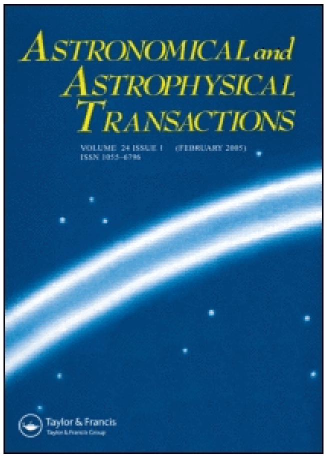

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RESTRICTIONS ON PARAMETERS OF POWER-LAW MAGNETIC FIELD DECAY FOR ACCRETING ISOLATED NEUTRON STARS

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In this short note we discuss the influence of power-law magnetic field decay on the evolution of old accreting isolated neutron stars. We show that, contrary to exponential field decay (Popov and Prokhorov, 2000), no additional restrictions can be made for the parameters of power-law decay from the statistics of isolated neutron star candidates in ROSAT observations.

We also briefly discuss the fate of old magnetars with and without field decay, and describe the parameters of old accreting magnetars.

KEY WORDS Neutron stars, magnetic fields, magnetic field of stars, X-ray stars, accretion

1 INTRODUCTION

Isolated neutron stars (INSs), which don't show radio pulsar activity, now attract much attention of astrophysicists due to recent observations of several candidates with the ROSAT satellite (see Neühauser and Trümper, 1999 and a review in Treves *et al.*, 2000). As we discussed in our previous paper (Popov and Prokhorov, 2000) INSs can be important for the discussion of different models of magnetic field decay (MFD) in NSs in general.

During its evolution an INS can pass through four phases: 'ejector', 'propeller', 'accretor', and 'georotator'. At the first stage the INS is spinning down according to the magneto-dipole formula till the so-called ejector period is reached. At the second stage captured matter cannot penetrate down to the surface of the INS, and the star continues to spin down faster than at the stage of ejection. Finaly, the so-called accretor period is reached, and matter can fall down: accretion starts. If the INS's velocity (or magnetic field) is high enough, the star can appear as a georotator, where matter cannot be captured, so long as the magnetosphere radius is larger than the radius of gravitational capture.

Table 1. Models A, B, C from Colpi *et al.* (2000).

Model	*A*	*B*	*C*
a	0.01	0.15	10
α	5/4	5/4	1
B_∞	$\approx 1.9 \times 10^{11}$ G	$\approx 2.4 \times 10^{10}$ G	$\approx 10^8$ G

Several models of MFD in NSs have been suggested during the last 20–30 years (see for example the recent brief review by Konar and Bhattacharya, 2000). Most of these models can be fitted by exponential or power-law decay, or by their combination with some set of parameters. INSs can be an important class of objects for verification of different theories of MFD, because in these sources the accretion rate is negligible, so it is not necessary to take into account the influence of accretion on the MFD (Urpin *et al.*, 1996). Spin-up/spin-down rates on the stage of accretion are also relatively low in comparison with NSs in binary systems. This means that in INSs MFD operates in the 'purest' form (Popov and Konenkov, 1998). That is why these objects have special importance, in our opinion, for investigations of the observational appearance of different effects of MFD.

Recently Colpi *et al.* (2000) discussed power-law models of MFD in INSs and applied them to highly magnetized NSs: 'magnetars'. Here we briefly discuss the later stages of evolution of INSs with the power-law MFD, and estimate if it is possible for them to reach the stage of accretion, and if so, what their properties can be at this stage.

Our analysis follows the papers of Popov and Prokhorov, (2000) and Colpi *et al.* (2000). So, we just repeat the calculations of Popov and Prokhorov (2000) but for the power-law decay, using some results of Colpi *et al.* (2000), and we refer to these papers for all details of terminology, calculations, etc.

2 POWER-LAW DECAY

Power-law (as also exponential) MFD is a widely discussed variant of NS field evolution. A power-law is a good fit for several different calculations of field evolution (Goldreich and Reisenegger, 1992; Geppert *et al.*, 2000). The power-law MFD can be described with the following simple formula (Colpi *et al.*, 2000):

$$\frac{\mathrm{d}B}{\mathrm{d}t} = -aB^{1+\alpha}. \tag{1}$$

So, we have only two parameters of decay: a and α. So long as this decay is relatively slow for the most interesting values of $\alpha \gtrsim 1$ (we use the same units as in Colpi *et al.*, 2000), we don't specify any bottom magnetic field, contrary to the assumption we made for more rapid exponential decay (Popov and Prokhorov,

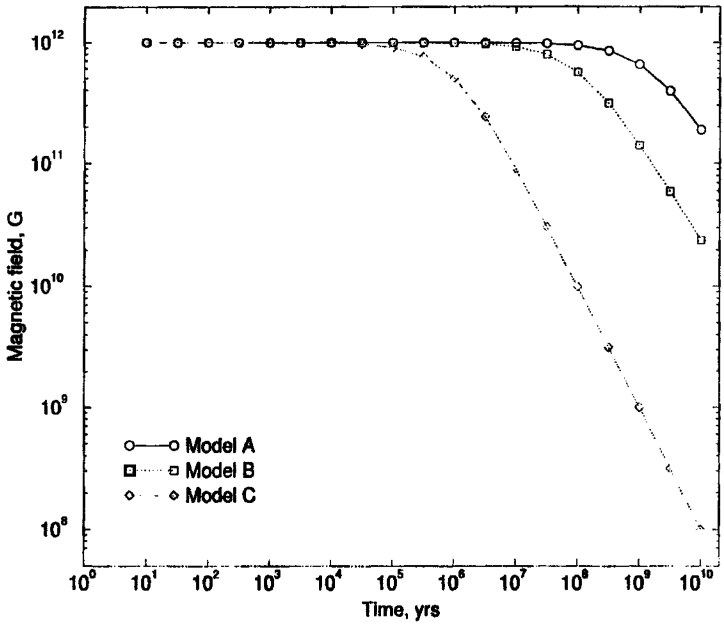

Figure 1 Power-law MFD. Model A: $a = 0.01$, $\alpha = 1.25$; solid line with circles. Model B: $a = 0.15$, $\alpha = 1.25$; dashed line with squares. Model C: $a = 10$, $\alpha = 1$; long-dashed line with diamonds. The models were described in details in Colpi *et al.* (2000) (see also Table 1).

2000). Even for Model C from Colpi *et al.* (2000) (see Table 1) with relatively fast MFD the magnetic field can decrease only down to $\sim 10^8$ G in 10^{10} yrs (see Figure 1), but for $\alpha < 1$ the magnetic field can decay significantly during the Hubble time (we call here the 'Hubble time' a time interval of 10^{10} yrs, which is nearly equal to the age of our Galaxy) for any reasonable value of a. And probably it is useful to introduce a bottom field in the latter case.

At the stage of ejection an INS is spinning down according to the magneto-dipole formula $P\dot{P} \approx bB^2$. Here (and everywhere below) $b = 3$, the values of the magnetic field, B, B_∞, and B_0, are taken in units of 10^{13} G and the time, t, in units of 10^6 yrs (as in Colpi *et al.*, 2000).

In the table we show parameters of Models A, B, C from Colpi *et al.* (2000). B_∞ is the magnetic field calculated for $t = t_{\mathrm{Hubble}} = 10^{10}$ yrs and for the initial field $B_0 = 10^{12}$ G. Models A and B correspond to ambipolar diffusion in the irrotational and the solenoidal modes, respectively. Model C describes MFD in the case of the Hall cascade.

In Figure 2 we show the dependence of the ejector period, p_e, and the asymptotic period, p_∞ on the parameter a for $\alpha = 1$ for different values of the initial magnetic field, B_0:

$$p_e = 25.7 B_\infty^{1/2} n^{-1/4} v_{10}^{1/2} \text{ s}, \tag{2}$$

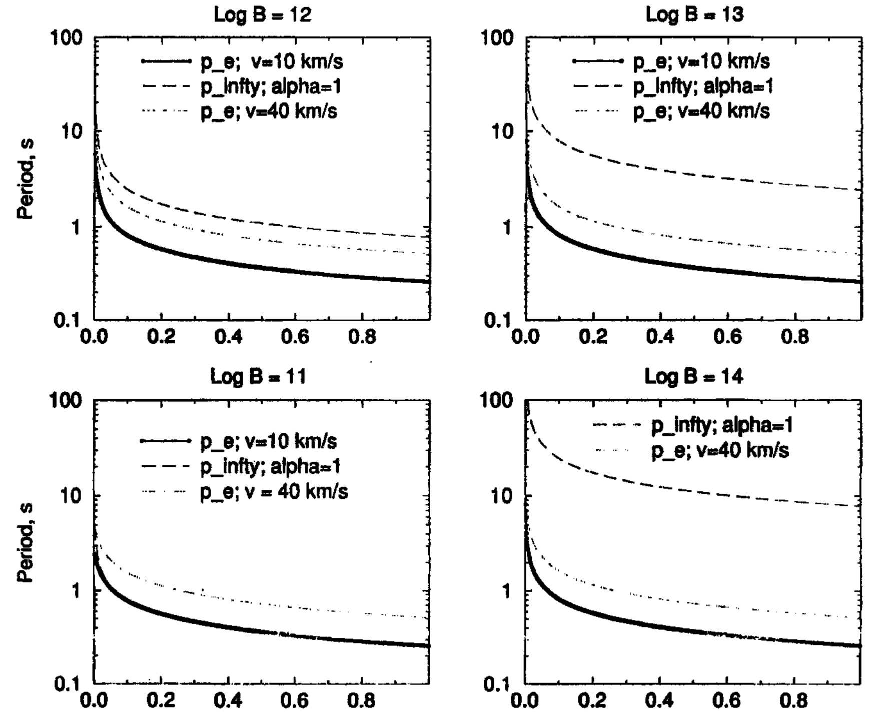

Figure 2 Periods vs. parameter a for different values of the initial magnetic field: 10^{11}, 10^{12}, 10^{13}, 10^{14} G.

$$p_\infty^2 = \frac{2}{2-\alpha}\frac{b}{a}B_0^{2-\alpha}. \tag{3}$$

Here v_{10} is the velocity $(v_{\rm INS}^2+v_s^2)^{1/2}$ in units of 10 km s^{-1}; $v_{\rm INS}$ is the spatial velocity of the INS and v_s is the sound velocity, n is the interstellar medium (ISM) number density. B_0 is the initial magnetic field. p_e was calculated for $t = t_{\rm Hubble} = 10^{10}$ yrs, i.e. for the moment when $B = B_\infty$.

It is clear from Figure 2 that for an initial field $\gtrsim 10^{11}$ G low-velocity INSs are able to come to the stage of accretion: for $B_0 = 10^{11}$ G, the lines for p_∞ and p_e for the lowest possible velocity, 10 km s^{-1}, coincide.

In Figure 3 we show 'forbidden' regions on the a–α plane, where an INS for a given velocity certainly cannot come to the stage of accretion in the Hubble time (compare with the 'forbidden' regions in Popov and Prokhorov, 2000). In a forbidden region an INS for specified parameters cannot leave the ejector stage even after 10^{10} years of evolution. If one also takes into account the propeller stage (between the ejector and accretor stages) it becomes clear that the 'forbidden' regions for an INS which cannot reach the stage of accretion is even larger. We note that the propeller stage can be shorter (probably much shorter, especially for a constant field) than the ejection stage (see Lipunov and Popov, 1995 for detailed

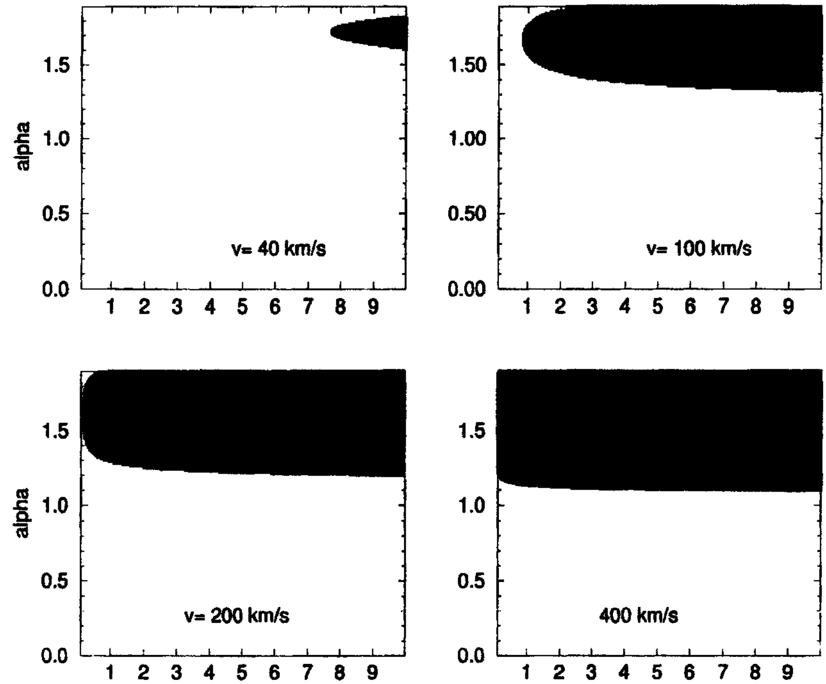

Figure 3 'Forbidden' regions for the initial field 10^{13} G and different INS spatial velocities: 40 km s^{-1}, 100 km s^{-1}, 200 km s^{-1}, and 400 km s^{-1}. In the filled regions NSs never leave the ejector stage.

arguments), so the 'forbidden' regions on Figure 3 cannot become much larger if one also takes into account the propeller stage. It is also important that we take a very low INS velocity and high ISM density. For most INSs, all plotted 'forbidden' regions should be larger.

One can see that for the most interesting cases (Models A, B, C from Colpi *et al.*, 2000) and $v < 200$ km s^{-1}, INSs can reach the accretion stage. It is an important point that the fraction of low velocity NSs is very small (Popov *et al.*, 2000) and most of them have velocities of about 200 km s^{-1}.

3 EVOLVED MAGNETARS

In the last several years a new class of objects – highly magnetized NSs, 'magnetars' (Duncan and Thompson, 1992) – have become very popular in connection with soft γ-repeaters (SGR) and anomalous X-ray pulsars (AXP) (see Mereghetti and Stella, 1995; Kouveliotou *et al.*, 1999; Mereghetti, 1999; and recent theoretical works Alpar, 1999; Marsden *et al.*, 2000; Perna *et al.*, 2000).

Magnetars come to the propeller stage with periods $\sim$ 10–100 s in Models A, B, C (see Figure 2 in Colpi *et al.*, 2000). Then their periods quickly increase, and NSs come to the accretion stage with significantly longer periods, and at that stage they evolve to a so-called equilibrium period (Lipunov and Popov, 1995; Konenkov and Popov, 1997) due to accretion of the turbulent ISM:

$$p_{\rm eq} \sim 2800 B^{2/3} I_{45}^{1/3} n^{-2/3} v_{10}^{13/3} v_{t10}^{-2/3} M_{1.4}^{-8/3} \text{ s.} \qquad (4)$$

Here v_t is a characteristic turbulent velocity, I is the moment of inertia, M is the INS mass.

An isolated accretor can be observed both with positive and negative sign of $\dot{p}$ (Lipunov and Popov, 1995). Spin periods of INSs can differ significantly from $p_{\rm eq}$ contrary to NSs in disc-fed binaries, and similar to NSs in wide binaries, where accreted matter is captured from the giant's stellar wind. This happens because the spin-up/spin-down moments are relatively small.

As the field is decaying, the equilibrium period is decreasing, coming to 28 s when the field is equal to 10^{10} G (we note here the recently discovered objects RX J0420.0−5022 (Haberl *et al.*, 2000) with spin period $\sim$ 22.7 s).

It is important to discuss the possibility that an evolved magnetar can appear as a georotator (see Lipunov, 1992 for a detailed description or Popov *et al.*, 2000, for a short description of different INSs' stages). This happens if

$$v \gtrsim 300 B^{-1/5} n^{1/10} \text{ km s}^{-1}. \qquad (5)$$

For all values of a and α that we used (see Figure 3) NSs, at the end of their evolution ($t = 10^{10}$ yrs), have magnetic fields $\lesssim 10^{12}$ G for a wide range of initial fields, so they never appear as georotators if $v < 580$ km s^{-1} for $n = 1$ cm^{-3}; but without MFD, magnetars with $B \gtrsim 10^{15}$ G and velocities $v \gtrsim 100$ km s^{-1} can appear as georotators.

In Popov *et al.* (2000) it was shown that the georotator is a rare stage for INSs because an INS can come to the georotator stage only from the propeller or accretor stage, but all these phases require relatively low velocities, and high-velocity INSs spend most of their lives as ejectors. This situation is opposite to binary systems, where a lot of georotators are expected for fast stellar winds (the wind velocity can be much faster than the INS velocity relative to the ISM).

Without MFD magnetars can also appear as accreting sources. In that case they can have very long periods and very narrow accretion columns (which means high temperature). Such sources have yet not been observed. The absence of some specific sources associated with evolved magnetars (binary or isolated) can put some limits on their number and properties (dr. V. Gvaramadze drew our attention to this point).

At the accretion part of INS evolution, periods stay relatively close to $p_{\rm eq}$ (but can fluctuate around this value), and INS magnetic fields decay down to $\sim 10^{10}$–10^{11} G in several billion years for Models A and B. This corresponds to a polar cap radius of about 0.15 km and a temperature of about 250–260 eV, higher than for the observed INS candidates with temperature about 50–80 eV. We calculate the polar cap radius, $R_{\mathrm{cap}} = R\sqrt{(R/R_{\mathrm{A}})}$, with the following formula:

$$R_{\mathrm{cap}} = 6 \times 10^3 B^{-2/7} n^{1/7} v_{10}^{-3/7} \text{ cm}. \tag{6}$$

Here $R_{\mathrm{A}} \simeq 1.8 \times 10^{10} n^{-2/7} v_{10}^{6/7} B^{4/7}$ cm is the Alfven radius. The temperature can be even larger than that given by the formula above so long as, for a very high field, matter can be channeled in a narrow ring, so the area of the emitting region will be just a fraction of the total polar cap area.

As the field decreases the radius of the polar cap increases, and the temperature falls. Sources with such properties (temperature about 250–260 eV) have not been observed yet (Schwope *et al.*, 1999). But if the number of magnetars is significant (about 10% of all NSs) accreting evolved magnetars may be found in the near future; so far we know about five accreting INS candidates (Treves *et al.*, 2000; Neühauser and Trümper, 1999), and their number may be increased in future. $\dot{p}$ measurements are necessary to understand the nature of such sources, if they are observed.

The recently discovered object RX J0420.0−5022 (Haberl *et al.*, 2000), with spin period $\sim$ 22.7 s, may be an example of an INS with decayed magnetic field accreting from the ISM, as previously observed in RX J0720.4−3125. Due to the restively low temperature, 57 eV, its progenitor cannot be a magnetar for a power-law MFD (Models A, B, C) or similar sets of parameters, because a very large polar cap is needed, which is difficult to obtain in these models. Of course RX J0420.0−5022 can be explained also as a cooling NS. The question 'are the observed candidates cooling or accreting objects?' is still open (see Treves *et al.*, 2000). If one finds an object with $p \gtrsim 100$ s and temperature about 50–70 eV, this can be a strong argument for its accretion nature, so long as such long periods for magnetars can be reached only for very high initial magnetic fields (see Figure 2 in Colpi *et al.*, 2000) for reasonable models of MFD and other parameters.

4 CONCLUSIONS

Our main result means that for power-law MFD (contrary to exponential decay) we cannot put serious limits on the decay parameters with the ROSAT observations of INS candidates so long as for all plausible models of power-law MFD INSs from a low-velocity tail are able to become accretors. For more detailed conclusions a NS census for power-law MFD is necessary, similar to the non-decaying and exponential cases (Popov *et al.*, 2000).

It might be possible to observe evolved accreting magnetars both for the case of MFD and for constant field evolution. These sources should be different from typical present-day INS candidates observed by ROSAT. The existence or absence of old accreting magnetars is very important for the whole of NS astrophysics.

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