Probing the magnetic field evolution of normal radiopulsars

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Abstract

We report on the nearly direct evidence of the evolutionary decay of the magnetic fields of normal radiopulsars. Adopting a novel, robust timing-based formula for the magnetic field estimation (see the poster by Biryukov, Astashenok and Beskin) and considering the subset of 76 pulsars with independently known ages (from PSR-SNR associations as well as kinematic ages) we calculate the parameters of their apparent $B(t)$ dependence. We found a quite significant trend in the data so that $B(t) \propto t^{-a}$ asymptotically with $a = 0.21 \pm 0.04$. This result is unlikely due to any selectional effects and appear to be well consistent with the existing theoretical models of pulsars magnetic field decay.

Introduction

The strength of the magnetic field of a given NS is believed to secularly evolve with time. Its evolution is generally driven by the Ohmic decay of the electric currents which flow in the star crust and/or core. This idea appears to be very productive for understanding the observational data in hand – the timing properties, x-ray luminosity and cooling of various types of highly magnetized neutron stars.

However, more or less direct measurements of NS magnetic fields can be only obtained with the methods that are based on the accretion and/or emission physics These methods are applicable only for a few dozen of high energy sources, typically in binary systems. At the same time the direct probing of NS magnetic field decay also requires a confident and independent measurements of NS ages.

Adopting the realistic spin-down law of normal radiopulsars in a form $P\dot{P} \propto B^2(1+\sin^2\alpha)$, we have recently proposed the refined formula for the simple, timing-based estimation of the magnetic field B of an isolated pulsar (**see the poster by Biryukov, Astashenok and Beksin, BAB16 hereafter**). In this work we extend and implement this result. So, if P is the NS spin period, then

$$\log B(P, \dot{P}) = \log B_{\rm md}(P, \dot{P}) + \Delta_{\rm B}^{(\rm eos)}(M, \alpha) + \Delta_\varepsilon \qquad (1)$$

where $B_{\rm md} = 3.2 \times 10^{19}\sqrt{P\dot{P}}$ Gs, while $\Delta_{\rm B}^{(\rm eos)}$ is the correction term depending on the NS mass M, obliquity α and adopted equation of state (EOS). The additional term Δ_ε is also added here in order to describe pulsars timing irregularities. It is can be generally assumed that observed spin-down rate $\dot{P}_{\rm obs} = \dot{P}(1-\varepsilon)$, where ε is the variational term. So

$$\Delta_\varepsilon = -\log\sqrt{1-\varepsilon}.$$

In the current work we implement (1) to constrain the surface magnetic field for $70+$ pulsars with independently known ages and probe the evolutionary decay of this parameter.

Objectives

- Collect a subset of isolated radiopulsars with confidently and *independently* known ages (relative to the most common spin-down age $\tau_{\rm sd} = P/2\dot{P}$).
- Constrain their surface magnetic fields using the refined timing-based estimator (1) and adopting one of the realistic equations of state.
- Analyze the apparent correlation $B(t)$ for these pulsars and make a conclusion about the evolutionary decay of their magnetic fields.
- Compare the apparent $B(t)$ cloud with the existing theoretical predictions.

Pulsars parameters

Ages

We have collected:

- The subset of 22 supernova remnants (SNRs) associated with normal pulsars, ages of which have been discussed in literature. The subset is mostly the compilation of the data already prepared in [5] and [2] with some extension, including a few other SNRs. Prior distributions of the ages of these pulsars have been suggested to be uniform in the interval $(t_{\rm snr,min}, t_{\rm snr,max})$.
- The subset of 36 well-constrained kinematic ages of isolated pulsars (mostly derived in [4]). The prior distributions of their logarithmic ages have been described with two-sided gaussian representing the asymmetric errors: $\log t_{\rm kin} = (\log t_{\rm kin,0})^{+\sigma_+}_{-\sigma_-}$.
- The kinematic ages of 18 isolated pulsars derived with low precision (all from [4]). Their priors have been modeled as uniform on the interval $(\log t_{\rm kin,0} - 1.5, \log t_{\rm kin,0} + 1.5)$ where $t_{\rm kin,0}$ is in years.

So, in total, our list of independently measured ages of normal radiopulsars consists of 76 records.

Magnetic fields

Within our research we model the strength of the pulsars surface magnetic fields accordingly to the equation (1). We use the observed spin periods P and their derivatives $\dot{P}$ as basic observational data, neglecting the small measurement errors σ_P and $\sigma_{\dot{P}}$.

The information about pulsars masses M, obliquities α and spin-down irregularities ε have been involved into analysis as prior distributions of these parameters. For M and α we use the same distributions as in our previous research (see BAB16).

In turn, the distribution of Δ_ε over the pulsars population is not so evident. Moreover, it remains unclear whether this correction has to be taken into account at all. Indeed, if the unmodeled timing irregularities of radiopulsars are the result of the complex evolution of either the angle α or moment of inertia I or magnetic field B, then $B \propto \sqrt{P_{\rm obs}\dot{P}_{\rm obs}}$ in the strict sense for any moment of time. Which means $\varepsilon \equiv 0$. On the other hand, it has been derived in [1] that

$$-0.8 \lesssim \varepsilon \lesssim 0.8 \qquad (2)$$

for real pulsars. Therefore, in the calculations below we have adopted the distribution for ε in three different ways: (I) $\varepsilon \equiv 0$; (II) $\varepsilon = 0.8\sin\varphi$, where variational phase $\varphi \sim \mathrm{uniform}(0, 2\pi)$; (III) $\varepsilon \sim \mathrm{uniform}(-0.8, 0.8)$.

The equation of state

The important point is that the formal uncertainty $\sigma[\Delta_{\rm B}^{(\rm eos)}]$ of the first correction term in (1) is weakly dependent on the choice of the equation of state (see BAB16). Indeed, a given EOS only introduces a constant bias $\langle\Delta_{\rm B}^{(\rm eos)}\rangle$ to the estimation $\log B(P, \dot{P})$. This bias is common for all pulsars and can not affect the shape (e.g. a slope) of an apparent correlation between the timing-based magnetic fields and pulsars' real ages. Although it affects the estimation of the average value of the initial magnetic field $\log B(0)$. Therefore, any realistic EOS can be, in principle, adopted within the probing of magnetic field evolution of radiopulsars. In orderr t o be concrete hereafter we adopted the BSk21 equation of state.

Results

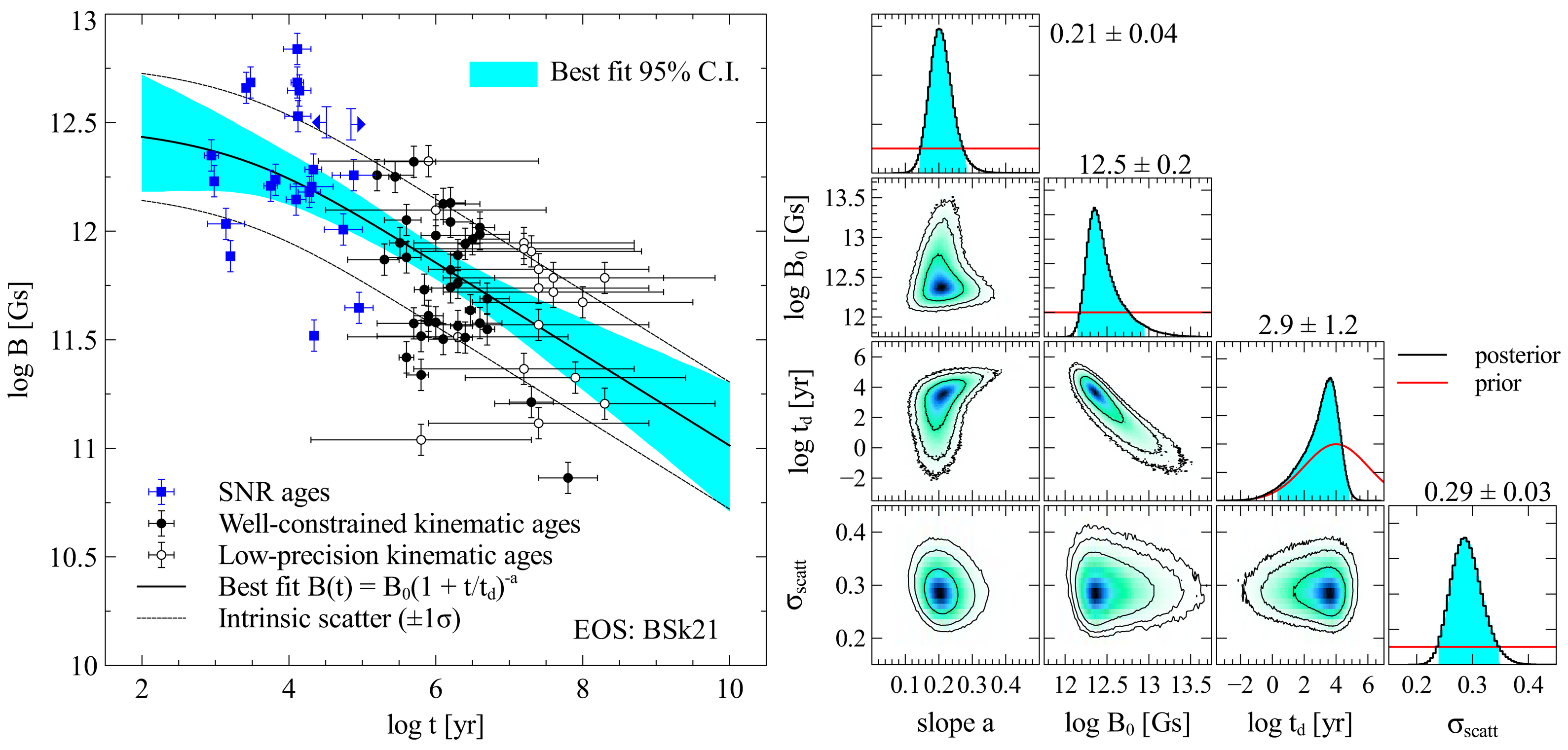

Figure 1: *Left plot*: The apparent dependence of the timing-based magnetic field values, calculated within the BSk21 equation of state, on the independent estimation of ages of 76 pulsars. The Bayesian best fit by the phenomenological model $B(t) = B_0(1 + t/t_d)^{-a}$ is shown by the solid line with corresponding 95% confidence filled by cyan. The dashed lines represent $\pm 1\sigma_{\rm intr}$ of the estimated intrinsic scatter in observed $\log B$ due to different physical parameters of pulsars. A highly significant evolutionary trend $B(t)$ can be seen. *Right plot*: The results of the Bayesian reconstruction of posterior distributions of the apparent magnetic field decay parameters assuming $\varepsilon = 0$. The posterior distributions of the slope a, initial magnetic field B_0, field decay timescale t_d and intrinsic scatter standard deviation $\sigma_{\rm scatt}$ are shown. The solid-line contours on the 2-d plots represent 68, 95 and 99% confidence areas respectively.

Variational term	initial $\log B_0$ [Gs]	slope a	time $\log t_d$ [yr]	intr. scatter, $\sigma_{\rm scatt}$ [dex]
$\varepsilon = 0$ (shown in the Fig. 1)	12.5 ± 0.2	0.21 ± 0.04	2.9 ± 1.2	0.29 ± 0.03
$\varepsilon = 0.8\sin\varphi$ with $\varphi \sim \mathrm{uni}(0, 2\pi)$	12.4 ± 0.2	0.20 ± 0.03	2.8 ± 1.1	0.20 ± 0.03
$\varepsilon \sim \mathrm{uni}(-0.8, 0.8)$	12.4 ± 0.3	0.21 ± 0.07	3.3 ± 1.5	0.08 ± 0.05

Table 1: Parameters of the Bayesian fit of the apparent $B(t)$ dependence assuming different models for the variational term Δ_ε in (1)

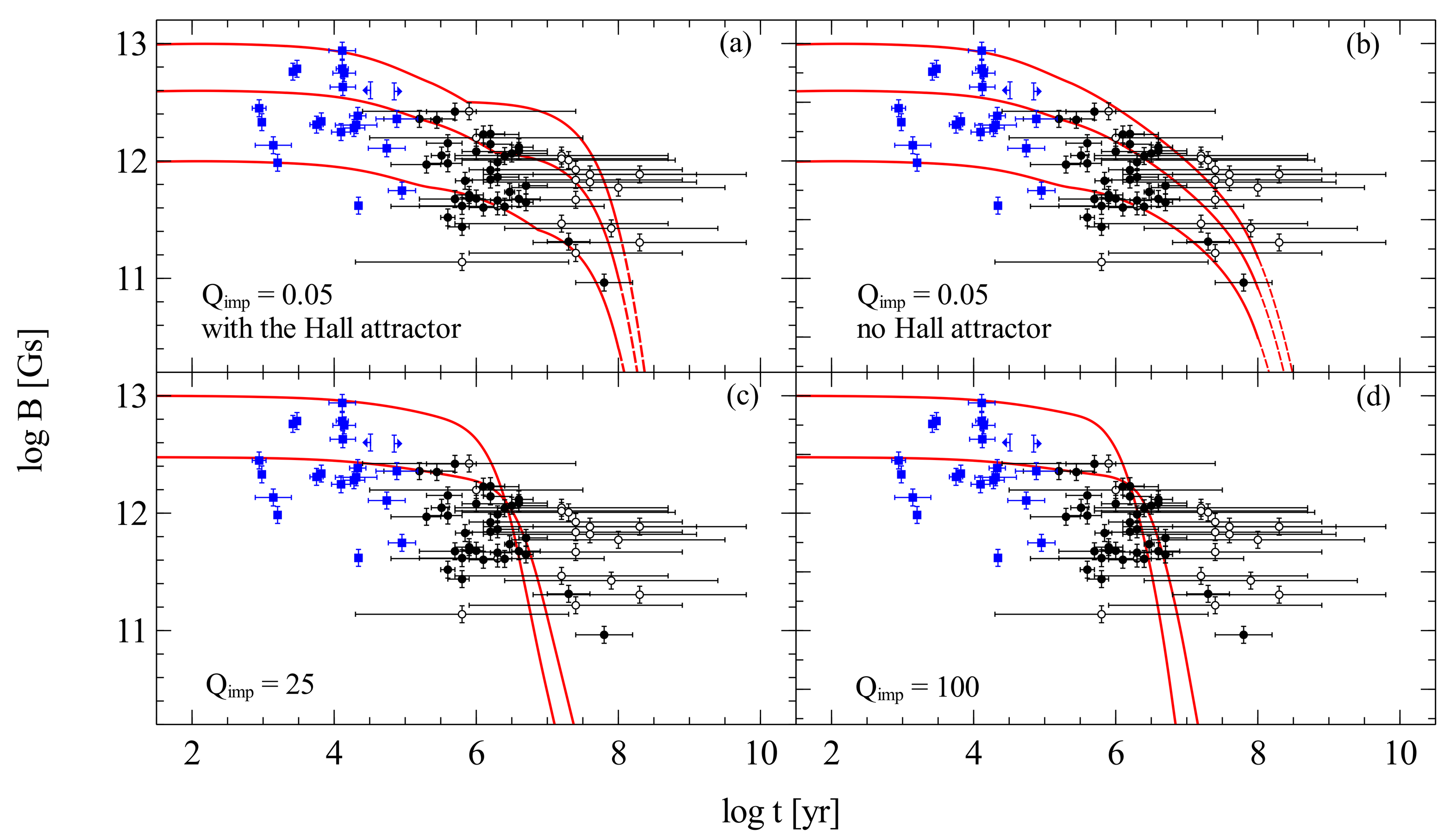

Figure 2: Theoretical curves of a pulsar magnetic field decay (red lines). **(a)** The phenomenological model proposed in [3] and calculated for initial magnetic field $B_0 = 10^{12}$, $10^{12.2}$ and 10^{13} Gs. It assumes quite low amount of the impurities in the NS crust and the existance of the Hall attractor at final evolutionary stages; **(b)** The same model as in the panel (a) but without Hall attractor; **(c)** The evolutionary tracks from [6] assuming larger amount of impurities and calculated for $B_0 = 3 \times 10^{12}$ and 10^{13} Gs; **(d)** The same model as in the panel (c) but for even larger impurities parameter Q.

Conclusions

- Using the ages of 22 supernova remnants associated with young pulsars and 54 kinematic ages of older sources as well as the refined version of the timing-based estimator of pulsars magnetic fields, we have found that $\log B$ of normal radiopulsars decays so that $B(t) \propto t^{-0.21 \pm 0.04}$ asymptotically.
- The ascertained trend $B(t)$ is consistent with the theoretical models of magnetic field decay in normal radiopulsars, especially with those assuming the low amount of impurities in a NS crust.

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