Restrictions on parameters of power-law magnetic field decay for accreting isolated neutron stars

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Abstract

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 & 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 parameters of old accreting magnetars.

Key words: *neutron stars – magnetic fields – stars: magnetic field – X-rays: stars – accretion*

1 Introduction

Isolated neutron stars (INSs), which don't show radio pulsar activity attract now much attention of astrophysicists due to recent observations of several candidates with the ROSAT sattelite (see Neühauser & Trümper 1999 and a review in Treves et al. 2000). As we discussed in our previous paper (Popov & Prokhorov 2000) INSs can be important for 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 so-called ejector period is reached. At the second stage captured matter cannot penetrate down to the surface of the INS, and the star continue to spin down faster than at the stage of ejection. At last, 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, as far as the magnetosphere radius is large than the radius of gravitational capture.

Several models of MFD in NSs were suggested during the last 20-30 years (see for example a recent brief review by Konar & Bhattacharya). 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 accretion rate is negligible, so it is not necessary to take into account the influence of accretion onto 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. It means, that in INSs MFD operates in the "purest" form (Popov & Konenkov 1998). That's why these objects have a special importance, in our opinion, for investigations of 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 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 yes, what can be their properties at this stage.

Our analysis follows the papers Popov & Prokhorov (2000), and Colpi et al. (2000). So, we just repeat calculations of Popov & 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 NSs' field evolution. Power-law is a good fit for several different calculations of the field evolution (Goldreich & Reisenegger 1992, Geppert et al. 2000). The power-law MFD can be described with the following simple formula (Colpi et al. 2000):

$$\frac{dB}{dt} = -aB^{1+\alpha}. \quad (1)$$

So, we have only two parameters of decay: a and α. As far 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 what we made for more rapid exponential decay (Popov & Prokhorov 2000). Even for the 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 Fig. 1). But for $\alpha < 1$ the magnetic field can decay significantly during the Hubble time (we call here *"the Hubble time"* time interval 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 in the later case a bottom field.

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) $b = 3$, values of magnetic field, B, B_∞ and B_0, are taken in units 10^{13} G and time, t, in units 10^6 yrs (as in Colpi et al. 2000).

In the table we show parameters of the Models A, B, C from Colpi et al. (2000). B_∞ is the magnetic field calculated for $t = t_{Hubble} = 10^{10}$ 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.

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_∞	$\approx 1.9 \cdot 10^{11}$ G	$\approx 2.4 \cdot 10^{10}$ G	$\approx 10^8$ G

In Fig. 2 we show 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:

$$p_e = 25.7\, B_\infty^{1/2} n^{-1/4} v_{10}^{1/2}\ \mathrm{s}, \quad (2)$$

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

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

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

In Fig. 3 we show "forbidden" regions on the plane a–α, where an INS for a given velocity for sure cannot come to the stage of accretion in the Hubble time (compare with "forbidden" regions

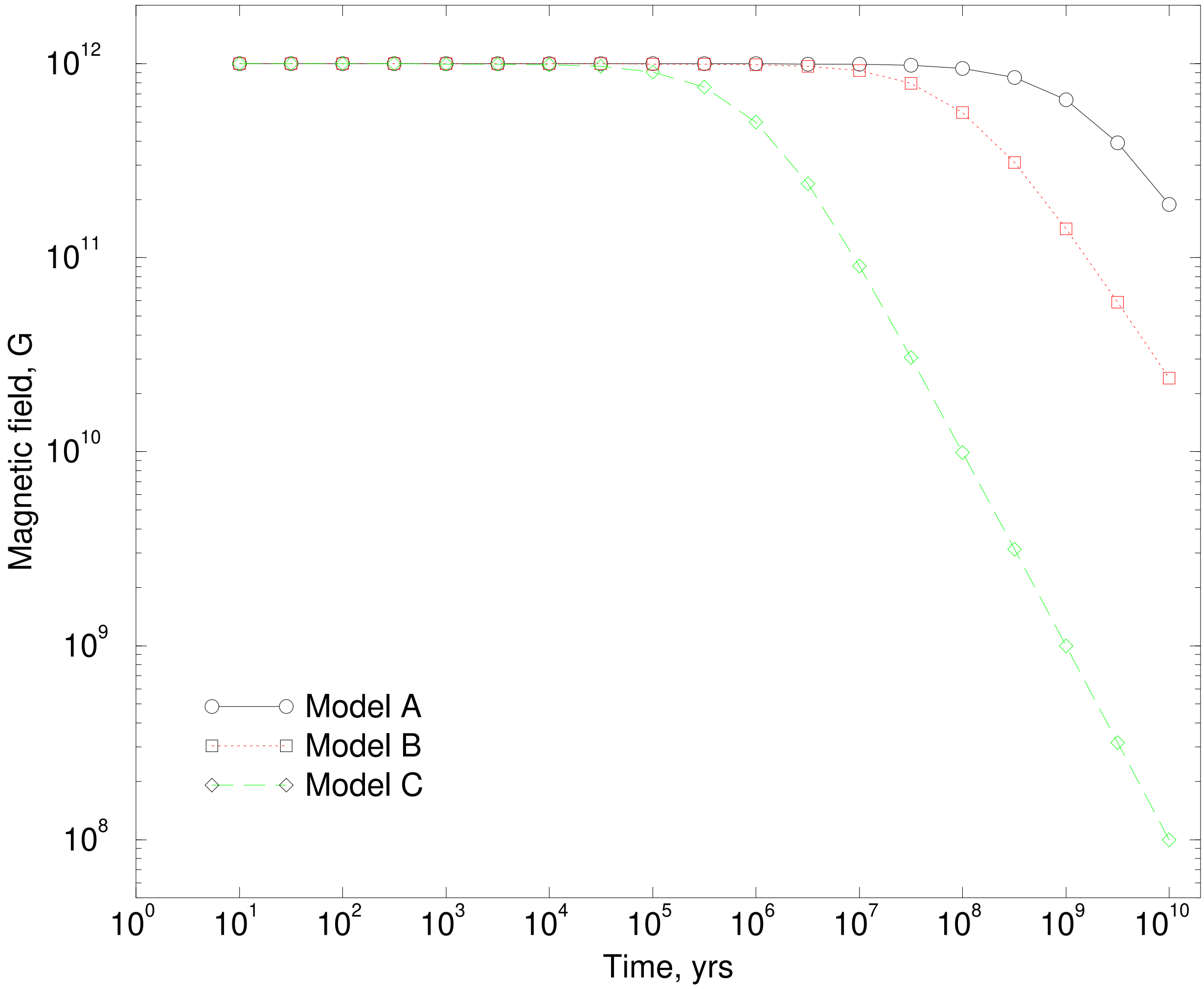

Figure 1: Power-law MFD. Model A: $a = 0.01, \alpha = 1.25$; solid line with circles. Model B: $a = 0.15, \alpha = 1.25$; dashed line with squares. Model C: $a = 10$, $\alpha = 1$; long-dashed line with diamonds. Models were described in details in Colpi et al. (2000) (see also Table 1).

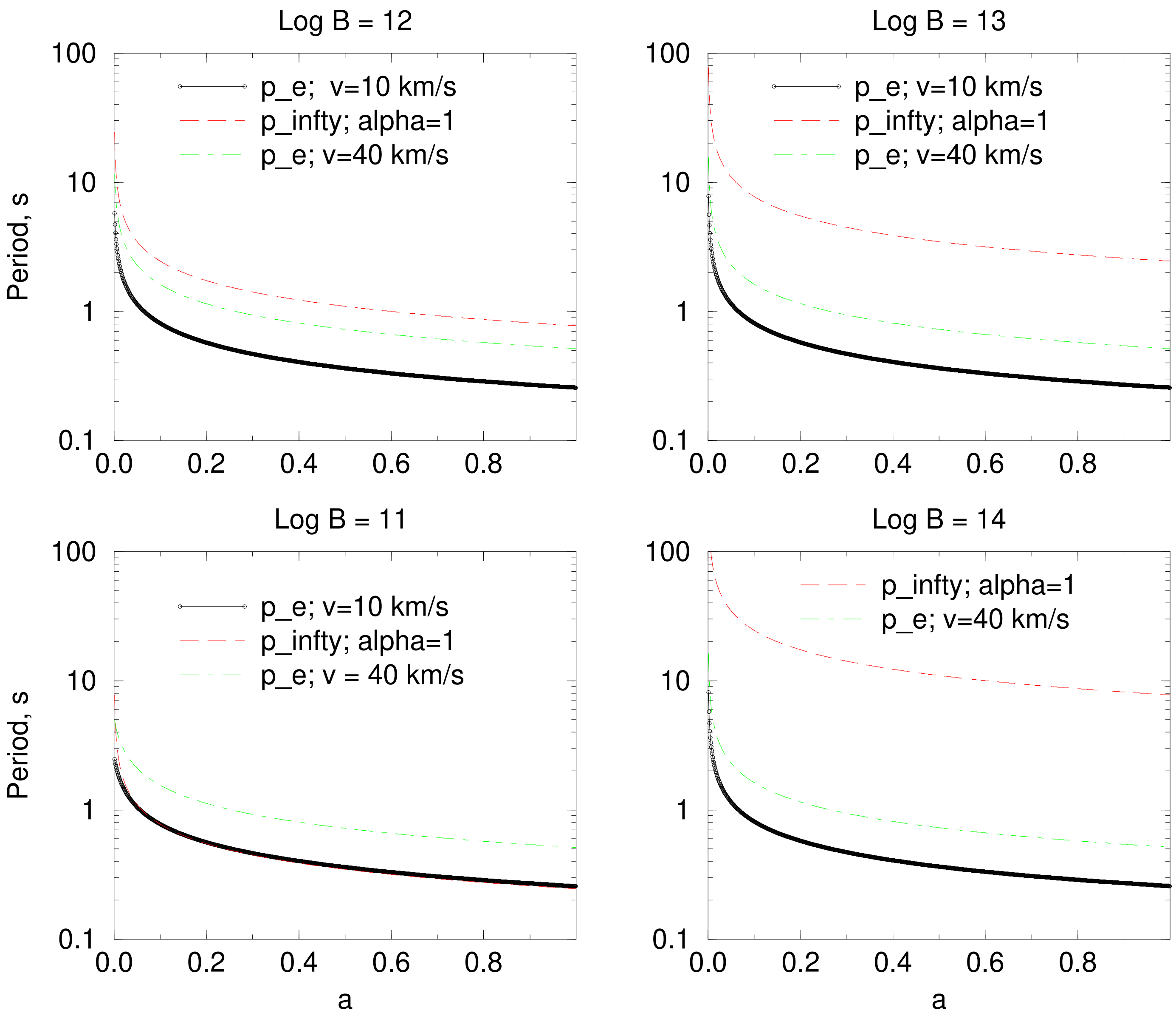

Figure 2: Periods vs. parameter a for different values of the initial magnetic field: $10^{11}, 10^{12}, 10^{13}, 10^{14}$ G.

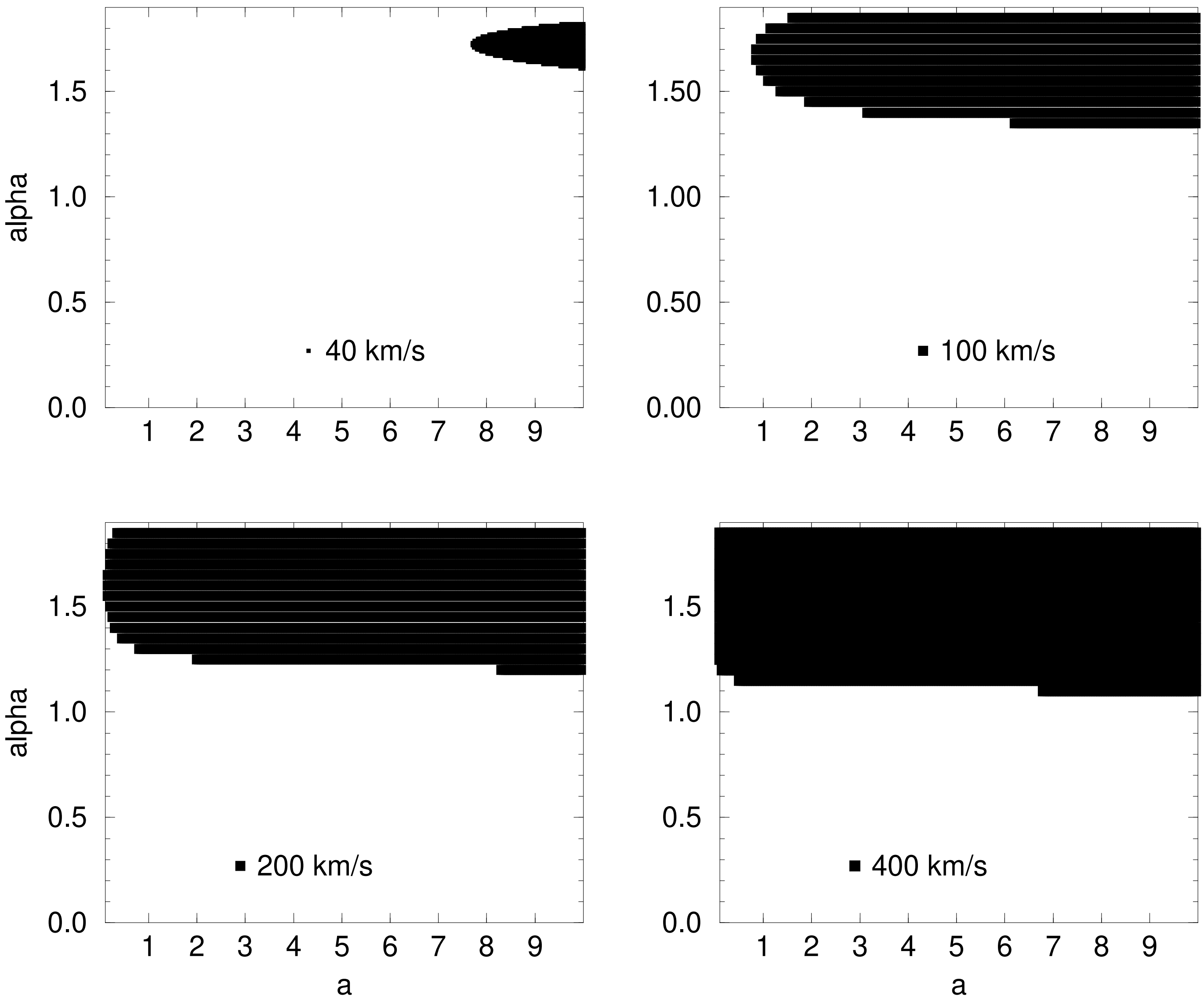

Figure 3: "Forbidden" regions for the initial field 10^{13} G and different INS's spatial velocities: 40 km/s, 100 km/s, 200 km/s and 400 km/s. In the filled regions NSs never leave the ejector stage.

in Popov & Prokhorov 2000). In a forbidden region an INS for specified parameters cannot leave the stage of ejector even after 10^{10} years of evolution. If one also takes into account the stage of propeller (between ejector and accretor stages) it becomes clear, that "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 constant field) than the stage of ejection (see Lipunov & Popov 1995 for detailed arguments), so the "forbidden" regions on Fig. 3 cannot become much larger if one also takes into account the stage of propeller. It is also important, that we take very low INS's velocity and high ISM density. For most part of 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 INSs can reach the stage of accretion. It is an important point, that fraction of low velocity NSs is very small (Popov et al. 2000) and most of them have velocities about 200 km/s.

3 Evolved magnetars

In the last several years a new class of objects - highly magnetized NSs, *"magnetars"* (Duncan & Thompson 1992) – became very popular in connection with soft γ-repeaters (SGR) and anomalous X-ray pulsars (AXP) (see Mereghetti & 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 the Models A, B, C (see Fig. 2 in Colpi et al. 2000). Then their periods quickly increase, and NSs come to the stage of accretion with significantly longer periods, and at that stage they evolve to a so-called equilibrium period (Lipunov & Popov 1995, Konenkov & Popov 1997) due to accretion of the turbulent ISM:

$$p_{eq} \sim 2800 B^{2/3} I_{45}^{1/3} n^{-2/3} v_{10}^{13/3} v_{t_{10}}^{-2/3} M_{1.4}^{-8/3}\,\mathrm{s} \tag{4}$$

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

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

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

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

$$v \gtrsim 300 B^{-1/5} n^{1/10}\,\mathrm{km/s}. \tag{5}$$

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

In Popov et al. (2000) it was shown, that 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 (wind velocity can be much faster than INS's velocity relative to ISM).

Without MFD magnetars also can appear as accreting sources. In that case they can have very long periods and very narrow accretion columns (that means high temperature). Such sources are not observed now. 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 INSs' evolution periods stay relatively close to p_{eq} (but can fluctuate around this value), and INSs' magnetic fields decay down to $\sim 10^{10} - 10^{11}$ G in several billion years for the Models A and B. It corresponds to the polar cap radius about 0.15 km and temperature about 250 – 260 eV, higher than for the observed INS candidates with temperature about 50 – 80 eV. We calculate the polar cap radius, $R_{cap} = R\sqrt{(R/R_A)}$, with the following formula:

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

Here $R_A \simeq 1.8 \cdot 10^{10} n^{-2/7} v_{10}^{6/7} B^{4/7}$ cm is the Alfven radius. The temperature can be even larger, than it follows from the formula above as far as for 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 is decreasing the radius of the polar cap is increasing, and the temperature is falling. Sources with such properties (temperature about 250-260 eV) are not observed yet (Schwope et al. 1999). But if the number of magnetars is significant (about 10% of all NSs) accreting evolved magnetars can be found in the near future, as far as now we know about 5 accreting INS candidates (Treves et al. 2000, Neühauser & Trumper 1999), and their number can be increased in future. $\dot{p}$ measurements are necessary to understand the nature of such sources, if they are observed.

Recently discovered object RX J0420.0-5022 (Haberl et al. 2000) with the spin period ~ 22.7 s, can be an example of an INS with decayed magnetic field accreting from the ISM, as previously RX J0720.4-3125. Due to relatively low temperature, 57 eV, its progenitor cannot be a magnetar for 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 can be a strong argument for its accretion nature, as far as such long periods for magnetars can be reached only for very high initial magnetic fields (see Fig. 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 parameters of decay with the ROSAT observations of INS candidates as far as for all plausible models of power-law MFD INSs from low velocity tail are able to become accretors. For more detailed conclusions a NS census for power-law MFD is necessary, similar to non-decaying and exponential cases (Popov et al. 2000).

An interesting possibility of observing evolved accreting magnetars appear 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. Existence or absence of old accreting magnetars is very important for the whole NS astrophysics.

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