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

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Abstract

The characteristic ages of neutron stars (NSs) 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.

1 Introduction

Generally it is assumed that neutron stars (NSs) lose energy by spinning down due to the emission of magnetodipole radiation. However, this simple model does not neatly describe the entirety of the NS population for a number of reasons. First, it predicts a braking index $n = 3$, which has not been observed in young neutron stars. Most of these objects have $n < 3$ (Espinoza, 2013), except for PSR J1640–4631 with $n = 3.15$ (Archibald et al., 2016). Second, the NSs with secure supernova remnant (SNR) associations show a remarkable disparity between the SNR age and the NS characteristic age, in some cases differing by several orders of magnitude (as compiled in SNRcat[1]). Generally, we are unable to explain the observed braking indices and enforce the consistency of the NS–SNR ages using a constant braking index, motivating a review of magnetic field evolution and of energy loss mechanisms.

We focus on the diverse population of NSs with 'anomalous' magnetic fields (i.e. much higher or lower than the canonical value of 10^{12} Gauss) and with secure associations with SNRs. These objects include the anomalous X-ray pulsars (AXPs), soft gamma repeaters

[1] http://www.physics.umanitoba.ca/snr/SNRcat

Observed properties of NSs

Name	n	τ (kyr)	τ_{SNR} (kyr)
AXP 1E 1841–045 (Kes 73)		4.75	0.75 - 2.10
AXP 1E 2259+586 (CTB 109)		228	10.0 - 16.0
CXOU J171405.7–381031 (G348.7)		0.95	0.35 - 3.15
SGR 0526–66 (N49)		3.36	< 4.80
SGR 1627–41 (G337.3)		2.16	< 5.0
HBP J1119–6127 (G292.2)	2.684 ± 0.002	1.62	4.20 - 7.10
HBP J1846–0258 (Kes 75)	2.19 ± 0.03	0.73	0.90 - 4.30
RX J0822.0–4300 (Puppis A)		214	3.70 - 5.20
1E 1207.4–5209 (PKS 1209–51/52)		3.01×10^5	2.00 - 20.0
CXOU J185238.6+004020 (Kes 79)		1.92×10^5	5.40 - 7.50

Table 1: A summary of our PSR sample with secure SNR associations. For a given PSR–SNR pair, we give the braking index n (when known), the NS's characteristic age (τ) and the SNR's age range (τ_{SNR}). See Rogers & Safi-Harb (2016a, 2016b) for details and references.

(SGRs), high magnetic field pulsars (HBPs) and central compact objects (CCOs) associated with SNRs of known ages.

2 Magnetic field evolution and relativistic particle winds

A variable braking index can be found using a time-dependent magnetic field. Let us suppose the time-dependent field can be written as $B(t) = B_i f_i(t)$, where the time-dependence has been gathered into the function $f_i(t)$ and B_i is a constant. We label a decaying field, with $i = D$, where B_D is the initial magnetic field. A growing field is labelled with $i = G$ and is parameterized in terms of the final field, B_G. This field evolution gives a time-dependent braking index

$$n = 3 - 4\frac{\dot{f}_i}{f_i} \tag{1}$$

which depends on the specific details of f_i. For decaying fields we use

$$f_D(t) = \begin{cases} \left(1 + \alpha\frac{t}{\tau_m}\right)^{-\frac{1}{\alpha}}, & \alpha \neq 0, 2 \\ \exp\left(-\frac{t}{\tau_m}\right), & \alpha = 0 \end{cases} \tag{2}$$

and growing fields have

$$f_G(t) = \epsilon + \begin{cases} 1 - \left(1 + \alpha\frac{t}{\tau_m}\right)^{\frac{\alpha-1}{\alpha}}, & 0 < \alpha < 1 \\ 1 - \exp\left(-\frac{t}{\tau_m}\right), & \alpha = 0 \end{cases} \tag{3}$$

with field index α, time-scale τ_m and a constant ϵ that relates the initial and final field strength. These parametric functions for field evolution and their implications are discussed

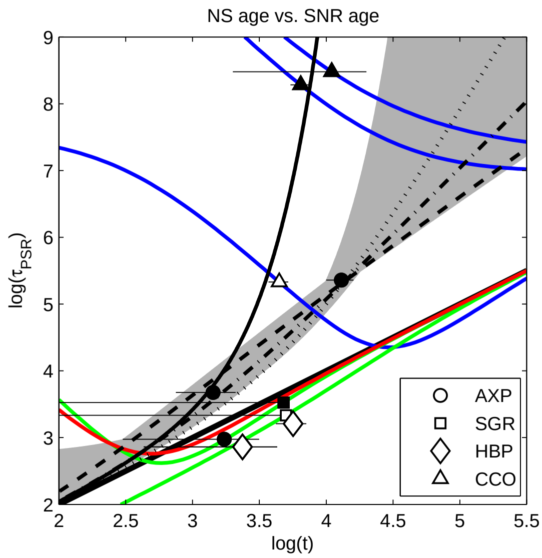

Figure 1: Evolutionary tracks for NS and SNR pairs with evolving magnetic fields. Coloured lines show field growth and black lines (CCOs and AXPs) show field decay. The grey regions are the joint fits to the AXPs. Filled symbols label objects with X-ray luminosity in excess of their spin-down energy loss, $L_X > \dot{E}$. This figure is reproduced from Rogers & Safi-Harb (2016b).

in Rogers & Safi-Harb (2016a, 2016b). We show the evolution of the NS characteristic age and the measured SNR ages in Figure 1. The solid black line is a joint fit to the CCOs, which requires exponential decay. The dashed, dotted and dash-dotted lines are the solutions found by Nakano et al. (2015) for the joint fit to the AXPs in the limit of a small initial period P_0. Our fits with general P_0 occupy the grey region. Field growth evolution is shown by the coloured curves. Since exponential field decay is considered an unphysical decay mode (Nakano et al., 2015) we favour field growth to explain the CCOs. In this scenario fall-back matter accretes on the surface of the NS following birth, which buries the observable field that slowly emerges (Ho, 2015). This scenario predicts the HBPs and CCOs are related by evolution, and should both show $n < 3$ which is observed in the HBPs J1846–0258 and J1119–6127 (Espinoza, 2013).

Another possibility for magnetar energy loss is the emission of a relativistic wind of particles. Suppose that a wind with luminosity L_p is active in addition to the dipole field, with a duty cycle D_p. The energy loss is

$$\dot{E}_{DW} = \dot{E}_D\,(1 - D_p) + \dot{E}_W D_p; \tag{4}$$

$\dot{E}_D$ is the energy loss from magnetodipole radiation, and the particle wind contribution is

$$\dot{E}_W = BR^3\Omega^2\sqrt{\frac{L_p}{6c^3}}. \tag{5}$$

The resulting braking index is

$$n = 3 + \frac{\Omega}{\dot{\Omega}} \frac{2D_p B R^3}{I} \sqrt{\frac{Lp}{6c^3}} \tag{6}$$

giving $1 \leq n \leq 3$ (Harding et al., 1999). In general, more complicated models exist that include the details of the particle acceleration gap and emission geometry. These models have been shown to work well in describing the change in HBP braking index in response to glitches when the effect of a varying particle luminosity is included (Kou et al., 2016). This is discussed further in Rogers & Safi-Harb (2016b).

3 Discussion and Conclusions

While we have focused on magnetic field evolution and particle wind emission, many alternatives exist. These include the physics of NS spin-down such as cooling, a variable moment of inertia due to the dynamics of a superfluid core and the influence of multipolar magnetic fields. Interactions with the surrounding environment such as the accretion of fall-back material or from a binary companion also affect NS evolution. Our work highlights the need to increase the sample of secure and reliable PSR–SNR associations, and motivates both a further refinement of the SNR ages and a more complete and long-term measurement of PSR braking indices.

Acknowledgments

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