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Magnetic field decay in normal radio pulsars

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We analyse the origin of the magnetic field decay in normal radio pulsars found by us in a recent study. This decay has a typical time scale \( \sim 4 \times 10^5 \) yrs, and operates in the range \( \sim 10^{12} \) – \( \sim 10^9 \) yrs. We demonstrate that this field evolution may be either due to the Ohmic decay related to the scattering from phonons, or due to the Hall cascade which reaches the Hall attractor. According to our analysis the first possibility seems to be more reliable. So, we attribute the discovered field decay mainly to the Ohmic decay on phonons which is saturated at the age \( \sim 10^7 \) yrs, when a NS cools down to the critical temperature below which the phonon scattering does not contribute much to the resistivity of the crust. Some role of the Hall effect and attractor is not excluded, and will be analysed in our further studies.

1 Introduction

Observational appearances of most (if not all) types of neutron stars (NSs) significantly depend on their magnetic fields. The magnetic field properties include not only its strengths, but also its topology. Evolution of both was a subject of numerous studies (see an early review in Chanmugam 1992 and more recent in Geppert 2009).

Theoretical models typically predict that the field might decay due to several reasons. However, analysis of observational data mostly yields controversial results. Especially, if we restrict our consideration to the normal radio pulsars only. On one hand, decay of magnetar fields seems to be inevitable for explanation of observational manifestations of these sources (see a review in Mereghetti, Pons & Melatos 2015). Another strong evidence in favour of field decay comes from the fact that fields of millisecond (recycled) pulsars are much weaker than those of normal ones, which can be explained by significant decay due to accretion in low-mass X-ray binaries (LMXBs). On other hand, there is no definitive answer if standard magnetic fields (\( \sim 10^{12} \) G) significantly decay on the time scale few million years – the lifetime scale of a normal radio pulsar.

Recently we proposed a modified data analysis to probe the magnetic field decay in normal radio pulsars (Igoshev & Popov 2014). Application of the new method resulted in discovery of magnetic field decay by a factor \( \sim 2 \) in the time interval \( \sim 10^5 - 3 \times 10^5 \) yrs. It was speculated that on longer time scales this decay might stall in order to be in correspondence with previous studies which had not found any significant field decay on longer time scales. In this paper we present preliminary results of our study on the reason for such non-uniform field evolution. The full consideration of the problem will be presented elsewhere (Igoshev & Popov, in prep).

2 Field decay in radio pulsars

In case of normal radio pulsars their magnetic field can not be directly measured. However, the basic pulsar properties such as period and period derivative should already contain some information about magnetic field evolution. Still, there is no straightforward way to extract the field evolution because both the kinematic magnetic field estimate \( \beta B = \sqrt{P \dot{P}} \), where \( \beta \) is a (probably time dependent) coefficient determined by NS properties, and the spin-down age \( \tau = P / (2 \dot{P}) \) are related to each other. It means that there is no good independent age estimate applicable to significant number of pulsars of different ages. Thus, it is necessary to use specific (statistical) methods to uncover magnetic field evolution from the data based on model-independent observable parameters, such as \( P \) and \( \dot{P} \).

In the previous study (Igoshev & Popov 2014) we presented a new path towards breaking the dependency between the spin-down age and the field estimate. A new method to study field evolution in normal radio pulsars was proposed. The method is extensively tested with population synthesis technique using synthetic populations with different magnetic field evolution.

Our method is similar to the well-known pulsar current approach (Vivekanand & Narayan 1981), but we study the “flow” of pulsars not along the direction of growing spin periods, but along the spin-down age. We propose to count a number of pulsars \( N_i \) in spin-down age intervals \( \Delta \tau_i \). If

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the birth rate is constant and selection effects are similar for pulsars with different spin-down ages, then the ratio of pulsars number at different intervals of spin-down age reflects the ratio of true ages of pulsars in these intervals.

With currently available data our method is applicable to sources with ages $\sim (1\text{-}5) \times 10^5$ yrs. We obtained that the field decays in this age interval by a factor of $\sim 2$. This can be fitted by an exponential decay with time scale $\tau \approx 4 \times 10^3$ yrs. We show the main result by Popov & Igoshev (2014) in Fig. 1. There (and in other plots) the magnetic field is represented as $B(t) = B_0 \times f(t)$, where $f(t)$ is the decay function which describes field evolution.

Obviously, the result presented in Fig. 1 is not in correspondence with most of the previous studies (see, for example, Faucher-Giguère & Kaspi 2006 and references therein) if it is assumed that the field continues to diminish with the same rate at larger ages. On other hand, moderate field decay in normal pulsars is not in contradiction with observations (Gullon et al. 2014). So, the stage of relatively rapid decay might be terminated. The method is statistical in its nature, and therefore it cannot shed light on the physical mechanism which governs the magnetic field decay at this interval of true ages. In the new study we address this question.

3 Hall cascade vs. Ohmic dissipation on phonons

Basing on current understanding of NS crust properties, there are two effects which can cause the magnetic field decay with a time scale $\sim 10^5$ years: the Hall effect and Ohmic decay (Geppert 2009, Cumming, Arras & Zweibel 2004). The former effect is not dissipative, it actually works similar to a turbulent cascade and redistributes the magnetic field energy from large scales (for example, dipole component) to smaller scales (in particular, if initially there existed $l$ multipole, then the attractor would consist of $l$ and $l + 2$ poloidal components, see Gourgouliatos & Cumming 2014b for details). Intensity of the Hall effect depends on the value of initial magnetic field.

Magnetic field decay in young NSs can be non-monotonic. There are several reasons for that. The first possibility is related to a specific property of the Hall cascade. The rate of field decay obtained in the article by Igoshev & Popov 2014 is close to the expected time scale of the Hall drift for normal magnetic fields $\sim 10^{12} - 10^{13}$ G. Recently it was demonstrated by Gourgouliatos & Cumming (2013) that after a relatively short stage of rapid decay driven by the Hall cascade, the magnetic field reaches an equilibrium stage which corresponds to the so-called Hall attractor where the Hall cascade stops. Later the magnetic field continues to decay mostly due to the Ohmic dissipation. So, the field evolution is non-monotonic with several characteristic time scales in different epochs.

The second possibility is related to existence of two regimes of Ohmic decay. In one of them resistivity is due to scattering from phonons. This mechanism is important till the crust of a NS is hot. In another, resistivity is determined by impurities in the matter crust. There is a critical temperature $T_U$ when magnetic field decay due to phonons stops. The time scale of decay on phonons can be $\sim 1$ Myr and even smaller while a NS is hot. For the decay on impurities the time scale depends on the parameter of impurities $Q$, and it can be very long if the parameter is much smaller than unity.

In our approach on every time step we use the formula proposed by Aguilera, Pons & Miralbes (2008):

$$B(t) = \frac{B_0 \times \exp(-t/\tau_{\text{Ohm}})}{1 + \tau_{\text{Ohm}}/\tau_{\text{Hall}}[1 - \exp(-t/\tau_{\text{Ohm}})]}. \quad (1)$$

In this model two distinct time scales are defined. The first one is related to Ohmic decay, $\tau_{\text{Ohm}}$, and the second one — to the Hall cascade, $\tau_{\text{Hall}}$. The equation also can be modified to include some minimal value of the field, at which the decay is saturated.
Let us consider which of two effects play the more important role in the crust of normal radio pulsars. The timescale of Ohmic decay is:

\[ \tau_{\text{Ohm}} = \frac{4\pi\sigma L^2}{e^2}. \]  

(2)

Where \( \sigma \) is local electric conductivity, \( L \) is the typical spatial scale of electric currents (can be the local pressure height, see Cumming et al. 2004), and \( c \) is the speed of light.

The timescale of the Hall evolution is:

\[ \tau_{\text{Hall}} = \frac{4\pi en_e L^2}{eB}, \]  

(3)

with \( n_e \) is local electron density, \( e \) is elementary charge, and \( B \) is local magnetic field.

As both timescales have the same dependence on the spatial scale \( \tau \sim L^2 \), we can get rid of it if we consider the ratio of two time scales:

\[ \frac{\tau_{\text{Ohm}}}{\tau_{\text{Hall}}} = \frac{\sigma B}{en_e c}. \]  

(4)

If we use the crust properties from Cumming et al. 2004 we can simplify Eq. (4):

\[ \frac{\tau_{\text{Ohm}}}{\tau_{\text{Hall}}} = 2.6 \times 10^{-3} B_{12} \rho_{1/3}^{1/6} \left( \frac{Y_e}{0.04} \right)^{2/3} \times \]

\[ \times 10^{0.37} \exp \left( \frac{t}{4.3 \times 10^5 \text{years}} \right). \]  

(5)

This equation is valid till the temperature is higher than \( T_U \), i.e. while scattering from phonons is important. For fields \( B \sim \text{few} \times 10^{12} \text{G} \) the two time scales are equal for ages \( \sim \text{few} \times 10^5 \text{yrs} \) (see Fig. 4).

In our study we develop a model which includes all these types of decay mainly following prescriptions from Cumming et al. 2004. To fix parameters of the crust we assume that the Hall time scale is equal to the scale found in Lioshev & Popov 2014 for fields \( \sim \text{few} \times 10^{12} \text{G} \). To take into account thermal evolution of NSs we use cooling curves from Shaternin et al. 2011.¹

To understand the role of each type of decay we make several runs when one or another of them are switched off. In Fig. 2 we present the field evolution only due to Ohmic decay via scattering from impurities. This parameter is taken to be small: \( Q = 0.05 \). This is a realistic assumptions for normal field NSs, oppositely for magnetars there is a contribution from the part of the crust in the pasta phase, where \( Q \) is much larger (see Gullon et al. 2014 and references therein for details). Then we include scattering from phonons, see Fig. 3. For the chosen parameters we see rapid decay which stops at \( \sim 2 \times 10^5 \text{yrs} \).

The time scale for the Hall effect depends on the initial field value. It can be shorter or longer than the time scale for Ohmic decay. In Fig. 4 we compare the time scales for different types of decay. As we see, for realistic parameters the Hall effect can be as important as Ohmic decay on phonons in the time interval of interest \( \sim (1-4) \times 10^5 \text{yrs} \).

For the Hall effect we also have to consider the possibility that the Hall attractor develops. Following Gourgouliatos & Cumming (2014a) we assume that the stage of attractor starts at \( 3 \tau_{\text{Hall}} \). As we do not probe early evolution we neglect possible field growth at early stages described by Gourgouliatos & Cumming (2015). In Fig. 5 we present our main results.

In Fig. 5 we present field evolution for the case without Hall cascade, with Hall cascade but without attractor, and finally, the one with all effects included. In addition, we plot typical ranges of time intervals when a NS age can be es-

¹ We thank Peter Shaternin for providing these data and helpful comments.
In our study we assumed that $\tau_{\text{Hall}}$ is compatible with the time scale from \cite{IgoshevPopov2014}. This influenced our estimates of properties of the layer where currents are situated. If this basic assumption is wrong, then the results might be modified significantly. We plan to study it in the future.

Of course, even if we can explore the whole set of parameters, we are limited by general model assumptions, and some (micro)physics is missing. It would be important to probe field properties and evolution with observational data to put constraints on models and to guide theoretical studies in the right direction.

5 Conclusions

In this paper we presented preliminary results of the analysis of the origin of the magnetic field decay in normal radio pulsars found by \cite{IgoshevPopov2014}. We demonstrate that the decay with a time scale $\sim 4 \times 10^5$ yrs and suppression at $\sim 10^6$ yrs (or slightly earlier) can be related to two processes. The first one is Ohmic decay due to phonons. It has the time scale in the appropriate range, and can be stopped when the NS temperature falls down to the critical value $T_U$.

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However, we think that the second possibility is less probable. May be the Hall effect also contributes to the field decay in normal radio pulsars (see Fig. 5), but the main contribution, according to our analysis, is due the Ohmic decay on phonons. A more detailed study will be presented elsewhere (Igoshev & Popov, in prep.).

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