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ROSAT X-ray sources and exponential field decay in isolated neutron stars

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Abstract. In this paper we semianalyticaly evaluate influence of the exponential decay of magnetic field on the fate of isolated neutron stars. The fact of ROSAT observations of several X-ray sources, which can be accreting old isolated neutron stars gives us an opportunity to put some limits on the parameters of the exponential decay.

We argue, that, if most part of neutron stars have approximately the same decay and initial parameters, then the combinations of the bottom magnetic momentum, μ_b, in the range $\sim 10^{28} - 10^{29.5}\,\mathrm{G\,cm^3}$ and characteristic time scale, t_d, in the range $\sim 10^7 - 10^8$ yrs for standard initial magnetic momentum, $\mu_0 = 10^{30}\,\mathrm{G\,cm^3}$, can be excluded, because for that sets of parameters neutron stars never come to the stage when accretion of the interstellar medium on their surfaces is possible even for low velocity of neutron stars and relatively high density of the interstellar medium. The region of excluded parameters increases with μ_0 decreasing.

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

1. Introduction

Evolution of neutron stars (NSs) can be called "magneto–rotational", because all main astrophysical manifestations of these objects are determined by their periods and magnetic fields.

Four main regimes, as described for example in Lipunov (1992), are possible for isolated NSs: ejector, when a star represents a radio pulsar, or a dead pulsar, spinning down due to magneto–dipole radiation; propeller, when surrounding captured matter cannot penetrate through the centrifugal barrier; accretor, when matter can reach the surface, and the NSs appear as an X-ray source; and georotator, when gravitation becomes

Send offprint requests to: S. B. Popov: polar@xray.sai.msu.su insignificant, because magnetic pressure dominates everywhere over the gravitational pull, and geo-like magnetosphere is formed.

Magnetic field decay in NSs is an uncertain subject. Many models were suggested (see, for example, Ding et al., 1993; Jahan Miri & Bhattacharya, 1994). The only strong observational result is that for the exponential (or nearly exponential) decay characteristic time scale, t_d, is longer than $\sim 10^7$ yrs, because no expected effects of decay are observed in radio pulsars (Lyne et al. 1998).

Field decay was used in the case of old accreting isolated NSs by Konenkov & Popov (1997) and Wang (1997) to explain properties of the source RX J0720-3125. And it seems, that if this source really is an accreting old NS and if it was born as a normal radio pulsar (with small period, $\ll 1$ s, and high magnetic field, $\sim 10^{12}$ G), its properties can be explained only if decay is working (or if this source was born with such unusual parameters). Recently the influence of the field decay in isolated NSs was investigated in Colpi et al. (1998) and Livio et al. (1998). An attempt to include field decay into population synthesis of isolated NSs was made in Popov et al. (1999).

Here we try to put some limits on the parameters of the exponential field decay, assuming, that old isolated NSs are observed as accreting X-ray sources (Walter, Wolk & Neühauser 1996; Haberl et al. 1996, 1998; Neühauser & Trümper 1999; Schwope et al. 1999), neglecting the possibility, that all of them can be highly magnetized NSs, "magnetars" (see a brief discussion on this assumption in Popov et al., 1999).

2. Calculations and results

The main idea of our work is to calculate the ejector time, t_E, i.e. a time interval spent by a NS on the ejector stage, for different parameters of the field decay and standard assumptions on the initial parameters of a NS, and to compare that time with the Hubble time, t_H.

For constant field t_E monotonically depends upon NS's velocity and ISM density:

$$t_E(\mu = const) \sim 10^9 \mu_{30}^{-1} n^{-1/2}\, v_{10}\,\mathrm{yrs}. \qquad (1)$$

If t_E for decaying field for some sets of parameters is greater than $t_H \sim 10^{10}$ yrs even for relatively high concentration of interstellar medium (ISM), $\sim 1\,\mathrm{cm}^{-3}$, and small spatial velocity of a NS, $\sim 10\,\mathrm{km\,s}^{-1}$ (this velocity is about the sound velocity in the ISM), than for that parameters of the decay, t_d and μ_b, no accreting NSs would be observed, and such sets can be excluded as progenitors of old accreting isolated NSs. In addition, if we assume, that most part of NSs evolve with similar t_d and μ_b and are born with some typical initial period, p_0, and initial magnetic momentum, μ_0 (that is supported by radio pulsars observations), then such sets of parameters should be totally excluded from models of the magnetic field decay.

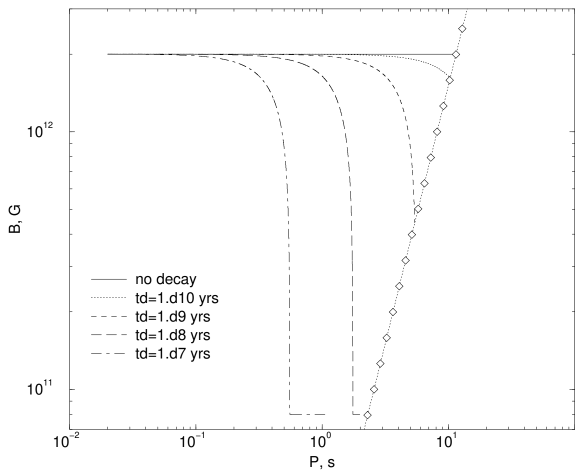

Fig. 1. Tracks on P-B diagram. Tracks are plotted for bottom polar magnetic field $8 \cdot 10^{10}$ G, initial polar field $2 \cdot 10^{12}$ G, NS velocity $10\,\mathrm{km s^{-1}}$, ISM density $1\,\mathrm{cm^{-3}}$ and different t_d. The final points for different tracks are corresponding to the following moments: for $t_d = 10^7$ yrs to $\sim 10^{10}$ yrs; for $t_d = 10^8$ yrs to $\sim 10^{10}$ yrs; for $t_d = 10^9$ yrs to $\sim 1.5 \cdot 10^9$ yrs; for $t_d = 10^{10}$ yrs to $\sim 2 \cdot 10^9$ yrs. Here we used $p_0 = 0.020$ s. The line with diamonds shows the ejector period, p_E.

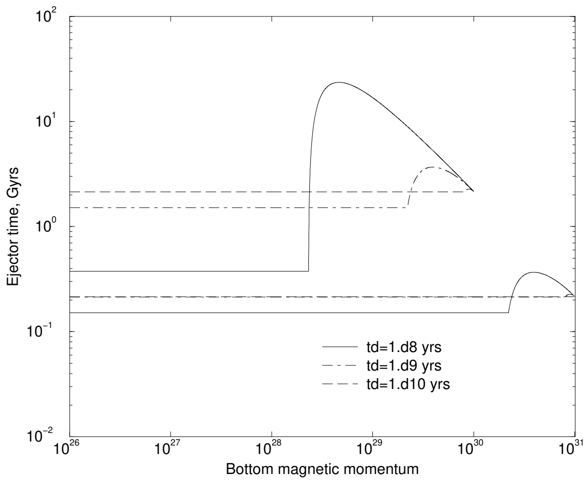

Fig. 2. Ejector time, t_E, (in billion years) vs. bottom magnetic momentum. Curves are shown for two values of the initial momentum: $10^{30}\,\mathrm{G\,cm^3}$ (upper curves) and $10^{31}\,\mathrm{G\,cm^3}$.

As the first approximation only t_E can be taken into account, because the time interval, spent on the propeller stage, t_P, is uncertain, but usually shorter, than t_E (see Lipunov & Popov, 1995). These authors argue, that for non-decaying magnetic field t_E is always longer than t_P. For decaying magnetic field the situation can be different, and t_P can be comparable to t_E. So we obtain here "upper limits", i.e. we calculate very strong limits on parameters t_d and μ_b, which can become only wider if one takes into account the propeller stage.

We assume exponential field decay:

$$\mu = \mu_0 \cdot e^{-t/t_d},\ \mu > \mu_b \tag{2}$$

where μ_0 is the initial magnetic momentum ($\mu = \frac{1}{2} B_p R_{NS}^3$, here B_p – polar magnetic field, and R_{NS}– NS radius), t_d – characteristic time scale of the decay, and μ_b – bottom magnetic momentum, which is reached in:

$$t_{cr} = t_d \cdot \ln\left(\frac{\mu_0}{\mu_b}\right). \tag{3}$$

After that moment magnetic field is assumed to be constant.

In Fig. 1 we show, as an illustration, evolutionary tracks of NSs on $P-B$-diagram for $v = 10\,\mathrm{km\,s^{-1}}$ and $n = 1\,\mathrm{cm^{-3}}$. Tracks start at $t = 0$, when $p = p_0 = 0.020$s and $\mu = mu_0 = 10^{30}\mathrm{G\,cm^3}$, and end at $t = t_H = 10^{10}$ yrs (for $t_d = 10^{10}$yrs, $t_d = 10^9$ yrs and for constant magnetic field) or at the moment, when $p = p_E$ (for $t_d = 10^8$ yrs and $t_d = 10^7$ yrs). The line with diamonds shows $p = p_E(B)$.

As far as the accretion rate from the ISM is small (even for our parameters), less than $\sim 10^{12}\,\mathrm{g\,s^{-1}}$, no influence of accretion onto decay was taken into account (see Urpin et al., 1996).

The ejector stage lasts until the critical ejector period, p_E, is reached:

$$p_E = 11.5\,\mu_{30}^{1/2} n^{-1/4} v_{10}^{1/2}\,\mathrm{s}, \tag{4}$$

where $v_{10} = \sqrt{v_p^2 + v_s^2}/10\,\mathrm{km\,s^{-1}}$. v_p– spatial velocity of a NS. Here the sound velocity, v_s, was taken into account, but as far as normally NSs spatial velocities are higher than $10\,\mathrm{km\,s^{-1}}$ and the sound velocity outside hot low density ISM regions is lower than $10\,\mathrm{km\,s^{-1}}$, we have $\sqrt{v_p^2 + v_s^2} \approx v_p$. n is a concentration of the ISM.

Initial period should be taken to be much smaller than p_E. We used $p_0 = 0$ s. Variations of p_0, if it stays much less than p_E, have little influence on our results, i.e. in that case t_E is determined only by p_E and history of the decay. We calculated spin-down according to magneto–dipole formula (but other regimes are possible, see Beskin et al. 1993 for a review):

$$\frac{dp}{dt} = \frac{2}{3}\frac{4\pi^2\mu^2}{pIc^3}, \tag{5}$$

where μ can be a function of time.

For our estimates we assumed constant velocity of NSs, v, equal to $10\,\mathrm{km\,s^{-1}}$ and constant ISM concentration, n, equal to $1\,\mathrm{cm^{-3}}$. These conditions give us a lower limit on t_E, because normally velocity is significantly higher (fraction of slow velocity NSs is less than few percents, see Popov et al., 1999), and ISM density is smaller than the specified values (partly because high velocity NSs spend most of their lives in low density regions far from the Galactic plane).

After simple algebra one can obtain a formula for t_E, depending upon t_d, μ_0, v, n and μ_b:

$$t_E = \begin{cases} -t_d \cdot \ln\left[\frac{A}{t_d}\left(\sqrt{1+\frac{t_d^2}{A^2}}-1\right)\right], \; t_E < t_{cr} \\ t_{cr} + A\frac{\mu_0}{\mu_b} - t_d\frac{1}{2}\left(\frac{\mu_0}{\mu_b}\right)^2\left(1-e^{-2t_{cr}/t_d}\right), \; t_E > t_{cr} \end{cases} \tag{6}$$

where coefficient A is determined by the formula:

$$A = \frac{3Ic}{2\mu_0\sqrt{2v\dot{M}}} \simeq 10^{17} I_{45} \mu_{0_{30}}^{-1} v_{10}^{-1/2} \dot{M}_{11}^{-1/2}\,\mathrm{s}, \tag{7}$$

where $\dot{M}$ can be formally determined as a combination of intrinsic NS's parameters, its velocity and ISM concentration using the Bondi formula even if a NS is not on the accretor stage:

$$\dot{M} \simeq 10^{11}\, n v_{10}^{-3}\,\mathrm{g\,s^{-1}}. \tag{8}$$

Results of t_E calculations for several values of μ_0 and t_d are shown in Fig. 2. Horizontal regions in the left parts of all curves appear because there a NS reaches the critical period $p = p_E$ before it reaches bottom magnetic momentum at $t = t_{cr}$, and t_E is not depended upon the rest field decay history. On the right side from the maximum on the curves a NS reaches $\mu = \mu_b$ with period significantly less than $p_E(\mu_b)$, and it takes a long time after $t = t_{cr}$ to reach $p = p_E$ (this time is longer for lower μ_b). On the left side from the maximum, but before the horizontal region, a NS reaches $\mu = \mu_b$ with a period close to p_E, and it is closer if μ_b is lower, so very quickly after $t = t_{cr}$ a NS can spin down to p_E. The first point at the right corresponds to the bottom momentum equal to initial momentum, i.e. to the case without decay.

One can see from that figure, that for some combination of parameters t_E is longer than the Hubble time. It means, that NSs never evolve further than the ejector stage.

We argue, that as far as accreting isolated NSs are observed, combinations of t_d and μ_b for which no accreting isolated NS appear can be excluded. We plotted it in Figs. 3 and 4.

Filled regions represent space of the parameters where t_E is longer than 10^{10} yrs, so in that region a NS never come to the accretor stage, and doesn't appear as accreting X-ray source. With the fact of observations of accreting old isolated NSs by ROSAT this region can be called “forbidden” for selected parameters of the exponential field decay (and for specified μ_0).

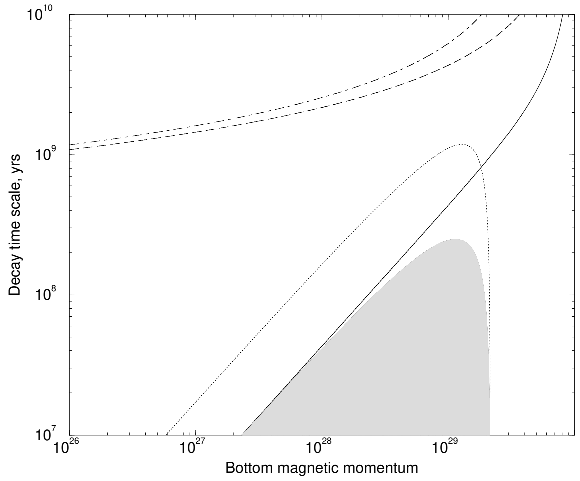

Fig. 3. Characteristic time scale of the magnetic field decay, t_d, vs. bottom magnetic momentum, μ_b. In the filled region t_E is greater than 10^{10}yrs. Dashed line corresponds to $t_H = t_d \cdot \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ years. Solid line corresponds to $p_E(\mu_b) = p(t = t_{cr})$, where $t_{cr} = t_d \cdot \ln(\mu_0/\mu_b)$. Both lines and filled region are plotted for $\mu_0 = 10^{30}\,\mathrm{G\,cm^{-3}}$. Dot-dashed line is the same as the dashed one, but for $\mu_0 = 5 \cdot 10^{29}\,\mathrm{G\,cm^3}$. Dotted line is a border of the 'forbidden" region for $\mu_0 = 5 \cdot 10^{29}\,\mathrm{G\,cm^3}$.

In the "forbidden" region in Fig. 3, which is plotted for $\mu_0 = 10^{30}\,\mathrm{G\,cm^3}$, all NSs reach the bottom field in a Hubble time or faster, and evolution on the late stages of their lives goes on with the field equal to the bottom. The left side is determined approximately by the condition:

$$p_E(\mu_b) = p(t = t_{cr}). \quad (9)$$

Small difference between the line, correspondent to the condition above, and the left side of the "forbidden" region appears because a NS can slightly change its period even with the momentum $\mu = \mu_b$, but due to small value of the field angular momentum losses are also small.

The right side of the region is roughly determined by the value of μ_b, with which a NS can reach the ejector stage with any t_d, i.e. this μ_b corresponds to the minimum value of μ_0 with which a NS reach the ejector stage without field decay.

NSs to the right from the "forbidden" region leave the ejector stage, because their field cannot decay down to low values, and spin-down is fast enough during all their lives as ejectors, because the bottom magnetic momentum there is relatively high. To the left from the "forbidden" region the situation is different. Spin-down of NSs is very small and they leave the ejector stage not because of spin-down, but due to decreasing of p_E, which depends upon the magnetic momentum.

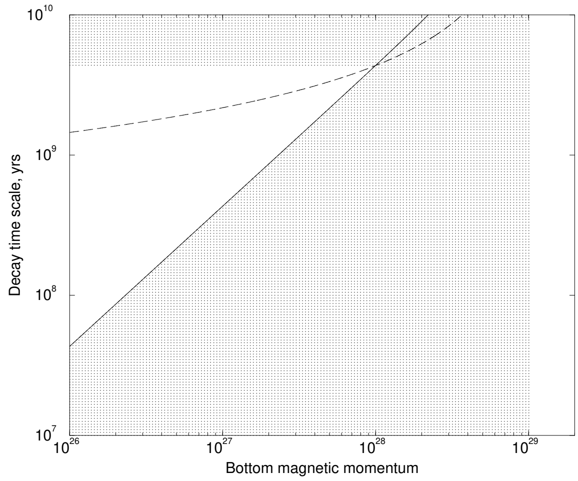

Fig. 4. Characteristic time scale of the magnetic field decay, t_d, vs. bottom magnetic momentum, μ_b. In the filled region t_E is greater than 10^{10} yrs. Dashed line corresponds to $t_H = t_d \cdot \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ yrs. Solid line corresponds to $p_E(\mu_b) = p(t = t_{cr})$, where $t_{cr} = t_d \cdot \ln(\mu_0/\mu_b)$. Both lines and region are plotted for $\mu_0 = 10^{29}$ G cm^{-3}.

Dashed line in Fig. 3 shows, that for all interesting parameters a NS with $\mu_0 = 10^{30}$ G cm^3 reach μ_b in less than 10^{10} yrs. Dot-dashed line shows the same for $\mu_0 = 0.5 \cdot 10^{30}$ G cm^3.

On Fig. 3 we also show the "forbidden" region and the line of reaching μ_b for $\mu_0 = 0.5 \cdot 10^{30}$ G cm^3.

Fig. 4 is plotted for $\mu_0 = 10^{29}$ G cm^3. For long t_d, $> 4 \cdot 10^9$ yrs, a NS again is not able to leave the ejector stage. It happens because the magnetic momentum can't decrease down to small value of μ (nearly μ_b), and p_E is not decreasing enough.

3. Discussion and conclusions

We tried to evaluate the region of parameters, forbidden for models of the exponential magnetic field decay in NSs using the fact of observations of old accreting isolated NSs in X-rays.

If the main fraction of NSs have nearly the same initial parameters and parameters of the decay, then the intermediate values of t_d ($\sim 10^7 - 10^8$ yrs) in combination with the intermediate values of μ_b ($\sim 10^{28} - 10^{29.5}$ G cm^3) for $\mu_0 = 10^{30}$ G cm^3 can be excluded, because for that sets of parameters NSs spend all their lives on the ejector stage, never coming to the accretor stage.

As one can see in Fig. 2, for higher μ_0 NSs should reach t_E even for $t_d < 10^8$ yrs, for smaller – the "forbidden" region should become wider. Results are depended on the initial magnetic field, μ_0, ISM concentration, n, and NS velocity, v, so one can say, that the observed accreting isolated NSs come from, for example, the objects with high initial magnetic field, and the rest are not visible because they are in the forbidden region. To explore this idea in details population synthesis of NSs for realistic distributions of v, μ_0 and n is needed. But we can say immediately, that the idea of obtaining accreting old isolated NSs from initially high field objects is not very promising, because the fraction of high field NSs can not be large (basing on radio pulsars observations), and as far as the fraction of low velocity NSs is not more than several percents (Popov et al. 1999) and the volume fraction filled with relatively high density ISM is also small, accreting old isolated NSs should come from "typical" population, i.e. from NSs with μ_0 about $10^{30}\,\mathrm{G\,cm^3}$ or less.

Actually, limits that we obtained are even stronger than they are in nature, because we didn't take into account, that some significant time (in the case of field decay) a NS can spend on the propeller stage (spin-down rate at this stage is very uncertain, see the list of formulae, for example, in Lipunov & Popov 1995 or Lipunov 1992). Calculations of this effect, and calculations for different models of non-exponential field decay are subjects for future work.

We cannot say anything about parameters of field decay in the case of accretion in close binaries, because there situation is completely different, and our results cannot be applied to millisecond radio pulsars or other objects in close binary systems.

We note, that there is another reason due to which very fast decay down to small values of μ_b also can be excluded, because it leads to huge amount of accreting isolated NSs. This situation is similar to "turning-off" the magnetic field of a NS (i.e., quenching any magnetospheric effect on the accreting matter), and for any velocity and density distributions we should expect significantly more accreting isolated NS than we have from ROSAT observations (of course, for high velocities X-ray sources will be very dim, but close NSs can be observed even for velocities ~ 100 km s^{-1}).

So, the existence of several old isolated accreting NSs, observed by ROSAT (if it is the correct interpretation of observations), can put important limits on the models of the magnetic field decay for isolated (without influence of accretion, which can stimulate field decay) NSs, and models, from their side, should explain the fact of observations of ~ 10 accreting isolated NSs in the solar vicinity. We cannot discuss numerous details of connection between decay parameters and X-ray observations of isolated NSs without detailed calculations, we just tried to show, that this connection should be taken into account and made some illustrations of it, and future investigations in that field are wanted.

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