Old isolated neutron stars in the Galaxy: evolution and field decay

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Abstract

Old isolated neutron stars form a large population of the Galactic objects, and at the present time most of them are unobserved. In this talk we briefly describe their main properties and show some examples.

As an example we discuss 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.

Key words: netron stars, evolution, magnetic field decay

1 Introduction

Among all astrophysical objects neutron stars (NS) (and black holes) attract most attention of physicists. NS were initially predict by Lev Landau immediatelly after neutron was discovered in 1932. But as far as there were no ideas how to observe so small (about 10 km in diameter) astronomical objects they were not a subject of intense search, and were found as radiopulsars occasionally in 1967 in England.

Now we know more than 1000 NS as radiopulsars and more than 100 NS emmiting X-rays, but the Galactic population of these objects is about $10^8 - 10^9$, so only a tiny fraction of one of the most facinating astrophysical objects is observed. Studying of the rest of population is crucially important to obtain initial parameters of NS, and to understand their evolution (for example, there are some argument for the proposition, that not all NS pass through the stage of radiopulsar in their young years; it can happen due to too long initial periods, too high (magnetars) or too low magnetic fields).

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 in soon after discovery of the first X-ray sources. Later it was supposed that INSs accreting matter of the interstellar medium (ISM) can be observed with the *ROSAT* satellite in the UV and X-ray ranges.

It was also proposed, that old INS can be observed in supernovae remnants, for example in RCW103 (Popov, 1998), if they were components of binary systems.

The estimates 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). Spatial distribution of accretion luminosity of INS (and black holes) was considered in (Popov, Prokhorov, 1998).

ROSAT observations showed, that only few INS are bright enough to appear on the X-ray sky. It can be a result of high initial velocities of INS, which they obtain during supernova explosion, as it appear in population synthesis (Popov et al. 1999).

In 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., 1997): 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 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 NS had to decay and calculate the magnetorotational evolution of the NS.

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 (young quickly spinning NS, spinning down due to losses of the kinetic energy onto emission of the magnitodipolar waves), propeller (NS ejecting plasma from alfven radius), accretor (NS spinning slow enough to allow plasma from ISM to accrete onto its surface), and georotator (usially fastly moving NS, which is not important for our purposes). Two critical periods P_E and P_A separate different stages of the NS evolution. These periods as well as period derivatives on ejector and propeller stages can be estimated using the formulae from (Lipunov, 1987). 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, then NS is an accretor.

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,

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

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. Here 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.

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 in many papers (see, Urpin, Muslimov, 1992; Urpin, Konenkov, 1997) at which we address the reader. The model contains two parameters, which determine the field evolution: the impurity parameter Q, and the density at the bottom of the layer initially occupied by the field, ρ_0.

Figure 1 shows the evolution of the NS surface magnetic field for various parameters ρ_0 and Q. We perfomed our calculations for the model of the NS based on the Friedman–Pandharipande (1981) 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 impurity concentration, characterized by Q.

Accretion may affect the field evolution. First, it heats the NS crust 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., 1997), we can obtain the constraints on the magnetic field, accretion rate, and luminosity.

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 $\dot{M}$:

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

2. The pulsation of X-ray emission means that the accreting matter is funneled by the magnetic field onto the polar caps. Using the known relation $R_{\mathrm{cap}} = \sqrt{(R/R_A)} \cdot R$, connecting the polar cap radius R_{cap}, the Alfven radius R_A, and the NS radius, we can estimate R_{cap} and obtain another constraint from the condition $R_{cap} < R$:

$$B > 3.4 \cdot 10^4 M_{1.4}^{1/4} R_6^{-5/4} \dot{M}_{-15}^{1/2}\,\mathrm{G}. \tag{3}$$

3. And finally, we know the polar cap temperature. Assuming that all heat released in the polar caps is radiated away we find the additional relation between B and $\dot{M}$:

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

Combining inequalities (2) and (3) and condition (4) yields the allowed range of the B and $\dot{M}$ values:

$$2 \cdot 10^5 < B[\mathrm{G}] < 10^9,$$

$$6 \cdot 10^{-17} < \dot{M}[M_\odot/\mathrm{yr}] < 4 \cdot 10^{-14}. \tag{5}$$

Now it is easy to show that spin-down time to $p = 8.38$ s greatly exceeds the Hubble time if one assumes that magnetic field of RXJ 0720.4-3125 has the same strength in the past. This means that in the past the given INS had a larger magnetic field that has decayed over the time of evolution.

Since the NS presently accretes the matter from the ISM, we can estimate its period derivative:

$$\dot{p} \approx p/t_{su} = p\,\frac{\dot{M} v_t R_G}{I\omega} < 10^{-12}\mathrm{s/s}.$$

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

The evolution of the spin period was calculated taking into account the decay of the magnetic field. 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 which corresponds to the stationary solution of the Fokker–Planck equation (Lipunov, 1987). Therefore the evolution of the spin 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 $M = 1.4M_{\odot}$ 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 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} (4). Therefore, the field should decay with a moderate rate to give the NS enough time to spin 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.

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. 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 strenght 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.

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, 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.

Due to decay, depending upon its timescale and minimum (bottom) magnetic field, relative numbers of different stages of INS (Ejectors, Propeller or Accretors) can be increased or decreased (Popov et al., 1999). Here we didn't addressed the problem of the whole population's properties, but constructed the evolutionary track of the single object.

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Figure captions.

Figure 1.

The evolution of the surface magnetic field of the isolated neutron star for the standard cooling scenario. 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 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).