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

E. V. Gotthelf

Columbia Astrophysics Laboratory, Columbia University, 505 West 120th Street, New York, NY 10027, USA

Abstract. A systematic X-ray survey of the most energetic rotation-powered pulsars known, based on spin-down energy loss rate, shows that all energetic pulsars with $\dot{E} > \dot{E}_c \approx 4 \times 10^{36}$ ergs s^{-1} are X-ray-bright, manifest a distinct pulsar wind nebula (PWN), and are associated with a supernova event, with over half residing in shell-like supernova remnants. Below $\dot{E}_c$, the 2–10 keV flux ratio F_{PWN}/F_{PSR} decreases by an order-of-magnitude. This threshold is consistent with the lower limit on the spectral slope $\Gamma_{\rm min} \approx 0.6$ observed for rotation-powered pulsars (Gotthelf 2003). The apparent lack of bright PWNe below $\dot{E}_c$ 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 $\dot{E}$ 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 ATNF pulsar catalog,[1] ordered by spin-down power $\dot{E}$ ($= I\omega\dot{\omega}$, where I is the neutron star moment of inertia and ω is its angular velocity). These include all known pulsars detected in both radio and X-ray with $\dot{E} > 1.8 \times 10^{36}$ ergs s^{-1} (except one millisecond pulsar in this range). Twenty-five objects are radio pulsars and 21 are X-ray pulsars, of which only three are detected in X-rays alone. So far, five 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). Here we compared these fluxes with $\dot{E}$ and present the flux ratio F_{PWN}/F_{PSR}, where F_{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, including the nine brightest X-ray PWNe used in the initial study of Gotthelf (2003). When ordered by $\dot{E}$ it is apparent that all pulsars with $\dot{E} \gtrsim 4 \times 10^{36}$ ergs 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

[1]See `http://www.atnf.csiro.au/research/pulsar/catalogue`.

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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 exists.

Table 1: Pulsars ordered by spin-down power.

Pulsar	Remnant	$\dot{E}$ $\times 10^{36}$ (ergs s^{-1})	Dist[a] (kpc)	$\epsilon^b = L_X/\dot{E}$	F_{PWN}/F_{PSR}	Code[c]
J0537−6910	N157B	481.6	49	0.003	15	s-x
J0534+2200	Crab (SN1054)	440.6	2.0	0.03	30	srx
J0540−6919	SNR 0540−69	146.5	49	0.05	4	srx
J0205+6449	3C 58 (SN1181)	27.0	3.2	0.0004	60	srx
J2229+6114	G106.3+2.7	22.5	12	0.001	9	-rx
J1513−5908	MSH 15−52	17.7	5.0	0.01	5	srx
J1617−5055		16.2	6.5	0.001	...	-rx
J1124−5916	G292.0+1.8	11.9	5.4	0.0002	10	-rx
J1930+1852	G54.1+0.3	11.6	5	0.002	5	srx
J1420−6048	Kookaburra	10.4	7.7	0.004	10	-rx
J1846−0258	Kes 75	8.3	19	0.15	23	s-x
J0835−4510	Vela SNR	6.9	0.3	0.0001	9	srx
J1811−1925	G11.2−0.3	6.4	5	0.006	9	s-x
J1112−6103		4.5	...	...	...	-r-
J1952+3252	CTB 80	3.7	2.5	0.0005	1.1	-rx
J1709−4429	G343.1−2.3?	3.4	2.5	0.0001	3.5	-rx
J2021+3651		3.4	10	...	...	-r?
J1524−5625		3.2	3.8	...	...	-r?
J1913+1011		2.9	4.5	...	...	-r?
J1826−1334		2.9	4.1	0.0008	2.3	-rx
J1801−2451		2.6	4.6	0.0008	0.1	-rx
J1016−5857		2.6	9.3	...	...	-rx
J1105−6107		2.5	7.1	...	...	-r-
J1119−6127	G292.2−0.5 (radio)	2.3	4	0.00005	0.2	-rx
J1803−2137		2.2	4.0	...	...	-rx
J1048−5832		2.0	3.0	...	...	-rx
J1837−0604		2.0	6.2	...	...	-r?
J0940−5428		1.9	4.3	...	...	-r?

[a]Best estimate of the pulsar distance from the literature.
[b]Efficiency, the ratio of pulsar luminosity ($L_X \equiv F_X 4\pi d^2 = L_{PWN} + L_{PSR}$) in the 2–10 keV band, following the procedure of Gotthelf (2003), and $\dot{E}$.
[c]s=*Chandra* survey PWN object (Gotthelf 2003); r=radio source; x=X-ray source.

In contrast, pulsars with $\dot{E} < \dot{E}_c \approx 4 \times 10^{36}$ ergs s^{-1} 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 PSRs J1709−4420 (Gotthelf, Halpern & Dodson 2002) and J2021+3651, a newly discovered pulsar with a similar $\dot{E}$ (Roberts, these 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, Srinivasan & Sangwook 1996). Finally, arcsecond localization of J1105−6107, previously

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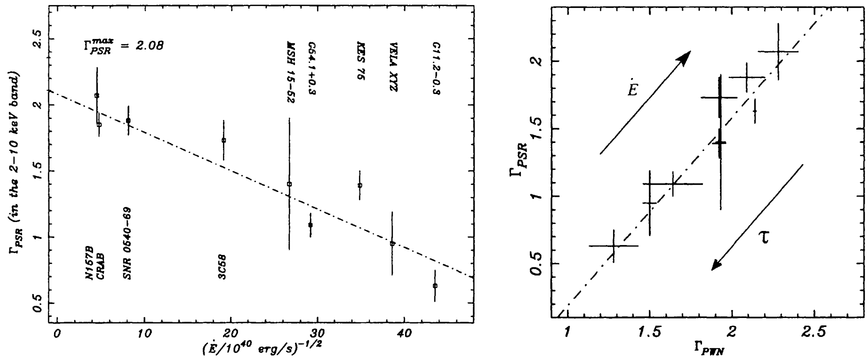

Figure 1. *Left panel:* A comparison between the 2–10 keV spectral slope of the nine brightest known pulsars ($\Gamma_{\rm PSR}$) and $\dot{E}_{40}^{-1/2}$, with $\dot{E}$ in units of 10^{40} ergs s^{-1}. The dashed line indicates the best-fit model. *Right panel:* Relationship between the above pulsars' $\Gamma_{\rm PSR}$ and that of their wind nebulae ($\Gamma_{\rm PWN}$), 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).

associated with X-ray emission (Gotthelf & Kaspi 1998), shows that the X-rays originate from an unrelated nearby source.

Evidently all pulsars with $\dot{E} > \dot{E}_c$ display bright PWNe while for the less energetic pulsars the nebular 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 sub-luminous relative to their PSR flux. This comparison is best done statistically since the distance estimates are mostly uncertain (factor ~ 2). Above $\dot{E}_c$, the average flux ratio for these pulsars is of order ~ 14, while the less energetic pulsars have a ratio of order ~ 1.5. This factor of 10 change in the relative X-ray flux cannot be explained as a distance bias, as the range of distances overlap between the less and more energetic pulsars (see Table 1).

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 $\dot{E}$ — the more energetic the pulsar, the steeper its spectrum. This relation is given by $\Gamma_{\rm PSR} = \Gamma_{\rm max} + \alpha\dot{E}^{-1/2}$ with a minimum observed $\Gamma_{\rm min} \approx 0.6$ (see Fig. 1). Most interestingly, $\Gamma_{\rm min}$ corresponds to $\dot{E}_c \approx 4 \times 10^{36}$ ergs 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 1973a, b), 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 Γ vs. $\dot{E}^{-1/2}$ relationship likely becomes invalid; some evidence for this is provided by preliminary spectra of faint PWNe belonging to the less energetic pulsars.

The basic result presented here is also seen in the radio band 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 $1.2 \times 10^{32} < \dot{E} < 2.8 \times 10^{36}$ ergs s^{-1} by Gaensler et al. (2000). Possible exceptions are PSRs J0908−4913, a pulsar with weak ($F_{PWN}/F_{PSR} < 1/16$ at 1.2–2.2 GHz), barely resolved radio emission (Gaensler et al. 1998), and J1856+0113 in SNR W44 with an apparent PWN. The latter object, however, is unusual and its exact nature requires further study.

Because $\dot{E}$ of the pulsars discussed here is unlikely to be correlated with local density, density 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 example of PSR J1119−6127, a ~ 1600-yr-old pulsar in the radio shell G292.2−0.5 lacking a PWN (e.g. Crawford et al. 2001).

2. Conclusions

The main conclusions of this study are: (a) $\dot{E}$ is a key evolutionary parameter for rotation-powered pulsars; (b) a threshold exists, $\dot{E}_c \approx 4 \times 10^{36}$ ergs s^{-1}, below which the generation of a PWN is greatly reduced (in X-rays) and/or undetected (in radio); (c) a Crab-like pulsar is defined as a rotation-powered pulsar with $\dot{E} > \dot{E}_c$; (d) 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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