RX J0720.4–3125 as a Possible Example of the Magnetic Field Decay of Neutron Stars

D. Yu. Konenkov[1]) and S. B. Popov[2])
1) A.F.Ioffe Institute of Physics and Technology
194021 St.Petersburg, Russia,
e-mail: dyk@astro.ioffe.rssi.ru
2) Moscow State University, 119899, Moscow, Russia
e-mail: polar@xray.sai.msu.su

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Abstract

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

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1 Introduction

Isolated neutron stars (INS) have received special attention in the last few years. The idea of observing such objects in the X-ray range has emerged rather long ago (Ostriker et al., 1970). Treves and Colpi (1991) supposed that INSs accreting matter of the interstellar medium (ISM) can be observed with the *ROSAT* satellite in the UV and X-ray ranges.

The estimations of energy characteristics, spectra and possibilities of observing INSs were made in several works (see, for example, Böhringer et al., 1987; Treves and Colpi, 1991; Blaes and Madau, 1993). A large number of works is devoted to the study of the spatial distribution of INSs (see, for example, Blaes and Rajagopal, 1991).

In the mid-1996, Haberl et.al. reported the discovery of the pulsating source RX J0720.4–3125 with the *ROSAT* satellite in the soft X-ray range. We shall use two observational characteristics of this source (Haberl et.al., 1996): the period $p = 8.38$ s and the blackbody temperature $T = (79 \pm 4)$ eV.

Using the hypothesis that this source is an INS accreting matter from the ISM (we do not follow alternative hypotheses: further observations will show if it is true or not), we estimate the accretion rate and the magnetic field strength of this source. We show that the INS could not increase its period to the observed value over the Universe lifetime if we assume that it was born with the present-day magnetic field strength. Finally we conclude that the magnetic field of this neutron star (NS) had to decay. Then, using the model of ohmic dissipation of the magnetic field we calculate the magnetorotational evolution of the NS.

The paper is organized as follows. In Section 2, we present the reference material on the evolution of the neutron star period and on the model of ohmic dissipation of the magnetic field; in Section 3, the analytical estimates of the neutron star parameters are made; the evolutionary tracks of the INS are computed in Section 4; and the conclusions are given in Section 5.

2 Evolution of the spin period and the magnetic field of the neutron star

2.1 Spin period

In the low-density plasma an INS may have four possible evolutionary states (Lipunov, 1987): ejector, propeller, accretor, and georotator. A particular state is determined by the relation between four characteristic radii: the light cylinder radius $R_l = c/\omega$; the stopping radius R_{st}; the radius of the gravitational capture $R_G = (2GM)/v_\infty^2$; and the corotation radius $R_{co} = (GM/\omega^2)^{1/3}$. Here, M is the NS mass, c is the speed of light, ω is the spin frequency, and v_∞ is the NS velocity with respect to the ISM.

The relationship between these radii determines two critical periods: P_E and P_A which separate different stages of the NS evolution. These periods can be estimated using the formulae (Lipunov, 1987):

$$P_E = 2\pi \left(\frac{2\,k_t}{c^4}\right)^{1/4} \left(\frac{\mu^2}{v_\infty \dot{M}}\right)^{1/4}, \quad R_l < R_G, \tag{1}$$

$$P_A = 2^{5/14}\pi(GM)^{-5/7}\left(\frac{\mu^2}{\dot{M}}\right)^{3/7}, \quad R_A < R_G. \tag{2}$$

Here μ is the magnetic dipole moment, $\dot{M} \equiv \pi R_G^2 \rho v_\infty$ is the accretion rate, ρ is the ISM density, and k_t is a dimensionless constant of the order of unity.

If $p < P_E$, then NS is at the ejector stage; if $P_E < p < P_A$, we have the NS at the propeller stage; and if $p > P_A$ and $R_{st} < R_G$, then NS is an accretor. In some cases the situation is possible when $p > P_A$, but $R_{st} > R_G$ and accretion is impossible because of the formation of the geolike magnetosphere. However, we shall not be interested in the georotator stage since we consider the accreting NSs for which $R_{st} < R_G$.

At the ejector stage, the evolution of the spin period is determined by the losses of the INS kinetic energy due to magnetic dipole radiation:

$$\dot{p} = \frac{8\pi^2 R^6}{3c^3 I} \cdot \frac{B^2(t)}{p}, \tag{3}$$

where R is the NS radius, I is the moment of inertia, and $B = \mu/R^3$ is the magnetic field strength.

At the propeller stage, the NS spin-down rate is determined by the transfer of the angular momentum to the surrounding matter (Illarionov and Syunyaev, 1975):

$$\dot{p} = \frac{2^{2/7}}{\pi}\frac{(GMR^2)^{3/7}}{I} p^2 B^{2/7} \dot{M}^{6/7}. \tag{4}$$

At the accretion stage, the NS is acted upon by two moments of forces:

$$\frac{d(2\pi I/p)}{dt} = K_{sd} + K_{turb}, \tag{5}$$

$$K_{sd} = -k_t \frac{\mu^2}{R_{co}^3}.$$

Here K_{sd} is the braking moment of forces which can arise due to the possible turbulization of the ISM. K_{turb} acts randomly and can either spin up or spin down the NS (Lipunov and Popov, 1995).

The change in the period of an accreting INS is due to its interaction with the turbulized ISM. This introduces specific features into the problem of the period evolution. If we adopt the hypothesis of spin acceleration of the NS in the turbulized ISM (Lipunov and Popov, 1995), the new characteristic period emerges,

$$P_{eq} = 960 k_t^{1/3} \mu_{30}^{2/3} I_{45}^{1/3} \rho_{-24}^{-2/3} v_{\infty_6}^{13/3} v_{t_6}^{-2/3} M_{1.4}^{-8/3} \text{ sec} = \tag{6}$$

$$= 3450 k_t^{1/3} \mu_{30}^{2/3} I_{45}^{1/3} \dot{M}_{-15}^{-2/3} v_{\infty_6}^{7/3} v_{t_6}^{-2/3} M_{1.4}^{-4/3} \text{ sec},$$

where μ_{30} is the magnetic dipole moment in units of 10^{30} Gs cm^2, I_{45} is the moment of inertia in units of 10^{45} g cm^2, ρ_{-24} is the ISM density in units of 10^{-24} g cm^{-3}, v_{∞_6} is the NS velocity relative to the ISM in units 10^6 cm/s, and v_{t_6} is the turbulent velocity in units of 10^6 cm/s. The period P_{eq} corresponds to the NS rms rotation rate obtained from the solution of the corresponding Fokker–Planck equation. In reality, the rotational period of INS fluctuates around this value. Note that here we make a more accurate estimate of the period than that made in the work of Lipunov and Popov (1995) (we are grateful to M.E. Prokhorov for his assistance in performing the corresponding calculations). We take into account the three-dimensional character of turbulence, i.e. the fact that the vortex can be oriented not only in the equatorial plane but also at any angle to this plane. In this case, diffusion occurs in the three-dimensional space of angular velocities.

2.2 Ohmic dissipation of the crustal magnetic field of the neutron star

The magnetic field decay in the neutron star crust has been investigated by many authors (see, f.e., Urpin and Muslimov, 1992). Such a decay is governed by the induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = -\frac{c^2}{4\pi}\nabla \times \left(\frac{1}{\sigma}\nabla \times \mathbf{B}\right) + \nabla \times (\mathbf{v} \times \mathbf{B}), \tag{7}$$

where σ is the conductivity; $\mathbf{v}$ is the velocity of the crust motion; and $\mathbf{v} = 0$ at the ejector and propeller stages. At the accretor stage in spherically symmetrical case, $\mathbf{v} = (-v_r, 0, 0)$, with the component

$$v_r = \frac{\dot{M}}{4\pi r^2 \rho(z)},$$

where r is the distance to the NS center, $\rho(z)$ is the density of matter at the depth $z = R - r$. Equation (7) is highly simplified in the case of the dipole field and reduced to the one-dimensional parabolic equation for the vector potential. The boundary conditions are set in the same ways as in the work of Urpin and Muslimov (1992).

The conductivity σ is determined basically by the scattering of electrons by phonons and impurities:

$$\frac{1}{\sigma} = \frac{1}{\sigma_{ph}} + \frac{1}{\sigma_{imp}}.$$

The phonon conductivity σ_{ph} depending on density and temperature dominates at high temperatures and at moderately high densities. At lower temperatures and higher densities the impurity conductivity σ_{imp} prevails. The impurity conductivity is independent of the temperature but is the function of concentration and the charge of impurities which are characterized by the parameter

$$Q = \frac{1}{n} \sum_{n'} n' \left(Z - Z' \right)^2 ,$$

where n and Z are, respectively, the concentration and the charge of the major ion species, and n' and Z' are the concentration and the charge of the impurity, the summation is over all impurity species. The analytical formula for the impurity conductivity was obtained by Yakovlev and Urpin (1980), while the phonon conductivity was taken from the work of Itoh et al. (1993). The initial field is assumed to be concentrated mainly in the surface layer of a certain thickness. The density of matter, ρ_0, at the inner boundary of this layer is the parameter of the model. The quantity Q is assumed to be independent of the depth.

The main results of the calculation of the decay of the INS magnetic field are the following. The magnetic field dissipation proves to be intimately related to the NS thermal evolution. For the *standard* cooling, at which the NS neutrino luminosity is determined chiefly by the modified URCA-processes (Pethick, 1992), in the first million years the field decays by a factor of $2 - 1000$, depending on the initial depth of the current layer and on the adopted equation of state for the star core (Urpin and Konenkov, 1997). As the NS cools down, the conductivity increases and the field decay slows down. The decay rate at the later stage depends on σ_{imp} and, therefore, on Q. For example, when $Q = 0.01$, the field does not decrease in the subsequent 10^8 yrs. However, as soon as the magnetic field diffuses through the entire crust and reaches the superfluid core (after $\sim 10^9$ yrs at $Q = 0.01$), the decay becomes exponential.

Figure 1 shows the decrease of the NS surface magnetic field with time for various parameters ρ_0 and Q. We perfomed our calculations for the model of the NS based on the Friedman–Pandharipande (1981) moderately hard equation of state in the star core, with the mass of the neutron star $M = 1.4 M_\odot$, the radius $R = 10.6\,\mathrm{km}$, and the crust thickness $\Delta R = 940\,\mathrm{m}$ (Van Riper, 1988). It is apparent that the decay at the initial stage ($t < 10^6\,\mathrm{yr}$) is determined by the initial depth of the current layer and that the subsequent decay rate depends on the amount of impurities.

Accretion may affect the field evolution. First, it heats the NS crust (Zdunik et al., 1992) and, therefore, decreases the conductivity. Second, the flux of matter toward the star center arises; it tends to bring the field to deeper layers. However, calculations show (Urpin et al., 1996) that accretion with the rate $\dot{M} < 10^{-14} M_\odot\,\mathrm{yr}^{-1}$ speeds up insignificantly the field decay.

3 Estimates of parameters of RX J0720.4–3125

Using the hypothesis that we observe an accreting isolated NS and taking the observed period $p = 8.38$ s and the temperature $T = (79 \pm 4)$ eV (Haberl et. al., 1996), we can obtain the constraints on the magnetic field, accretion rate, and luminosity.

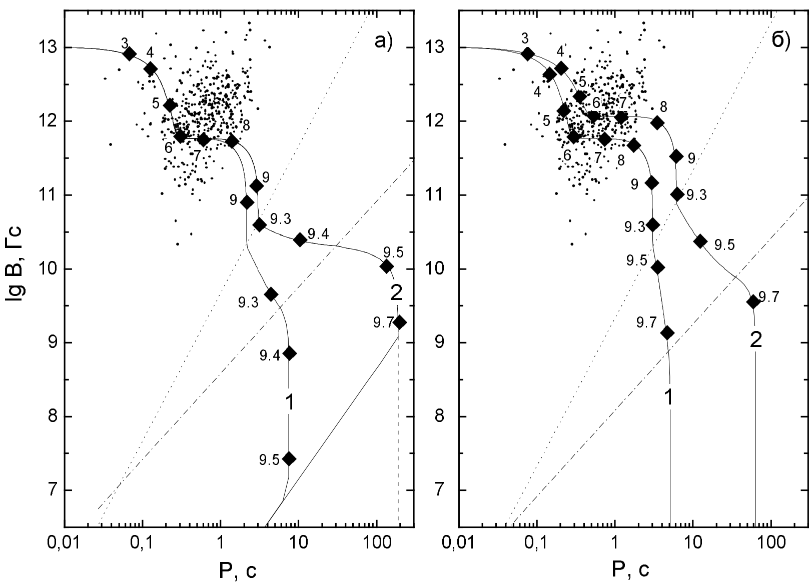

Figure 1: The change of the surface magnetic field of the isolated neutron star with time for the model of standard cooling. Curves 1, 2, and 3 correspond to the initial depths of the current layer, 10^{11}, 10^{12}, and 10^{13} g cm^{-3}, respectively. The solid curves correspond to Q = 0.001; the dashed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

1. If we really observe the accretor, then $p > P_A(B, \dot{M})$, where P_A is defined by (2). This yields the first constraint on B and $\dot{M}$:

$$B < 4.6 \cdot 10^9 M_{1.4}^{5/6} R_6^{-3} \dot{M}_{-15}^{1/2}\,\mathrm{G}, \tag{8}$$

2. We see the pulsating radiation, it means that the accreting matter is funneled by the magnetic field onto the polar caps. Using the known relation $R_{\rm cap} = \sqrt{(R/R_A)} \cdot R$, connecting the polar cap radius R_{cap}, the Alfven radius R_A, and the NS radius, we can estimate R_{cap} as

$$R_{\rm cap} = 0.53 \cdot B_9^{-2/7} \dot{M}_{-15}^{1/7} R_6^{9/14} M_{1.4}^{1/14}\,\mathrm{km},$$

where $B_9 = B/10^9$ G. From the condition $R_{cap} < R$ (or $R_A > R$) we obtain another constraint:

$$B > 3.4 \cdot 10^4 M_{1.4}^{1/4} R_6^{-5/4} \dot{M}_{-15}^{1/2}\,\mathrm{G}. \tag{8}$$

3. And finally, we know the polar cap temperature. From the condition

$$2\pi R_{\rm cap}^2 \sigma T^4 = \frac{GM\dot{M}}{R}$$

we find the additional relation between B and $\dot{M}$:

$$B = 2.5 \cdot 10^7 \left(T/79\ \mathrm{eV}\right)^7 R_6^4 M_{1.4}^{-3/2} \dot{M}_{-15}^{-5/4}\,\mathrm{G}. \tag{9}$$

Combining inequalities (8) and (9) and condition (10) yields the allowed range of the B and $\dot{M}$ values:

$$\begin{gathered} 2 \cdot 10^5 < B[\mathrm{G}] < 10^9, \\ 6 \cdot 10^{-17} < \dot{M}[M_\odot/\mathrm{yr}] < 4 \cdot 10^{-14}. \end{gathered} \tag{10}$$

This range of possible $\dot{M}$ values corresponds to the allowed range of luminosities L:

$$7 \cdot 10^{29} < L[\mathrm{erg/s}] < 5 \cdot 10^{32}.$$

Let us estimate the spin-down time to $p = 8.38$ s assuming that the NS was born as a radio pulsar with $p_0 \ll p_E$. The time of spin-down to $p = p_E$ at a constant magnetic field is deduced from (3) and (1):

$$\begin{aligned} t_E &= \frac{3c^3 I}{16\pi^2 R^6 B^2} P_E^2 = \\ &= 4 \cdot 10^{12} \dot{M}_{-15}^{-1/2} I_{45} v_{\infty_6}^{-1/2} R_6^{-3} B_9^{-1}\,\mathrm{yrs}. \end{aligned}$$

For $B < 10^{10}$ G and $\dot{M} < 10^{-13} M_\odot\,\mathrm{yr}^{-1}$ the spin-down time exceeds the age of the Universe. The spin-down at the propeller stage takes an additional time. Thus, we come to the conclusion that with the estimated values of the magnetic field strength, the accretion rate, and the velocity of motion relative to the ISM the NS could not spin down to $p = 8.38$ s. This means that in the past the given INS had a larger magnetic field that has decayed over the time of evolution.

4 The evolutionary tracks of neutron star on the $B-P$ diagram

The evolution of the spin period was calculated from formulae (3) and (4) taking into account the decay of the magnetic field at the ejector and propeller stages. Since the treatment of the spin-up rate in the turbulized ISM at the accretor stage is not quite a simple matter, we applied to the description of the period evolution the following simplifying model. When the NS gets to the accretor stage, the spin-down momentum substantially exceeds the spin-up momentum because the acceleration occurs in the turbulized ISM and there is no constant spin-up momentum, unlike in a binary system. However, we can obtain an analog of the equilibrium period (Section 2.1) which corresponds to the stationary solution of the Fokker–Planck equation (Lipunov, 1987; Lipunov and Popov, 1995). Therefore the evolution of the rotational period at this stage was treated as a stationary spindown from P_A to P_{eq} after which the period was set to be P_{eq}, which, in its turn, changed due to the magnetic field decay.

We calculated the magnetic and spin evolution of the NS with mass $M = 1.4 M_\odot$ for the accretion rates $10^{-15} M_\odot \mathrm{yr}^{-1}$ and $10^{-16} M_\odot \mathrm{yr}^{-1}$, moving through the ISM with density $\rho = 10^{-24}$ g/cm^3. Such accretion rates at the given ISM density correspond to the velocities of motion 19 and 41 km/s. We assumed the NS to be born as an ordinary pulsar with a short period ($p_0 = 0.01$ s) and a "standard" initial magnetic field $B_0 = 10^{13}$ G. The model of the ohmic decay of magnetic field allows one to obtain both the high and low dissipation rate. However, in this case we should fit the parameters of the model so as to obtain the accreting INS with a period of 8.38 s and a field of $2 \cdot 10^7$ G for the accretion rate $\dot{M} = 10^{-15} M_\odot$ yr^{-1} or with a field of $4 \cdot 10^8$ G for the accretion rate $10^{-16} M_\odot$ yr^{-1} (10). Therefore, the field should decay with a moderate rate to give the NS enough time to slow down to $p = 8.38$ s. Moreover, it is desirable at the initial stage of evolution to provide the agreement with magnetic fields and periods of the observed radio pulsars. Basing on these assumptions we can obtain the estimates of the parameters ρ_0 and Q, as well as the lower limit on the INS age.

The evolutionary tracks of the NS for the accretion rates $\dot{M} = 10^{-15} M_\odot$ yr^{-1} and $\dot{M} = 10^{-16} M_\odot$ yr^{-1} are shown in panels a) and b) of the Fig.2.

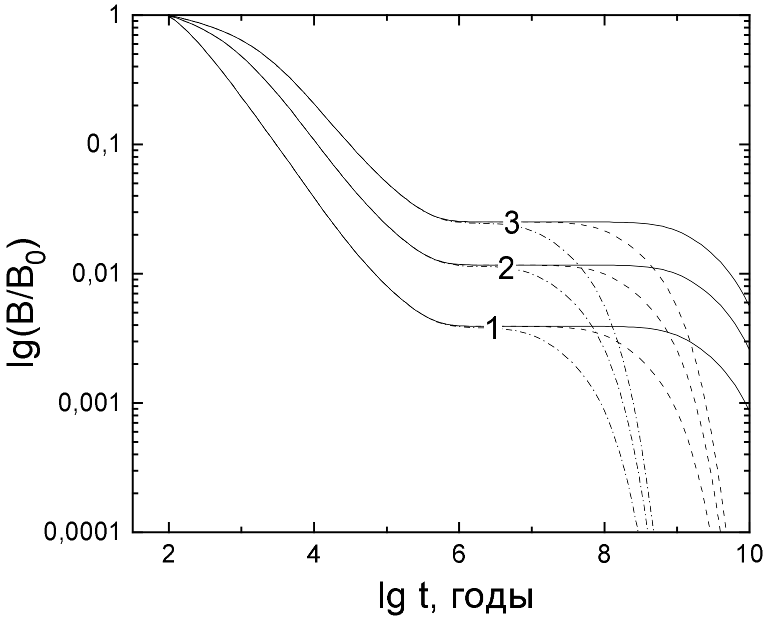

Figure 2: The evolutionary tracks of the neutron star for the accretion rates $\dot{M} = 10^{-15} M_\odot\,\mathrm{yr}^{-1}$ (a) and $\dot{M} = 10^{-16} M_\odot\ \mathrm{yr}^{-1}$ (b). The model parameters are described in the text. The dashed lines correspond to $p = P_E$; the dot-dashed lines, to $p = P_A$. 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 (Taylor et al., 1993).

Tracks 1 in both panels of Fig. 2 illustrate the evolution with the maximum possible rate of magnetic field dissipation with time. The model parameters for the accretion rate $\dot{M} = 10^{-15} M_{\odot}$ yr^{-1} are: $\rho_0 = 3 \cdot 10^{13}$ g/cm^3, $Q = 0.02$, and $v = 10^6$ cm/s. The NS was born at the point (p_0, B_0) at the left upper corner of the $B - P$ diagram. In the first 10_6 yrs, the field decays by about 20 times, while the NS slows down to $p \approx 0.3$ s. At that time the NS represents a typical radio pulsar. Subsequently, due to the cooling, the field decay slows down. In the next $8 \cdot 10^7$ yrs the field decays to $4.5 \cdot 10^{11}$ G, the period increases, and the radiopulsar dies. However, the ejector stage continues for $1.2 \cdot 10^9$ years. During this stage, the field decays to $2.5 \cdot 10^{10}$ G, the period increases to 2.1 s, and the NS goes over to the propeller stage (1) which lasts $\sim 10^9$ yrs. At this stage, further deceleration of the NS occurs, according to (4), to $p = 5.7$ s, and the field decays to $3 \cdot 10^9$ G. The star goes over to the accretor stage and becomes the source of periodic X-ray radiation. The core heating speeds up insignificantly the field decay (Urpin et.al., 1996). The field decays to $2 \cdot 10^7$ G over $4 \cdot 10^9$ yrs. The period does not increase because the field is weak enough. As soon as P_{eq} becomes equal to the current period, the spin-up of the NS due to the interaction with the ISM may occur. The period fluctuates around P_{eq}, but we do not estimate here the amplitude of these fluctuations.

Tracks 2 illustrate the evolution with slower field decay. Such a decay can be obtained, for example, for the crust with lower impurity content. For $\dot{M} = 10^{-15} M_{\odot}$ yr^{-1}, we set $Q = 0.01$, while the other parameters remained the same as for track 1 in Fig. 2a. Tracks 1 and 2 coincide at the initial stage of evolution, when the dissipation rate does not depend on the impurity concentration. However, in 10^7 yrs the tracks diverge. As a result, the star resides at the ejector stage $2 \cdot 10^9$ yrs going over to the propeller stage with $p = 3$ s and $B = 4 \cdot 10^{10}$ G. The spin-down rate at the propeller stage is much higher than in the first case for three reasons: due to the longer spin period, the stronger magnetic field during the NS transition from the ejector to the propeller stage, and to the lower rate of the field decay caused by the lower value of the Q parameter. At the accretor stage, the NS spin period decreases to 190 s over $2 \cdot 10^9$ yrs, and when the field decays to $4 \cdot 10^8$ G, the effect of acceleration in the turbulized ISM may begin to act. The track in the absence of such acceleration ($v_t = 0$) is shown by the dashed line. In this case the final period turns out to be about 200 s. The turbulent acceleration may decrease this period. However, the self-consistent calculation of the evolution of the NS period at the accretor stage with allowance for the magnetic field decay would require the solution of the Fokker–Planck equation for the distribution function in the space of angular velocities, which is beyond the scope of this work.

At the accretion rate $\dot{M} = 10^{-16} M_{\odot}$ yr^{-1} we used for track 1 the following parameters: $\rho_0 = 3 \cdot 10^{13}$ g/cm^3, $Q = 0.01$, and $v_t = 10^6$ cm/s. The NS comes to the propeller stage in $2.7 \cdot 10^9$ yrs having a period of 3.1 s and a magnetic field of $2 \cdot 10^{10}$ G. The transition to the accretor stage occurs when the NS has a period of 4.9 s and a magnetic field of

$7 \cdot 10^8$ G. Deceleration at this stage does not occur because the magnetic field is low. The full time taken for the field decay to $4 \cdot 10^8$ G is $6 \cdot 10^9$ yrs. In this case $p = 5$ s. The second track in Fig. 2b was calculated for the greater initial depth of the current layer corresponding to $\rho_0 = 6 \cdot 10^{13}$ g/cm^3. As a consequence, at the initial stage of evolution the magnetic field decays with a slower rate, the ejector stage lasts $2.1 \cdot 10^9$ yrs, and the propeller stage lasts $1.9 \cdot 10^9$ yrs. For the field $4 \cdot 10^8$ G, the period is 63 s.

5 Conclusion

The observed period and the temperature of the X-ray source RX J0720.4– 3125 can be accounted for by using the hypothesis for the ISM accretion onto an old INS. We showed that the NS magnetic field is low in this case ($B < 10^9$ G). The time taken for deceleration to $p = 8.38$ s with such a magnetic field exceeds the age of the Universe. We supposed that the NS was born with higher value of magnetic field and that the field strength has substantially decreased during the evolution. Using the model of ohmic dissipation of the magnetic field in the NS crust, we calculated the possible evolution of the NS on the $B-P$ diagram. The observed rotational period can be obtained at $Q = 0.01 - 0.05$. However, the evolution of the period depends on the field dissipation rate and, therefore, on the parameters of the decay model. Thus, the twofold change in the impurity parameter Q caused the spin period to change more than by the order of magnitude at the accretor stage (Fig. 2a, tracks 1 and 2). For this reason, observations of periods of old INSs may become an important test for the validity of the model of evolution of neutron stars.

The decay of the magnetic field may affect the estimate of the total number of the observed accreting INSs. In particular, because the formation of a periodic X-ray source at the propeller stage calls for rather strong magnetic field (Popov, 1994), its decay may reduce the number of sources of this kind. At the same time, the absence of pulsations for other INS candidates may suggest that their field has already decayed to such extent that it cannot funnel the plasma toward the INS polar caps.

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