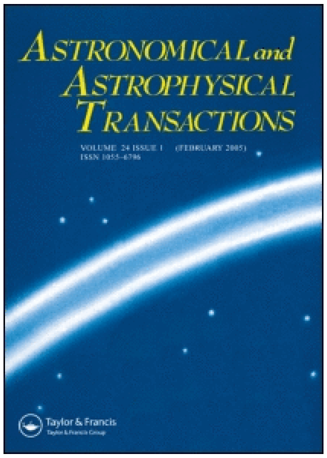

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ROSAT X-RAY SOURCES AND EXPONENTIAL FIELD DECAY IN ISOLATED NEUTRON STARS

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In this paper we semianalytically evaluate the 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 the 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 $\sim 10^{28}$–$10^{29.5}$ G cm^3 and characteristic time scale, t_b in the range $\sim 10^7$–10^8 yrs for standard initial magnetic moment, $\mu_0 = 10^{30}$ G cm^3, can be excluded, because for that set 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 field decay, X-ray sources

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 insignificant, because magnetic pressure dominates everywhere over the gravitational pull, and geo-like magnetosphere is formed.

Field decay was used in the case of old accreting isolated NSs by Konenkov and Popov (1997) and Wang (1997) to explain properties of the source RX J0720-3125.

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, see 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 (Haberi *et al.*, 1998; Neühauser and Trümper, 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:

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

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), ~ 1 cm^{-3}, and small spatial velocity of a NS, ~ 10 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.

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 and Popov, 1995).

We assume exponential field decay:

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

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

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

After that moment magnetic field is assumed to be constant.

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

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

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

where $v_{10} = \sqrt{v_p^2 + v_s^2}/10$ 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 km s^{-1} and the sound velocity outside hot low density ISM regions is lower than 10 km s^{-1}, we have $\sqrt{v_p^2+v_s^2}\approx v_p$. n is a concentration of the ISM.

The initial period should be taken to be much smaller than p_E. We used $p_0=0$ s. We calculated spin-down according to magneto dipole formula (but other regimes are possible, see Beskin *et al.*, 1993 for a review):

$$\frac{\mathrm{d}p}{\mathrm{d}t}=\frac{2}{3}\frac{4\pi^2\mu^2}{pIc^3} \tag{5}$$

where μ can be a function of time.

For our estimates we assumed constant velocity of NSs, v, equal to 10 km s^{-1} and constant ISM concentration, n, equal to 1 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.

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

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

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:

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

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 the data in Figures 1 and 2. Filled regions represent space of the parameters where t_E is longer than 10^{10} yrs, so in that region a NS never reaches the accretor stage, and does not 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).

In the 'forbidden' region in Figure 1, which is plotted for $\mu_0=10^{30}$ G cm^3, all NSs reach the bottom field in a Hubble time or faster, and evolution of the late stages of their lives goes on with the field equal to the bottom. The left side is determined approximately by the condition:

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

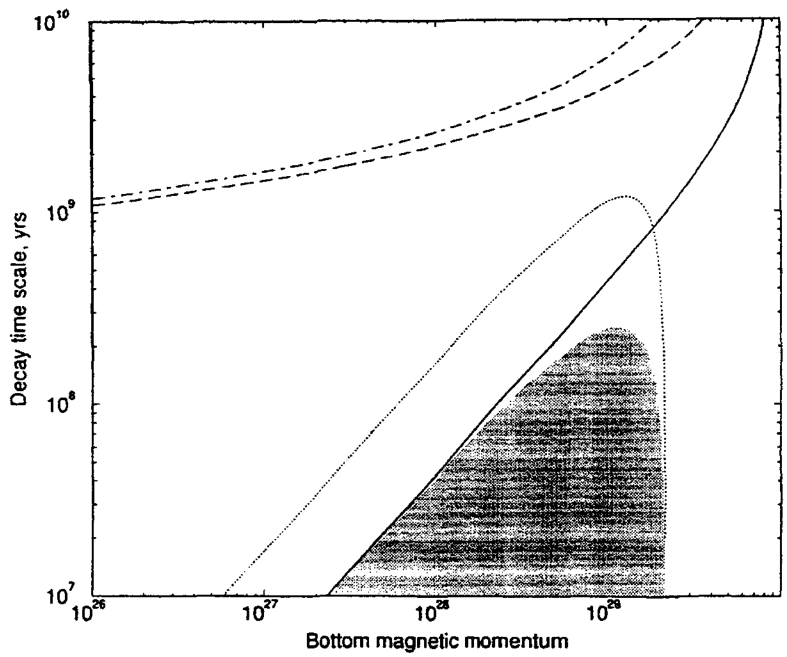

Figure 1 Characteristic time scale of the magnetic field decay, t_d vs. bottom magnetic momentum, μ_b. In the filled region t_E is greater than 10^{10} yrs. Dashed line corresponds to $t_H = t_d \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ years. Solid line corresponds to $p_E(\mu_b) = p(t = t_{\rm cr})$, where $t_{\rm cr} = t_d \ln(\mu_0/\mu_b)$. Both lines and filled region are plotted for $\mu_0 = 10^{30}$ G cm^{-3}. Dot-dashed lino is the same as the dashed one, but for $\mu_0 = 5 \times 10^{29}$ G cm^{-3}. Dotted line is a border of the 'forbidden' region for $\mu_0 = 5 \times 10^{29}$ G cm^3.

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 moment 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 moment.

Dashed line in Figure 1 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 $\mu_0 = 0.5 \times 10^{30}$ G cm^3.

On Figure 1 we also show the 'forbidden' region and the line of reaching μ_b for $\mu_0 = 0.5 \times 10^{30}$ G cm^3.

Figure 2 is plotted for $\mu_0 = 10^{29}$ G cm^3. For long t_d, $> 4 \times 10^9$ yrs, a NS again is not able to leave the ejector stage. It happens because the magnetic moment cannot

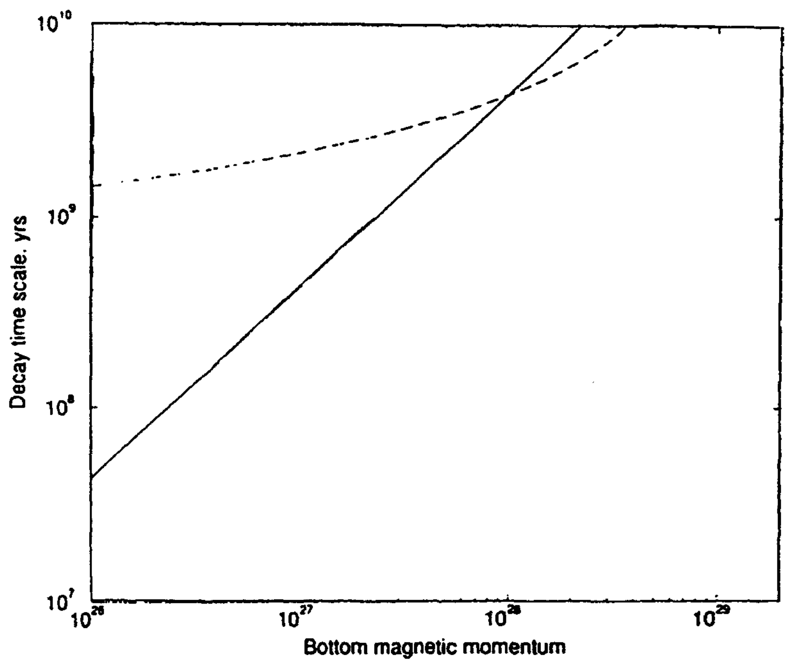

Figure 2 Characteristic time scale of the magnetic field decay, t_d vs. bottom magnetic momentum, μ_b. In the filled region t_E is greater than 10^{10} yrs. Dashed line corresponds to $t_H = t_d \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ yrs. Solid line corresponds to $p_E(\mu_b) = p(t = t_{cr})$, where $t_{cr} = td\ln(\mu_0/\mu_b)$. Both lines and region are plotted for $\mu_0 = 10^{29}$ G cm^{-3}.

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 set of parameters NSs spend all their lives on the ejector stage.

So, the existence of several old isolated accreting NSs, observed by ROSAT can put important limits on the models of the magnetic field decay for isolated NSs, and the 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 we made some illustrations of it, and indicated that future investigations in that field are required.

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