in efficiency in the X-ray band cannot be explained as a distance bias, i.e., the bright PWNe are systematically closer, as the range of distances overlap between the less and more energetic pulsars (see Table 1). Deeper observations of the faint PWNe are needed to search for extended emission yet missed.

A possible explanation for a critical $\dot{E}_c$ is provided in Gotthelf (2003), where the spectra of the most energetic pulsars are shown to depend on their spin-down power $\dot{E}$ - the more energetic the pulsar, the steeper its spectral slopes. This rule follows an inverse square-root law, $\Gamma_{PSR} = \Gamma_{max} + \alpha \dot{E}^{-1/2}$ with a minimum observed spectral slope of $\Gamma_{min} \approx 0.5$ (see Fig. 1). Most interestingly, $\Gamma_{min}$ corresponds to $\dot{E}_c \approx 3.4 \times 10^{36}$ erg s$^{-1}$, right at the observed threshold for bright PWNe. Since the spectral index likely reflects the spectrum of the injected wind particles (Pacini & Salvati 1973), a critical phenomena in the acceleration process may be responsible for the observed threshold, perhaps turning off the pulsar wind or the PWN shock and allowing the nebula to fade with time and/or $\dot{E}$. For this fossil PWN, the above $\Gamma$ vs $\dot{E}^{-1/2}$ relationship likely becomes invalid; some evidence for this is provided by preliminary spectra of faint nebulae belonging to the less energetic pulsars.
The basic result presented herein is also seen in the radio waveband where only the most energetic rotation-powered pulsars are found to display a radio PWN (Cohen et al. 1983; Frail & Scharringhausen 1997; Gaensler et al. 2000). The $\dot{E}_c$ threshold is also found to be applicable at these wavelengths, as none of the less energetic pulsars display a radio PWN at all, despite a sensitive search at 1.4 GHz around 27 pulsars with $1.2 \times 10^{32} < \dot{E} < 2.8 \times 10^{36}$ erg/s by Gaensler et al. (2000). Possible exceptions are PSR J0908-4913, a pulsar with weak ($F_{\text{PWN}}/F_{\text{PSR}} < 1/16$ @ 1.2–2.2 GHz), barely resolved radio emission (Gaensler et al. 1998), and PSR J1856+0113 in SNR W44 with an apparent PWN. The latter object, however, is unusual and its exact nature requires further study.

Because the $\dot{E}$ of the pulsars in the survey herein are unlikely to be correlated with the local density, this parameter is not a key factor for producing a detectable radio PWN as often claimed. Nor is a young age likely a sufficient condition for generating a PWN, considering the examples of PSR J1119–6127, a young pulsar ($P/2\dot{P} = 1.6$ kyr) in the radio shell G292.2–0.5 lacking a PWN (e.g. Crawford et al. 2001).

2. Conclusions

- The spin-down energy loss rate is a key evolutionary parameter for rotation-powered pulsars.
- A threshold exist $\dot{E}_c \approx 3.4 \times 10^{36}$ erg s$^{-1}$ below which the generation of a PWN is greatly reduced (in X-rays) and/or undetected (in radio).
- A Crab-like pulsar is defined as a rotation-powered pulsars with $\dot{E} > \dot{E}_c$.
- A young age or a high local density environment is not a sufficient condition for generating a PWN, as often suggested.

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