Insights into pulsars' magnetic field evolution and energy loss mechanisms from studying pulsar-SNR associations

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Abstract

The characteristic ages of neutron stars are often inconsistent with their hosting supernova remnant (SNR) ages. We address this discrepancy by studying a sample of pulsars, including those with extreme magnetic fields (such as magnetars and the Central Compact Objects, CCOs), securely associated with SNRs. We discuss the implications of our study to magnetic field evolution in neutron stars and their distinct energy loss mechanisms.

Constant Power-Law Torque

The magnetic fields of neutron stars are generally assumed to be well represented by a dipole. However, the dipole field is too simple to represent real neutron stars. It produces a spin-down torque with a braking index n=3, often causing the characteristic age and SNR age to significantly differ from one another.

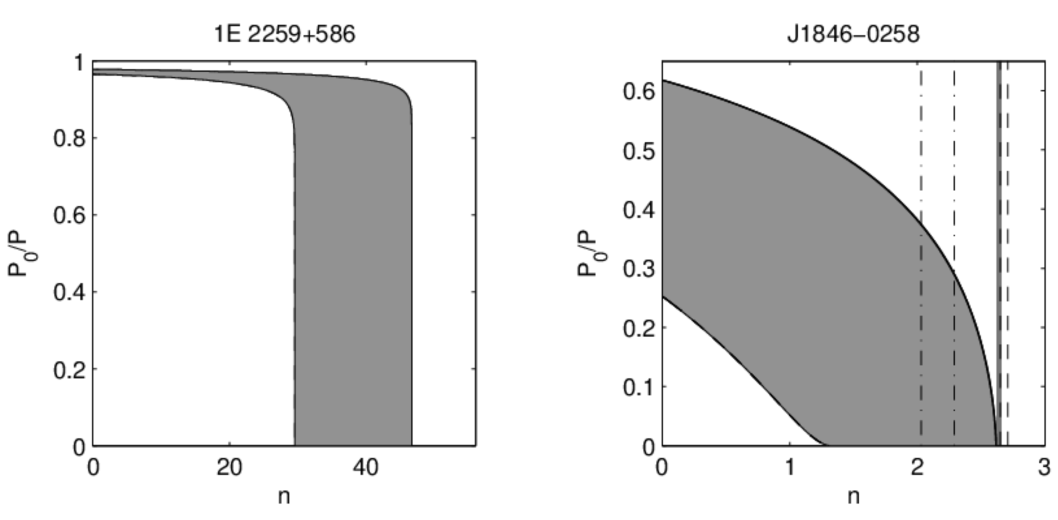
The dipole age formula for general torque with braking index (n) and arbitrary initial period (P_0) is shown below, and compared to the SNR age estimate summarized in the Table below (1).

$$\tau = \frac{P}{(n-1)\dot{P}}\left[1-\left(\frac{P_0}{P}\right)^{(n-1)}\right]$$

NS (SNR)	τ (kyr)	t_{SNR}(kyr)
AXP 1E1841-045 (Kes 73)	4.75	0.75 - 2.10
AXP 1E 2259+586 (CTB 109)	228	10 - 16
CXOU J171405.7-381031 (G348.7)	0.95	0.35 - 3.15
Swift J1834.9-0846 (W41)	4.94	60 - 200
SGR 0526-66 (N49)	3.36	< 4.8
SGR 1627-41 (G337.3)	2.16	< 5.0
PSR J1119-6127 (G292.2)	1.62	4.2 - 7.1
PSR J1846-0258 (Kes 75)	0.73	0.9 - 4.3
RX J0822.0-4300 (Puppis A)	214	3.7 - 5.2
1E 1207.4-5209 (PKS 1209)	1.02×10^5	2.0 - 20.0
CXOU J185238.6+004020 (Kes 79)	1.92×10^5	5.4 - 7.5

Table 1: PSR-SNR ages for a selected sample (1, 3). Listed are secure associations for magnetars (AXPs and SGRs), the high-B pulsars (HBPs) and Central Compact Objects (CCOs).

The behaviour of τ is shown below in two examples. A constant power-law torque can satisfy the SNR age constraints, but may not simultaneously fit the measured braking indices of the HBPs (e.g., J1846-0258), which seem to be time-dependent.



HBP Name	Braking index (n)
PSR J1119-6127 (G292.2)	2.684±0.002
PSR J1846-0258 (Kes 75)	2.16±0.13

Contrary to the assumption of a point-like magnetic dipole in vacuum, the braking indices of young pulsars differ from n=3.

Magnetic Field Evolution

A number of alternative scenarios exist to explain the age discrepancy between neutron stars with extreme magnetic fields and their associated SNRs. A magnetic field that evolves in time produces a braking index n:

$$n = 3 - 4\tau\frac{\dot{f}}{f}$$

Magnetic field decay (2) is a mechanism that can affect the braking index by introducing a time dependency to the dipole field. Suppose the field decays as:

$$B_{\rm D}(t) = B_{\rm init} f_{\rm D}(t)$$

$$f_{\rm D}(t) = \begin{cases} \left(1+\alpha\frac{t}{\tau_{\rm m}}\right)^{-\frac{1}{\alpha}}, & \alpha \neq 0,2 \\ \exp\left(-\frac{t}{\tau_{\rm m}}\right), & \alpha = 0 \end{cases}$$

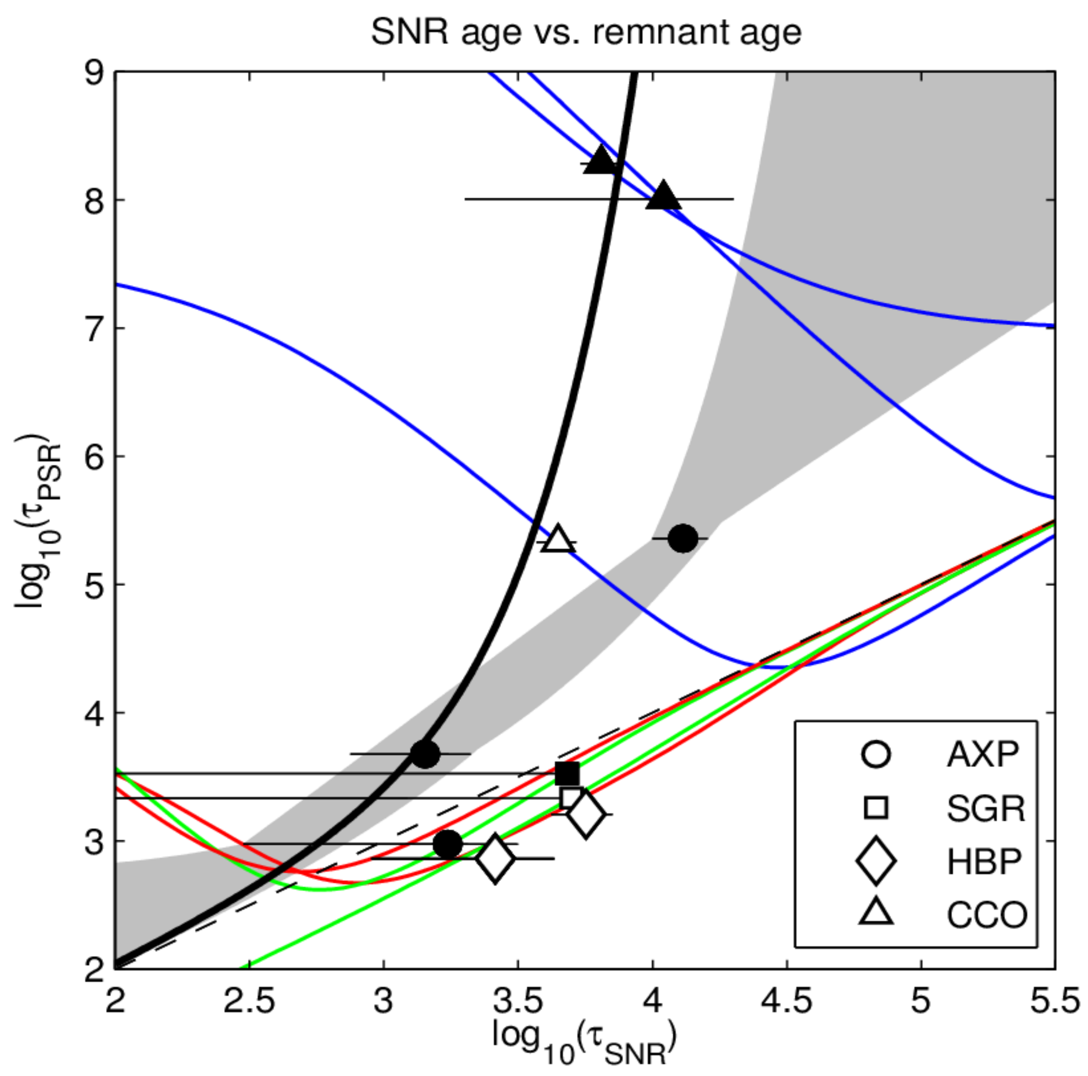
with index α, time-scale τ_m and initial field B_{init}.

A scenario which can account for braking indices and SNR age discrepancy may be solved by magnetic field growth (3), which occurs when a magnetic field is buried by an initial phase of fall-back accretion. If a field is buried its re-emergence causes the external field to grow (4):

$$B_{\rm G}(t) = B_{\rm final} f_{\rm G}(t)$$

$$f_{\rm G}(t) = \epsilon + \begin{cases} 1-\left(1+\alpha\frac{t}{\tau_{\rm m}}\right)^{\frac{\alpha-1}{\alpha}}, & 0<\alpha<1 \\ 1-\exp\left(-\frac{t}{\tau_{\rm m}}\right), & \alpha = 0 \end{cases}$$

with parameters as above, except final field strength B_{final}.



Field evolution in Neutron Stars: The constraints imposed by a joint fit to the AXPs using field decay are shown in gray. We make no assumptions about the initial spin periods. This family of solutions includes those found by Nakano et al 2015 (5) studying 1E2259+586. The CCOs are approximately fit by an exponential decay (solid black line), but are more naturally explained by field growth (blue curves). Growth was also used to fit the HBPs (red) and SGRs (green). See (3) for details.

While field decay can explain the evolution of the CCOs, the exponential behaviour required is considered an unlikely mode of field decay due to rapid evolution at relatively recent times in the past. However the age discrepancy of the CCOs can be naturally accommodated by field growth. Field growth makes sources look old early on, explaining why the characteristic age and SNR age vary significantly for those young objects. In this evolutionary scenario all objects with growing fields pass through a CCO phase, thus connecting the apparent different classes of neutron stars.

Relativistic Winds

Another possibility is the emission of a relativistic particle wind (6). This is particularly relevant for the pulsars powering wind nebulae. The particle wind reduces the dipole field strength and reduces the braking index 1 < n < 3. The wind is active with a duty cycle D_P and the remainder of the time spins down like a magnetic dipole.

$$\dot{E}_{DW} = \dot{E}_D(1-D_p) + \dot{E}_W D_p$$

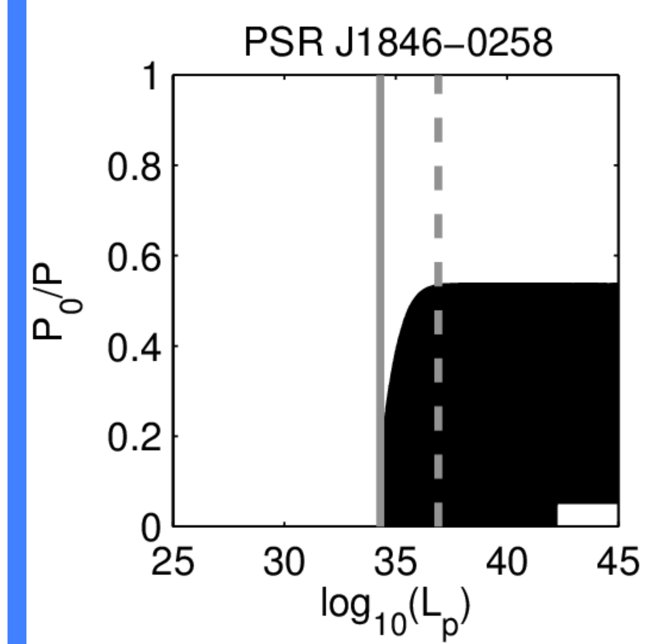
The energy of a spinning down magnetic dipole is given by dE_D/dt:

$$\dot{E}_D = \frac{B^2R^6\Omega^4}{6c^3}$$

$$\dot{E}_W = B_0 R^3\Omega^2\sqrt{\frac{L_p}{6c^3}}$$

The wind has a particle luminosity L_p and carries a total energy E_D.

The expression for the energy loss is integrated from the initial spin period (P_0) to the observed period (P). When the duty cycle D_P=0, the NS spins down like a dipole (n=3) and when D_P=1 the NS spins down by a pure wind (n=1).



An example of a constraint due to wind emission. The initial period P0 of the J1846 system can be constrained by assuming braking by wind emission. The solid line is the observed X-ray luminosity and the dashed line the rotational energy loss.

Alternatives and Summary

The specifics of the spin-down mechanism in magnetars, HBPs and CCOs are not known in detail. We have focused here on an evolving magnetic field and the emission of a particle wind. However there are many other such mechanisms that modify the physics of the NS spin-down, including cooling, variable moment of inertia due to the dynamics of a superfluid core and multipolar magnetic fields. Interactions with the surrounding environment, such as accretion of fall-back material or from a binary companion also affect NS evolution. We intend to study a variety of other such mechanisms in future work.

This work was motivated by the observed diversity of PSRs in SNRs blurred by observations connecting the different classes. This study further highlights the need to increase the sample of secure and reliable PSR-SNR associations, and motivates a refinement of the SNR ages, e.g., through high-resolution X-ray spectroscopic studies of SNR shells and/or proper motion measurement of the shock velocity.

Acknowledgements/References

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