Magnetic field decay and period evolution of the source RX J0720.4-3125

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Abstract

We studied possible evolution of rotational period and magnetic field of the X-ray source RX J0720.4-3125 assuming this source to be an isolated neutron star accreting from interstellar medium. Magnetic field of the source is estimated to be $10^6 - 10^9$ Gs (most probably $\approx 2 \cdot 10^8$ Gs), and it is difficult to explain the observable rotational period 8.38 s without invoking hypothesis of the magnetic field decay. We used the model of ohmic decay of crustal magnetic field. The estimates of the accretion rate ($10^{-14} - 10^{-16} M_{\odot}$/yr), velocity of the source relative to the interstellar medium ($10 - 50$ km/s), the neutron star age ($2 \cdot 10^9 - 10^{10}$ yrs) are obtained.

(remark added in proof: As we found out in July 1997 when this paper was already submitted, common results were recieved independently by John C.L. Wang // Astrophys. J., 1997, V.486. P.L119)

1 Introduction

Recently isolated neutron stars (INSs), which are not observed as radiopulsars, became of great interest both for observers and theorists. The idea of observations of such sources was proposed more than 25 years ago [6], and in 1991 Treves and Colpi [8] suggested, that INSs, accreting from interstellar medium (ISM), can be observed in great number in UV and X-rays by *ROSAT*. Here we present the results of the work on the source RX J0720.4-3125 observed by Haberl et al. [12]. In [12] it was proposed, that RX J0720.4-3125 is an accreting INS with the rotational period 8.38 s.

There are four possible stages of an INS in low density plasma: Ejector (E), Propeller (P), Accretor (A) and Georotator (G). The stage is determined by relations between specific radii: R_l- light cylinder radius, $R_{st}-$ stopping radius, $R_G = (\frac{2GM}{v_\infty^2})-$ the radius of the gravitational capture and $R_{co} = (\frac{GM}{\omega^2})^{1/3}-$ the corotation radius.

As a result we have two critical periods: P_E and P_A, separating different stages. If $p < P_E$, we have an Ejector (i.e. a pulsar), if $P_E < p < P_A$, the NS is on the Propeller stage, and if $p > P_A$ and $R_{st} < R_G$ – we have an accreting NS. It is possible, that $p > P_A$, but $R_{st} > R_G$. In this case a geo-like magnitosphere is formed, and we call it Georotator.

For describtion of period evolution it is useful to use a gravimagnetic parameter, y, (it is described in [4]).

On the figure 1 three examples of evolutionary tracks of an INS on p-y-diagram are presented. All of them are ended at the Accretor stage.

I. $E \longrightarrow P \longrightarrow A-$ evolution of an INS in the ISM with the constant density without magnetic field decay.

II. $E \longrightarrow P \longrightarrow A \longrightarrow P \longrightarrow A-$ evolution of an INS, passing through a giant molecular cloud without magnetic field decay.

III. Evolution with magnetic field decay.

We are especially interested in the third case.

2 Analitical estimates of the X-ray pulsar's parameters

In this part we show mainly estimates which were not included into the article [3].

Lets consider the situation, when the Alfven radius, R_A, and the corotation radius, R_{co}, are equal. This equation gives us the accretion period, P_A:

$$P_A \approx 6 \cdot 10^2 \mu_{30}^{6/7} \rho_{-24}^{-3/7} v_{\infty_6}^{9/7} \left(\frac{M}{M_\odot}\right)^{-11/7} s \qquad (1)$$

here μ_{30} – magnetic momentum in units $10^{30}\mathrm{Gs} \cdot \mathrm{cm}^2$, ρ_{-24} – density of the ISM in units $10^{-24}\mathrm{g/cm}^3$, v_{∞_6} – velocity of the INS relative to the ISM in units 10^6cm/s.

During accretion $p > P_A$. If these two periods are equal:

$$\mu_{30}^{6/7} = \frac{8.38}{6 \cdot 10^2} \rho_{-24}^{3/7} v_{\infty_6}^{-9/7} \left(\frac{M}{M_\odot}\right)^{11/7}$$

So, $\mu_{30} = 0.007 \rho_{-24}^{1/2} v_{\infty_6}^{-3/2} \left(\frac{M}{M_\odot}\right)^{11/6}$ for $P_A = p = 8.38\ s$ (the period of RX J0720.4-3125). For the NS's radius $R = 10\,\mathrm{km}$ we have $B < 7 \cdot 10^9$ Gs.

If we use the hypothesis of the acceleration of an INS from the turbulizated ISM, we have an equation, which gives an estimate of the magnetic field of the INS based on the equilibrium period, P_{eq}, [3, 5]:

$$P_{eq} = 2355 k_t^{1/3} \mu_{30}^{2/3} I_{45}^{1/3} \rho_{-24}^{-2/3} v_{\infty_6}^{13/3} v_{t_6}^{-2/3} \left(\frac{M}{M_\odot}\right)^{-8/3} \mathrm{s} \qquad (2)$$

Here I_{45} – the momentum of inertia in units $10^{45}\mathrm{g} \cdot \mathrm{cm}^2$, v_{t_6} – the turbulent velocity in units 10^6cm/s.

So we have:

$$\mu_{30} = \left(\frac{8.38}{2355}\right)^{3/2} k_t^{-1/2} I_{45}^{-1/2} \rho_{-24} v_{\infty_6}^{-13/2} v_{t_6} \left(\frac{M}{M_\odot}\right)^4$$

And finaly $B \approx 2.1 \cdot 10^8$ Gs.

In [3] we showed, that the magnetic field can't be less than $10^5 - 10^6\, Gs$, because in the opposite case we can't observe pulsations of the X-ray flux.

Lets suppose, that the INS was born with a period about 0.01 – 0.02 s (the exact value is not very important, because the only necessary condition is $P_{initial} << 8.38$ s, and initially the INS was on the Ejector stage). So, the star had to decelerate till 8.38 s. Lets estimate the time of this deceleration.

The time of deceleration is determined by the *final*, not by the initial period!

$$P_E \approx 10 (k_t)^{1/4} \mu_{30}^{1/2} \rho_{-24}^{-1/4} v_{\infty_6}^{-1/2} s$$

$$\frac{dI\omega}{dt} = -k_t \frac{\mu^2}{R_l^3},\ R_l = c/\omega,\ \omega = 2\pi/p$$

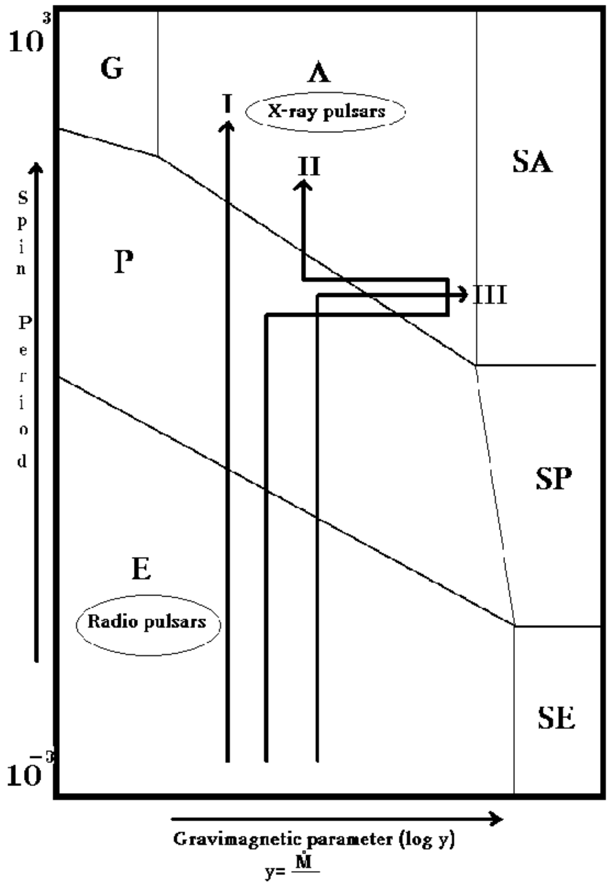

Figure 1: P-y diagram

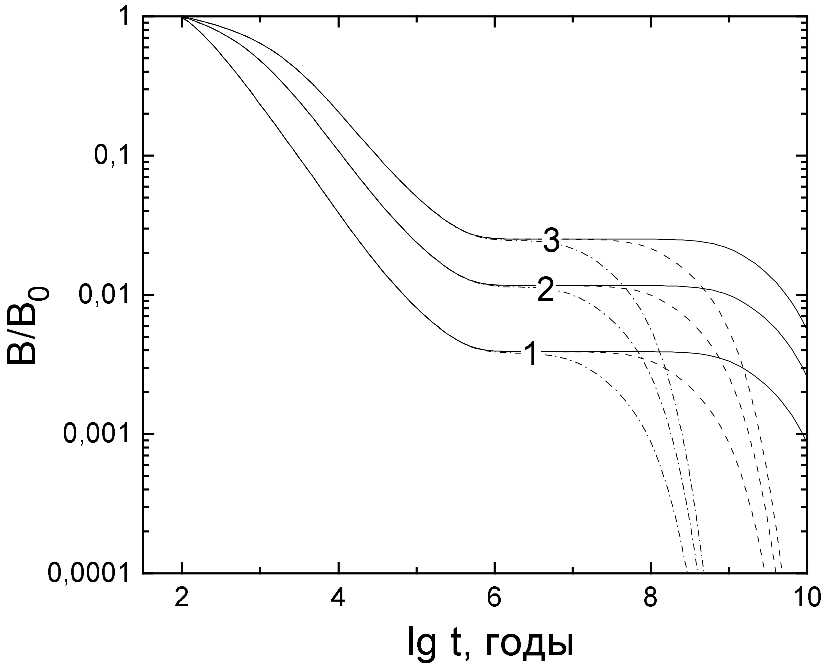

Figure 2: Changes of the surface magnetic field of an isolated neutron star with time for the model of standard cooling. Curves 1, 2, and 3 correspond to the initial depths of the current layer, 10^{11}, 10^{12}, and 10^{13} g cm^{-3}, respectively. The solid curves correspond to Q = 0.001; the dashed curves, to Q = 0.01; the dot-dashed curves, to Q = 0.1.

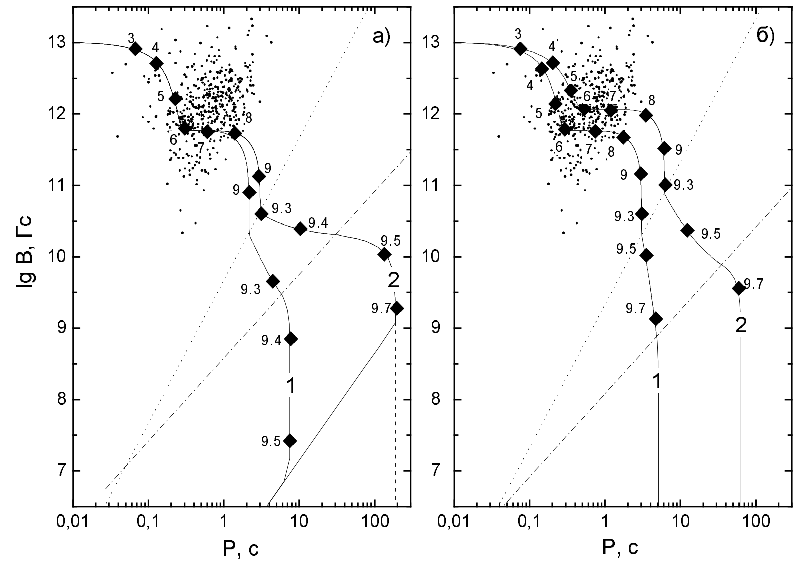

Figure 3: The evolutionary tracks of the neutron star for the accretion rates $\dot{M} = 10^{-15} M_{\odot}\,\mathrm{yr}^{-1}$ (a) and $\dot{M} = 10^{-16} M_{\odot}\ \mathrm{yr}^{-1}$ (b). The model parameters are described in the text. The dashed lines correspond to $p = P_E$; the dot-dashed lines, to $p = P_A$. The dashed line in Fig. 2a shows for the second track the neutron star evolution with no acceleration in the turbulized intestellar medium. The numbers near the marks in tracks denote the logarithm of the neutron star age in years. The observed radio pulsars are indicated by dots.

$$\frac{1}{p^2} I \frac{\Delta p}{\Delta t} = k_t \frac{\mu^2 (2\pi)^2}{c^3 p^3}$$

So for $\Delta p = p$:

$$\Delta t = \frac{I p^2 c^3}{k_t \mu^2 (2\pi)^2} =$$

$$= 3 \cdot 10^7 P_E^2 k_t^{-1} \mu_{30}^{-2} I_{45} yrs =$$

$$= 3 \cdot 10^9 k_t^{-1/2} \mu_{30}^{-1} \rho_{-24}^{-1/2} v_{\infty_6}^{-1} I_{45} yrs$$

For $\mu_{30} < 0.01$ $\Delta t > 3 \cdot 10^{11} yrs >> t_{Hubble}$. I.e. the star couldn't initially have low magnetic field.

As far as the NS is on the Accretor stage, its period should be much greater than the ejection period, P_E:

$$p > P_{Propeller} > P_E$$

$P_E \approx 10s$ for standart parameters. It means, that if the star is on the accretor stage with p=8.38 s, the field is much less than the standart value: $B << 10^{12}$ Gs.

Lets try to estimate the characteristic time of acceleration and deceleration of such a NS:

$$t_{su} = t_{sd} = \frac{I\omega}{\dot{M} v_t R_G} =$$

$$= 20 yrs \cdot I_{45} v_{\infty_6}^5 \rho_{-24}^{-1} \left(\frac{p}{10^5 s}\right)^{-1} \left(\frac{v_t}{10^6 cm/s}\right)^{-1}$$

where t_{su}, t_{sd} - characteristic times of the period changes.

For p=10 s $t_{su} = 2 \cdot 10^5$ yrs. If v_t is less than $10^6 cm/s$, than t_{su} is greater. So, $\dot{p} \approx p/t_{su} <\approx \frac{8.38}{2 \cdot 10^5 \cdot 3 \cdot 10^7} \approx 10^{-12} s/s$

3 Calculations of the magnetic field decay

So, we can say, that the magnetic field of the source dissipated, and the characteristic time of the dissipation , t_d, was short enough: $t_d < t_E$ (t_E- Ejector's time). Because of that we have rapidly rotating INS on the Accretor stage.

The detailes of calculations one can find in [3].

We calculated the magneto-rotational evolution of the star with the mass $M = 1.4 M_\odot$ for accretion rates $10^{-15} M_\odot$/yr and $10^{-16} M_\odot$/yr passing through the ISM with the density $\rho = 10^{-24}$g/cm^3. These rates correspond to velocities ≈ 20 and ≈ 40 km/s.

The magnetic field decay was studied by different authors (see [10]).For conductivity we used formulae from [13] and [2]. Initially the magnetic field was localized in the surface layer. Low accretion rates don't have much influence on the magnetic field decay [1, 9].

On the figure 2 we show the decrease of the surface magnetic field for different parameters. We used the model of the NS structure from [11].

On figure 3 the evolutionary tracks for the accretion rates $10^{-15} M_\odot$/yr (fig. 3a) and $10^{-16} M_\odot$/yr (fig. 3b) are shown.

4 Conclusions

Observations of the accreting INSs can be an important test for theories of the magnetic field decay. In that case we have a very "pure" example of the decay, because a lot of effects of the interaction of the magnetic field, the surface of the NS and surrounding plasma are not important.

Observations of the source RX J0720.4-3125 [12] showed the existence of the INS with the rotation period which can be easily explained with the assumption of the magnetic field decay. It can be important for estimates of the total number of observable INS and for their appearence as periodic X-ray sources [7].

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5 References

1. Zdunik J.L., Haensel P., Paczyński B., Miralda-Escude J.// Astrophys. J. 1992. V.384. P.129.
2. Itoh N., Hayashi H., Kohyama Y. // Astrophys. J. 1993. V.418. P.405.
3. Konenkov D.Yu, Popov S.B.// Astronomy Letters. 1997. V.23, P. 200 (astro-ph/9707318)
4. Lipunov V.M.// *Astrophysics of neutron stars*, Springer, 1992.

5. Lipunov V.M., Popov S.B.// Astron. Zhur.. 1995. V.72, P. 711. (see also astro-ph/9609185)
6. Ostriker J.P., Rees M. J., Silk J. // Astrophys. J. Letters 1970. V.6, P.179
7. Popov S.B.//Astron. Circ 1994. No.1556. P.1.
8. Treves A., Colpi M.// Astron. and Astrophys., 1991, V. 241, P. 107.
9. Uprin V., Geppert U., Konenkov D.// Astron. and Astrophys. 1996. V.307. P.807.
10. Urpin V.A., Muslimov A.G.// Astron. Zhur. 1992. V.69. P.1028.
11. Friedman B., Pandharipande V.R.// Nucl. Phys. 1981. A361. P.502.
12. Haberl F., Pietsch W., Motch C., Buckley D.A.H.// IAU Circ. 1996. No. 6445.
13. Yakovlev D.G., Urpin V.A.// Astron. Zhur. 1980. V.24. P.303.