The origin of long-period X-ray pulsars

N.R. Ikhsanov1,2*

1Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
2Central Astronomical Observatory of the Russian Academy of Sciences, Pulkovo 65–1, 196140 Saint-Petersburg, Russia

Accepted ; Received

ABSTRACT

Several relatively bright, persistent X-ray sources display regular pulses, with periods in the range of $0.7 \times 10^4$ s. These sources are identified with massive close binaries in which a neutron star accretes material onto its surface. The observed pulsations in all of them, but one, are unambiguously associated with the spin period of the neutron star. Analyzing possible histories of these pulsars I conclude that the neutron stars in these systems undergo spherical accretion and their evolutionary tracks in a previous epoch contained three instead of two states, namely, ejector, supersonic propeller, and subsonic propeller. An assumption about a supercritical value of the initial magnetic field of the neutron stars within this scenario is not necessary. Furthermore, I show that the scenario in which the neutron star in 2S0114+650 is assumed to be a magnetar descendant encounters major difficulties in explaining the evolution of the massive companion. An alternative interpretation of the spin evolution of the neutron star in this system is presented and the problem raised by association of the $10^3$ s pulsations with the spin period of the neutron star is briefly discussed.

Key words: accretion, accretion disks – X-rays: binaries – (stars:) neutron stars – (stars:) magnetic fields

1 INTRODUCTION

A newly formed neutron star is presumed to rotate rapidly with a period of a fraction of a second. Its rotational rate then decreases, initially by the conventional spin-powered pulsar energy-loss mechanism (ejector state), and later by means of the interaction between the magnetosphere of the neutron star and the stellar wind of its companion (propeller state). As the spin period of the neutron star reaches a critical value the accretion of material onto its surface starts (accretor state) and the star switches on as an X-ray pulsar (for a review see, e.g., Bhattacharya & van den Heuvel [1991], Iben, Tutukov & Yungelson 1995).

This scenario has been numerically studied by Urpin, Koenkjen & Geppert (1998). Their calculations have been performed under assumptions that the initial magnetic field of the neutron stars is subcritical (i.e. $B_0 < B_{el} = m^2 c^5 / (4\pi h) = 4.4 \times 10^{13}$ G) and has a crustal origin. They have also assumed that the accretion onto the stellar surface starts as soon as the centrifugal barrier at its magnetospheric boundary becomes ineffective. The period at which this condition is satisfied is defined by equating the corotational radius of the star, $r_c = (GM_P^3 / 4\pi^3)^{1/3}$, to its magnetospheric radius $r_m = \kappa (\mu^2 / 3R \sqrt{2GM})^{2/7}$, that gives

$$P_{cd}(t_d) \simeq 18 \kappa^{3/7} m^{-5/7} \left( \frac{\mu(t_d)}{10^{10} \text{ G cm}^3} \right)^{6/7} \left( \frac{\dot{M}(t_d)}{10^{35} \text{ g s}^{-1}} \right)^{-3/7} \text{s}, \quad (1)$$

(*) E-mail: ikhsanov@ast.cam.ac.uk

(for a discussion see, e.g., Pringle & Rees 1972, Illarionov & Sunyaev 1975; Stella, White & Rosner 1986). Here $\kappa$ is the parameter accounting for the geometry of the accretion flow, which ranges from 0.5 to 1 (Ghosh & Lamb 1978), and $t_d$ is the total spin-down time of the star in the ejector and propeller states. $M$, $P$, and $\mu$ are the mass, spin period, and the dipole magnetic moment of the neutron star, respectively. $\dot{M} = \pi r_d^2 \rho w V_{rel}$ is the mass with which a neutron star interacts in a unit time as it moves through the wind of a density $\rho_w$ with a velocity $V_{rel} = \sqrt{V_{lin}^2 + V_{w}^2}$, where $V_{lin}$ is the linear velocity of the neutron star's orbital motion and $V_w$ is the wind velocity of its massive companion. The parameter $r_d = 2GM_{n}V_{r}^2$ denotes the Bondi radius of the neutron star, and $m = M/1.4 M_{\odot}$. The acceleration torque applied to the star in the accretor state has been evaluated as $K_m = \zeta \dot{M}(GM_{n})^{1/2}$, where $\zeta$ is the efficiency parameter, which in the calculations has been normalized to 0.1. Finally, the evolutionary tracks of neutron stars have been computed on a time scale $t_m \sim 2 \times 10^6$ yr, which corresponds to the life-time of a 30 $M_{\odot}$ star on the main sequence (Bhattacharya & van den Heuvel 1991).

According to their results the spin period of a neutron star rapidly increases during the ejector and propeller states to a maximum value $\sim P_{cd}(t_d)$ and gradually decreases as the accretion of material onto their surface starts (see Figs. 2 and 4 in Urpin et al. 1998). The maximum period, which a neutron star with $B_0 < B_{el}$ is able to reach on a time scale $t_d < t_m$ under the above conditions is limited to a few hundred seconds. In particular, for the case $B_0 = 10^{13}$ G, the longest period is $\sim 500$ s, which the neutron star reaches at $\dot{M} \sim 10^{-15} M_{\odot}$ yr$^{-1}$. The magnetic field of the neutron
star at the end of the propeller state is a factor of 3 weaker that its initial value, $B_{\text{tot}} \sim 0.3B_0$, and decreases by almost an order of magnitude on a time scale of binary evolution, $B_{\text{tot}} \sim 1B_0$.

The long-period pulsars within this scenario are expected to be relatively weak X-ray sources. Indeed, solving Eq. (1) for $B_0$ and putting the result to $L_x = \dot{M}GM/r_{\text{ns}}$ one finds

$$L_x \leq 4 \times 10^{33} \, m^{-2/3} \left( \frac{P_s}{500 \, \text{s}} \right)^{7/3} \left( \frac{B_{\text{tot}}}{0.3B_0} \right)^2 \left( \frac{r_{\text{ns}}}{10^6 \, \text{cm}} \right)^{-1} \, \text{erg s}^{-1},$$

where $r_{\text{ns}}$ is the neutron star radius. The pulsars remain in the low-luminosity state as long as the mass transfer is operated via the wind-fed mechanism. As the massive companion overflows its Roche lobe the mass-transfer rate increases. However, this transition will unavoidable be accompanied with a formation of an accretion disc and, therefore, a rapid spin-up of the neutron star on a time scale of $\tau_d$.

There are, however, seven X-ray pulsars whose periods substantially exceed 500 s (see Table 1). These sources are associated with massive close binaries in which a magnetized neutron star accretes material onto its surface. All of them but one are persistent X-ray emitters with an average luminosity $\gtrsim 10^{34}$ erg s$^{-1}$, which implies $B_0 \gtrsim 10^{12} \, \text{M}_\odot$ yr$^{-1}$. Observations of a cyclotron line in the X-ray spectrum of X Per suggest that the surface field of the neutron star is $3.3 \times 10^{12}$ G (Coburn et al. 2001). There is some evidence (see, e.g., Li & van den Heuvel 1999) that the magnetic field of neutron stars in other sources listed in Table 1 is of the same order of magnitude.

The origin of these sources within the above scenario is rather unclear. Indeed, the value of $P_{\text{d}}(t_{\text{d}})$ for $B_{\text{tot}} \approx 0.3B_0$ and $B_0 \gtrsim 10^{12} \, \text{M}_\odot$ yr$^{-1}$ is limited to $\leq 300$ s. For a neutron star with $B_0 \ll B_\ast$, to reach a period of $\sim 10^7$ s the strength of the wind should be $\lesssim 6 \times 10^{-14} \, \text{M}_\odot$ yr$^{-1}$. In this case, however, the luminosity of the pulsar during the wind-fed accretor state is $\lesssim 7 \times 10^{35}$ erg s$^{-1}$, i.e. by a factor of 130 smaller than the average X-ray luminosity of the sources listed in Tab. 1. On the other hand, a possibility that the massive star overflows its Roche lobe at least in the case of X Per, J2239.3+6116, and 2S0114+650 can be excluded. Hence, the only way to explain the origin of the long-period pulsars within the above scenario is to invoke a rather controversial assumption that the mass-loss rate of their massive companions has recently been increased by more than two orders of magnitude. Finally, the $10^4$ s spin period of neutron star in 2S0114+650 represents an exceptional case which within the above scenario appears to be a miracle.

A possibility to improve the situation by assuming that the neutron star in 2S0114+650 was born as a magnetar (i.e. $B_0 \gg B_\ast$, see, e.g., Thompson & Duncan 1993) has been discussed by Li & van den Heuvel (1999). They have shown that the spin-down time scale of a star with $B_0 \sim 10^{15}$ G to a period $\sim 10^4$ s under the condition $\dot{M} \lesssim 10^{14}$ g s$^{-1}$ is close to $10^7$ yr, which is comparable with the characteristic time of magnetic field decay of magnetars (Colpi et al. 2000). Following this finding they have suggested a scenario in which the neutron star in 2S0114+650 is assumed to be a magnetar descendant undergoing a spherical accretion with a very low angular momentum transfer rate. They have also pointed out that this scenario, being applied to other long-period pulsars, may shed a new light to the origin of strong magnetic field of neutron stars in such systems as A0535+26, Vela X-1, GX 1+4, 4U 1907+09, 4U 1538-52, and GX 301-2.

It appears, however, that the rotational rate of a neutron star, which forms during the first supernova explosion in a massive binary system, is insufficient for its magnetic field to be amplified over the critical value $\dot{M}GM/r_{\text{ns}}$ (Thompson & Murray 2001; Hegedus et al. 2001, Petric et al. 2005). It is more likely, that magnetars form at the latest stages of binary evolution, namely, during the second supernova explosion or, the most probably, during a coalescence of two neutron stars (see, e.g., Price & Rosswoog 2006, and references therein). In this case, however, the fraction of magnetars in binary systems can unlikely exceed 1 per cent and most of them are expected to have a black hole companion (for a discussion see, e.g., Popov & Prokhorov 2006). Moreover, the kicks which magnetars are expected to get during their formation are too large for the binary system to survive (Wheeler et al. 2000, and references therein). In this light, a probability for a magnetar to be accompanied with a massive main sequence star appears to be almost negligible.

While these are not compelling arguments against the long-period pulsars to be descendants of magnetars, they suggest that alternative possibilities to solve the problem might be more fruitful. One of them is discussed in this paper. Namely, I show that the spin periods of long-period pulsars can be explained in terms of evolutionary tracks constructed by Davies et al. (1979) and Davies & Pringle (1981) and recently improved by Ikhsanov (2001a) provided the neutron stars in these systems undergo spherical accretion. These tracks contain an additional, the so called subsonic propeller, state, which has not been taken into account in the models considered by Urpin et al. (1998), Popov & Prokhorov (2006), and recently improved by Ikhsanov (2001a). The spin period of a neutron star during this state increases in a relatively short time, $\tau_d \ll t_{\text{d}}$, to a value expressed by Eq. (23), which under the conditions of interest lies in the interval $10^{-3} - 10^{-4}$ s. The assumption about the supercritical value of the initial magnetic field of neutron stars for the interpretation of long-period pulsars within this scenario is not required.

Table 1. Very long-period X-ray pulsars

| Name                  | Sp. type | $P_s$, s | $P_{\text{orb}}$, d | log $L_x$* | Ref.** |
|-----------------------|----------|----------|---------------------|------------|--------|
| J170006-4157          |          | 715      |                     | 34.7       | [1]    |
| 0352-309              | B0 Ve    | 837      | 250                 | 34.7 - 35.5| [2, 3] |
| (X Per) (O9.5 Ile)    |          |          |                     |            |        |
| J1035.7-5647†         | B0 V-IIIe| 862      |                     | 34 - 35    | [4, 5] |
| J2239.3+6116          | B0 Ve    | 2447     | 262.2               | 33 - 36    | [6, 7, 8]|
| (B2 IIIe)             |          |          |                     |            |        |
| J1013.6-7201          | O5 Ve    | 1323     |                     | 35 - 36.8  | [9]    |
| J1046.9+6121          | B1 III- Ve| 1412     |                     | 36 - 36    | [10]   |
| (V831 Cas)            |          |          |                     |            |        |
| 2S0114+650            | B1 Ia    | 10008†   | 11.6                | 35.7 - 36  | [11, 12]|

* $L_x$ is expressed in erg s$^{-1}$.
** References to the table: [1] Torii et al. (1999); [2] Delgado-Marti et al. (2001); [3] Haberl et al. (1998); [4] Reig & Roche (1999); [5] Motch et al. (1999); [6] in ‘t Zand et al. (2000); [7] in ‘t Zand et al. (2001); [8] Zdziarski (2002); [9] Haberl & Pietsch (2005); [10] Haberl & Sasaki (2000); [11] Reig et al. (1999); [12] Hall et al. (2000).
2 ACCRETION FLOW GEOMETRY

The state of neutron stars in the long-period pulsars is unambiguously identified with an accretor. The equation governing the spin evolution of stars in this state reads (Davidson & Ostriker 1973, Ghosh & Lamb 1978)

$$2\pi I_0 \frac{d}{dt} P' = K_{su} + K_{sd},$$

where $K_{su}$ and $K_{sd}$ are the acceleration and deceleration torques applied to the neutron star, respectively. The deceleration torque is associated with interaction between the stellar magnetic field and material situated at a distance $r \geq r_c$. The average value of this torque does not significantly depend on the geometry of the accretion flow beyond the magnetosphere and in the general case can be expressed as (Lynden-Bell & Pringle 1974; Wang 1981; Lipunov 1992)

$$K_{sd} = -k_\xi \frac{\mu^2}{r_c^3},$$

(5)

where ($k_\xi \leq 1$) is the dimensionless parameter of the order of unity. In contrast, the acceleration torque is very sensitive to the flow geometry and varies from its maximum value, $K_{su} \approx \xi \sqrt{G M r_{su}}$, in the case of a disc, to a significantly smaller value,

$$K_{su}^{\text{sph}} \approx \frac{1}{4} \xi \sqrt{3 G M r_{su}^2},$$

(6)

in the case of a spherical accretion (Davidson & Ostriker 1973; Wang 1981). Here $r_{su}$ is the orbital radius and $P_{sph}$ is the system orbital period. The parameter $\xi$ is the factor by which the angular momentum accretion rate is reduced due to inhomogeneities (the velocity and density gradients) in the accretion flow. Numerical simulations (see, e.g., Anzer et al. 1987; Taam & Fryxell 1988; Ruffert 1999) suggest that the average value of this parameter is $< \xi > \approx 0.2$.

As follows from Eq. (3), the spin period of an accreting neutron star evolves to the so-called equilibrium period, which is defined by setting $K_{su} = K_{sd}$. The value of the equilibrium period in the case of a disc and spherical accretion, respectively, are

$$P_{eq}^{\text{d}} \approx 18 \times 10^{-12} k_1^{1/2} m^{-3/7} g_{1/5}^{1/7} \left( \frac{B}{3.3 \times 10^{12} G} \right)^{5/7},$$

(7)

and

$$P_{eq}^{\text{sph}} \approx 910 \times 10^{-12} k_1^{1/2} \xi_{0.2}^{-1/2} m^{-3/2} g_{1/5}^{1/2} \left( \frac{B}{3.3 \times 10^{12} G} \right) \times$$

$$\times \left( \frac{V_{rel}}{400 \text{ km s}^{-1}} \right)^2 \left( \frac{P_{sph}}{250 \text{ d}} \right)^{1/2},$$

(8)

where $P_{250} = P_{sph}/250$ days, and $\xi_{0.2} = \xi/0.2$. The normalization of parameters in these equations is appropriate for X Per, which is the best studied persistent long-period pulsar.

As easy to see, the value of $P_{eq}^{\text{d}}$ under the conditions of interest is much smaller than the spin period of neutron stars in the pulsars listed in Tab. II. Hence, if a persistent accretion disc in these systems existed the acceleration torque applied to the neutron star would significantly exceed the deceleration torque. The neutron star in this case would regularly spinning-up at a rate $\dot{P} \approx P_{250}^{3/2} \sqrt{G M r_{su}}/2\pi I_0 \sim 5 \times 10^{-8} \text{ s}^{-1}$, which implies the lifetime of the long-period pulsars to be $< 1000 \text{ yr}$ (see Eq. 5). In particular, if the neutron star in 2S 0114+650 accreted material from a disc its spin period would substantially increase on a time scale of only 100 yr, which is 4–5 orders of magnitude smaller than the average lifetime of accretors in massive stars (Urpin et al. 1998). Thus, a probability to observe neutron stars accreting from a disc at a rate $\sim 10^{15} \text{ g s}^{-1}$ during their long-period stage is almost negligible.

Furthermore, observations of X-ray source in X Per show no evidence for a regular spin-up of this pulsar. Instead, it exhibits apparent erratic pulse frequency variations on a time scale of a few days, which are superposed with a 10–20 yr spin-up/spin-down trends around the average period of 837 s (Haber et al. 1994; Delgado-Martí et al. 2004, and references therein). The transitions between the spin-up and spin-down stages occur without any significant variations of the system X-ray luminosity, and therefore, cannot be associated with the transitions of the neutron star between the accretor and propeller states. The spin-down events in this case could occur only if the value of acceleration torque applied to this star is much smaller than $K_{su}$, which argues against the presence of a persistent accretion disc in this system.

In contrast, the assumption about spherical geometry of the accretion flow allows us to interpret the spin period of the neutron star in X Per in terms of the equilibrium period, $P_{eq}^{\text{sph}}$, provided the average (on a time scale of $> 20$ yr) value of the wind velocity is $350 - 400 \text{ km s}^{-1}$. The spin-up/spin-down behaviour of the source within this scenario can be associated with apparent variations of the stellar wind velocity (e.g., due to activity of the massive component and the orbital motion of the neutron star whose trajectory is inclined to the plane of decretion disc of the Be-companion) and, possibly, the flip-flop instability of the accretion flow (see, e.g., Taam & Fryxell 1988). The spherical accretion model is also effective for the interpretation of other long-period pulsars provided their orbital periods are of the same order of magnitude as that of X Per, and the average wind velocity is $\sim 400 - 800 \text{ km s}^{-1}$.

The only exception is 2S 0114+650. The condition $P_{sph} = P_{eq}^{\text{sph}}$ in the case of this source implies $V_{rel} \gtrsim 3000 \text{ km s}^{-1}$, which by a factor of 2–3 exceeds the upper limits to the stellar wind velocity of B-type stars inferred from the UV observations (800 – 1500 km s$^{-1}$), see, e.g., Bernacca & Bianchi 1981; Snow 1981; Marlborough 1982). On the other hand, assuming that the wind velocity of the massive companion is limited to $\lesssim 1500 \text{ km s}^{-1}$ one finds $P_{eq}^{\text{sph}} \lesssim 26$ minutes. This indicates that either the neutron star is a very young accretor and its period significantly exceeds the equilibrium one, or the value of the parameter $\xi$ in the particular case of this system is significantly smaller than its average value inferred from the numerical simulations (see above). However, it cannot be excluded that this apparent discrepancy occur because of a mistaken association of the $10^4 \text{s}$ pulsations with the spin period of the neutron star. As recently shown by Koenigsberger et al. (2006), these pulsations may reflect a modulation of the B-supergiant wind caused by tidal interaction between the non-synchronously rotating binary components. As the material of the wind is captured by the neutron star and is accreted onto its surface the X-ray luminosity of the source would be modulated with the same period, which under the conditions of interest lies within the interval of 2–3 hours. This scenario weakens the association of $10^3 \text{s}$ pulsations with the spin period of the neutron star and, therefore, leaves the question about the rotational rate of the star open (for a discussion see, Koenigsberger et al. 2006). As mentioned above, the condition $P_{sph} = P_{eq}^{\text{sph}}$ for reasonable values of $V_{rel}$ predicts $P_{sph} \sim 10 - 26$ minutes. In this light, it is interesting to note that a detection of $\sim 15$ minutes pulsations has been reported by Koenigsberger et al. (1983) and Yamauchi et al. (1990). These pulsations, however, have not been found in later X-ray observations of this system.

Summarizing this section I can conclude that a presence of accretion disc in the long-period pulsars is very unlikely. The neutron stars in these systems are, therefore, undergoing spherical accretion.
3 SUBSONIC PROPELLER

Let us now address the main question, namely, what is the maximum period to which a neutron star undergoing spherical accretion can be spun-down on a time scale \( t < t_{\text{sd}} \) ? A comprehensive analysis of this question has been first presented by Davies et al. (1979) and Davies & Pringle (1981). As they have shown the spherically accreting neutron star in the state of propeller is surrounded by a hot quasi-stationary turbulent atmosphere. The atmosphere forms as soon as the pressure of relativistic wind ejected by the neutron star in the spin-powered pulsar state can no longer balance the pressure of the surrounding material, and the latter, penetrating to within the accretion radius of the star, interacts with the stellar magnetic field. This interaction leads to formation of the magnetosphere with the equatorial radius \( r_m \), which is defined by equating the ram pressure of the flow with the magnetic pressure due to dipole field of the neutron star. The kinetic energy of the flow at the magnetospheric boundary is converted into its thermal energy in the adiabatic shock. The temperature of material in the shock increases to the adiabatic (or so-called free-fall) temperature, \( T_{\text{ff}} = GMm_p/k_r \), where \( m_p \) and \( k_B \) are the proton mass and Boltzmann constant, respectively. The heated gas expands with the velocity \( V_{\text{ff}} = (2GM/r)^{1/2} \), which significantly exceeds the sound speed in the material captured by the star. The gas expansion is, therefore, leading to a formation of the back-flowing shock, which propagates through the flow and heats it up to the adiabatic temperature. Under the condition \( \dot{M} \lesssim \dot{M}_{\text{sd}} \simeq 2 \times 10^{-6} \, m \, (V_{\text{ff}}/10^2 \text{ cm s}^{-1}) \) (Ikhsanov 2002) the atmosphere is extended up to the Bondi radius of the star, \( r_c \), at which the thermal pressure of the heated material is equal to the ram pressure of the surrounding gas, \( \sim \rho_{\text{in}} V_{\text{ff}}^2 \). The formation of the atmosphere prevents the stellar wind from penetrating to within the Bondi radius of the neutron star. As the neutron star moves through the wind of its companion the surrounding gas overflow the outer edge of the atmosphere with the rate \( \dot{M} \) and the mass of the atmosphere is conserved.

As long as the magnetospheric radius of the star exceeds its corotational radius (which is equivalent to the condition \( P_r \lesssim P_{\text{eff}(t_{\text{sd}})} \)) see Introduction) the linear velocity of the magnetosphere (which is assumed to co-rotate with the star) at the radius \( r_m \) exceeds the sound speed in the surrounding material (the corresponding state is usually referred to as supersonic propeller, Davies & Pringle 1981). The heating rate of the atmosphere due to the propeller action by the star in this case significantly exceeds the rate of plasma cooling due to the bremsstrahlung emission and turbulent motions (for a discussion see also Lamb et al. 1973, and references therein). The atmosphere during this state remains hot, \( T(r) \simeq T_{\text{sd}}(r) \). The rotational energy loss by the neutron star is converted up through the atmosphere by the turbulent motions and lost through its outer boundary. The spin-down rate of the star in this state (see Table in Davies et al. 1979) is the same as that evaluated by Illarionov & Sunyaev (1978) and used by Urpin et al. (1998) in their calculations. This indicates that the evolution of the spin and the magnetic field of a spherically accreting neutron star up to a moment when its period reaches \( P_{\text{eff}(t_{\text{sd}})} \) can be treated within the results presented by Urpin et al. (1998). In particular, this suggests that the surface field of the star to the end of the supersonic propeller state is only by a factor of 3 weaker than the initial field.

As the spin period exceeds \( P_{\text{eff}(t_{\text{sd}})} \), the linear velocity of the magnetosphere at the radius \( r_m \) becomes smaller than the sound speed corresponding to the temperature \( T_{\text{sd}}(r_m) \). However, the effective acceleration applied to the hot gas moving along the curved field lines, \( g_{\text{eff}} = \frac{GM}{r_m^2} \cos \theta - \frac{V_\theta^2(r_m)}{r_{\text{curv}}(\theta)} \) (9)

is directed outwards from the star as long as the temperature of the material situated over the boundary is \( \lesssim T_{\text{sd}}(r_m) \) (Illarionov & Lamb 1976, Arons & Leah 1976).

\[ T_{\text{sd}}(r_m) > T_{\text{sd}}(r_\text{cr}) \simeq 0.1T_{\text{sd}}(r_m). \] (10)

Here \( r_{\text{curv}} \) is the curvature radius of the field lines, \( \theta \) is the angle between the radius vector and the outward normal to the magnetospheric boundary and \( V_\theta(r_m) \) is the ion thermal velocity in the material located at the inner edge of the atmosphere. Furthermore, the magnetospheric boundary under the condition (10) is stable with respect to interchange instabilities and the plasma penetration rate into the magnetosphere is limited to the rate of Bohm diffusion (Elsner & Lamb 1984), which under the conditions of interest is \( \dot{M} \sim \dot{M}_{\text{sd}} \) (Ikhsanov & Pustilnik 1996). Here \( \dot{M}_{\text{sd}} \) is the so-called break period, which is (Ikhsanov 2001a)

\[ \dot{M}_{\text{sd}}(t_{\text{sd}}) \simeq 2000 \, m^{-4/21} \left( \frac{B(t_{\text{sd}})}{0.3B_{\text{sd}}} \right)^{16/21} \left( \frac{\dot{M}_{\text{sd}}}{10^{15} \, \text{ g s}^{-1}} \right)^{5/7} \, \text{ g s}^{-1}. \] (12)

Under the conditions of interest, the break period significantly exceeds \( P_{\text{eff}(t_{\text{sd}})} \). This means that a spherically accreting neutron star is able to switch its state from the supersonic propeller to accretor only via an additional intermediate state, which is called the subsonic propeller. The star during this state remains surrounded by the hot adiabatic atmosphere and its spin period increases from \( P_{\text{eff}} \) to \( P_{\text{sd}} \) on a time scale of \( (10^1 \, \text{ g s}^{-1}) \) (Davies & Pringle 1981)

\[ t_{\text{sd}} \approx 4 \times 10^7 \, I_{45} m^2/7 \left( \frac{B(t_{\text{sd}})}{0.3B_{\text{sd}}} \right)^{-8/7} \left( \frac{\dot{M}_{\text{sd}}}{10^{15} \, \text{ g s}^{-1}} \right)^{-3/7} \, \text{ yr}. \] (13)

The accretion luminosity of the star during this state is limited to \( \dot{E}_{\text{sd}} = \dot{M}GM(r_{\text{sd}}) \), which under the conditions of interest is \( \lesssim 10^{34} \, \text{ erg s}^{-1} \). Finally, the surface magnetic field of the star in the subsonic propeller state would not evolve significantly since \( t_{\text{sd}} \ll t_{\text{sd}} \).

4 LONG-PERIOD PULSARS

The results of incorporation of the subsonic propeller state into the evolutionary tracks presented by Urpin et al. (1998) are shown in Tab 2 (the corresponding evolutionary scenario will be further referred to as DFP-scenario). The second column of the Table shows the ratio of the average (on a time scale of \( t \gtrsim t_{\text{sd}} \)) stochastic strength of the stellar wind during the spin-down epoch, \( \langle \dot{M} \rangle \), to the average mass capture rate by the neutron star inferred from the X-ray luminosity, \( \dot{E}_{\text{sd}} \). The third column represents
the ratio of the initial surface field of the neutron star to the critical field.

The long-period pulsars in Table 2 are divided into three groups. The first group contains 4 sources whose origin within DFP-scenario can be explained provided the average strength of the wind during the system evolution has not been changed significantly and that the initial magnetic field of the neutron stars was subcritical. The value of the ratio \( B_\text{ns}/B_{\text{cr}} \) for these sources has been evaluated from Eq. (24) by setting \( \beta < \beta_0 > / \beta_0 = 1 \) and taking into account that \( B(t_{\text{sd}}) = 0.3 B_0 \).

An application of DFP-scenario to J0103.6-7201 and J0146.9+6121 (the second group) leads us to a conclusion that either the wind during a previous epoch was by a factor of 2–5 weaker than that inferred from the X-ray luminosity of these sources or the value of \( B(t_{\text{sd}}) \) was a factor of 2 larger than the average one estimated by Urpin et al. (1998), or both. According to the results reported by Vink et al. (2000) and Fullerton et al. (2006) it is not unusual for massive stars to lose material with a higher rate at later stages of their evolution. It also cannot be excluded that the X-ray luminosity of these sources is slightly overestimated or has been measured during a high state of activity of the massive companions, which usually lasts 3–20 years. In this light, the assumption about a weaker wind in a previous epoch of J0103.6-7201 and J0146.9+6121 seems to be rather reasonable. On the other hand, the duration of the spin-down epoch of neutron stars with the initial field \( \sim B_\text{ns} \) and the wind of \( \sim 10^{16} \text{g s}^{-1} \) is by a factor of 2–3 shorter than the average one evaluated by Urpin et al. (1998). This indicates that the assumption about a higher value of \( B(t_{\text{sd}}) \) has certain theoretical grounds as well. However, both of these arguments are not compelling to exclude a possibility that the neutron stars in J0103.6-7201 and J0146.9+6121 were born as magnetars.

The third ‘group’ is represented by only one (but the most puzzling) source 2S 0114+650. The origin of this source within DFP-scenario can be explained provided the strength of the wind in a previous epoch was by a factor of \( \sim 30 \) smaller than the mass capture rate by the neutron star inferred from the observed X-ray luminosity. Indeed, for the condition \( \beta_\text{ns} = 10^3 \text{s} \) in the case of \( B_0 < B_{\text{cr}} \) to be satisfied the strength of the wind should be \( \beta < \beta_0 > < 10^2 \text{g s}^{-1} \). The neutron star under these conditions is able to reach a period of \( 10^4 \text{s} \) within a time \( t_{\text{sd}} < t_{\text{ms}} \) (see Fig. 2 in Urpin et al. 1998, and Eq. (13)).

On the other hand, an attempt to interpret this source within the scenario of Li & van den Heuvel (1999) leads us to a significantly stronger limitation to the value of \( \beta \). Indeed, the neutron star within their scenario is presumed to switch to the accretor state as soon as its spin period reaches \( P_{\text{cd}}(t_{\text{sd}}) \). Setting \( B_0 \sim 10^3 \text{G} \) they have evaluated the spin-down time scale as \( t_{\text{sd}} < 10^4 \text{yr} \) and, correspondingly, \( B(t_{\text{sd}}) \sim (1 - 4) \times 10^{14} \text{G} \), which implies \( \beta(t_{\text{sd}}) \sim 10^{12} \mu_5^2 \text{G cm}^{-3} \). Putting this value to Eq. (1) and solving the equation for \( \beta(t_{\text{sd}}) \) one finds \( \beta(t_{\text{sd}}) \sim 2 \times 10^{13} \mu_5^2 \text{g s}^{-1} \times k^{-1/2} \mu_5^{-1/3} (P_{\text{cd}}(t_{\text{sd}})/10^3)^{-7/3} \). This means that the interpretation of the long spin period of the neutron star in 2S 0114+650 within the magnetar hypothesis requires the strength of the wind in a previous epoch to be by a factor of 250 smaller than that inferred from the X-ray luminosity of the source.

One of the ways to improve the situation is to assume that the evolutionary tracks of magnetars contain the subsonic propeller state. In this case the neutron star can comfortably reach a period of \( 10^4 \text{s} \) even if the strength of the wind is \( \sim 10^{15} \text{g s}^{-1} \) (see Sect. 5). However, a necessity to invoke this assumption is not obvious. According to the evolutionary tracks reported by Meynet et al. (1994), a possible progenitor of the B1-supergiant was a O9.5 V star. The typical mass-loss rate of this type stars (see, e.g., Crowther, Lennon & Walborn 2006; Fullerton et al. 2006 and references therein) is by a factor of 10–50 smaller than the mass-loss rate of the massive companion in 2S 0114+650 inferred from the optical observations (Aab & Bychkov 1984; Reig et al. 1996). This indicates that the value of the ratio \( \beta < \beta_0 > / \beta_0 \) given in Tab. 2 has good observational grounds and, therefore, allows us to interpret this object in terms of DFP-scenario assuming the initial magnetic field of the neutron star to be subcritical. Finally, I would like to remind that the association of the \( 10^3 \text{s} \) pulsations with the spin period of the neutron star cannot be considered as finally justified (see Sect. 2). If the spin period of the neutron star is indeed smaller than that currently adopted the origin of this source can be interpreted within DFP-scenario in terms of the subcritical initial field almost without any additional assumptions.

### 5 DISCUSSION

The main result of this paper is that the problem posed by the existence of relatively bright persistent long-period X-ray pulsars can be solved by an incorporation of the subsonic propeller state into the evolutionary tracks of neutron stars in massive close binaries computed by Urpin et al. (1998). This solution implies that the neutron stars in these systems undergo spherical accretion and their initial magnetic field is subcritical. The spin periods of the neutron stars in this case are close to the equilibrium period expressed by Eq. (8) provided the relative velocity between the star and surrounding gas is \( V_{\text{rel}} \sim 400 \sim 800 \text{km s}^{-1} \). The only exception is the neutron star in 2S 0114+650 whose equilibrium period for a reasonable estimate of \( V_{\text{rel}} \) is by an order of magnitude smaller than \( 10^4 \text{s} \). It should be, however, noted that the association of the \( 10^3 \text{s} \) pulsations with the spin period of the neutron star in this system remains so far controversial.

The evolutionary scenario presented seriously weakens the hypothesis that the neutron stars in the long period pulsars are magnetar descendants. In particular, it is shown that the interpretation of the long-period pulsar 2S 0114+650 within this hypothesis is not possible unless an assumption about a significantly (by a factor of 250) weaker wind in a previous epoch is invoked. Furthermore, this hypothesis implies that magnetars form during the first supernova explosion in a massive binary system, which is not consistent with the current views on the process of magnetar formation. At the same time the above arguments are not compelling to exclude the magnetar hypothesis completely and therefore, a brief discussion about possible appearances of magnetars in close binaries appears to be rather reasonable.

### Table 2. Parameters of long-period pulsars inferred from DFP-scenario

| Name               | \( \beta < \beta_0 > / \beta_0 \) | \( B_0/B_{\text{cr}} \) |
|--------------------|----------------------------------|-------------------------|
| J170006-4157       | 1                                | 0.08                    |
| 0352+309/X Per      | 1                                | 0.3                     |
| J1037.5-5647        | 1                                | 0.3                     |
| J2239.3+6116        | 1                                | 0.1                     |
| J013.6-7201         | 0.2 – 1                          | 1                       |
| J0146.9+6121/V831 Cas | 0.6                             | 1                       |
| 2S 0114+650         | 0.03                             | 1                       |

* See, however, discussion in the text.
The main evolutionary stages of a magnetar with an initial magnetic field of \( B_0 \sim 2 \times 10^{15} \) G (\( \mu_0 = 10^{33} \) G cm\(^3\) in a binary system are as follows (for a discussion see, e.g., Ikhsanov 2001b and references therein). The ejector stage, which lasts

\[
\tau_a \sim 10^5 \mu_3^{-1} I_{15}^{1/2} V_8^{-1/2} \text{ yr},
\]

(14)

and ends as the spin period of the neutron star is

\[
P_s = P_{\text{init}} \sim 53 \mu_3^{1/2} \mu_{15}^{1/4} V_8^{-1/4} \text{ s},
\]

(15)

where \( V_8 = V_{\text{rel}}/10^8 \) cm s\(^{-1}\).

The parameters of the propeller stage depend on the geometry of the accretion flow beyond the neutron star’s magnetospheric boundary. If the magnetospheric radius of the star is smaller than the so-called circularization radius, which is defined as

\[
r_{\text{circ}} = \frac{J}{\mu^2 G M},
\]

(16)

where

\[
J = H_0 = \frac{1}{4} \mu^2 \Omega_{\text{orb}} r_{\text{eff}}^2
\]

(17)

is the rate of accretion of angular momentum, the formation of a disc would be expected. Combining Eqs. (16) and (17) and solving the result for \( V_{\text{rel}} \) one finds the condition for a disc formation as

\[
V_{\text{rel}} \lesssim V_{\text{ci}} \approx 75 \left( \frac{\mu_3}{10^9} \right)^{1/4} \left( \frac{\mu_{15}}{10^{-3}} \right)^{1/4} \mu_{15}^{1/8} \frac{V_8}{75 \text{ km s}^{-1}} \text{ km s}^{-1}.
\]

(18)

It is taken into account here that the magnetic field of a magnetar on a time scale of \( \sim 10^5 \) yr decreases by almost an order of magnitude (see, e.g., Colpi et al. 2000). If this condition is satisfied the spin period of the neutron star during the propeller stage decreases to a value of

\[
P_s \sim P_{\text{d,cd}}^{(0)} \approx 400 \left( \frac{\mu_3}{10^9} \right)^{3/10} \mu_{15}^{7/10} \frac{V_8}{15} \text{ s},
\]

(19)

on a time scale of

\[
\tau_{\text{d,cd}}^{(0)} \approx 2 \times 10^4 \left( \frac{\mu_3}{10^9} \right)^{7/10} \mu_{15}^{-11/14} \frac{V_8}{15} \left( \frac{V_{\text{rel}}}{75 \text{ km s}^{-1}} \right)^{1/2} \text{ yr},
\]

(20)

and the magnetar switches its state to an accretor. Here \( \kappa_{0.5} = \kappa/0.5 \).

If the plasma flow beyond the magnetospheric boundary has a spherical geometry the duration of the supersonic propeller state would be

\[
\tau_{\text{d,cd}}^{(0)} \approx 6 \times 10^4 I_{15}^{-1} \mu_{15}^{1/2} \frac{V_8}{15} \text{ yr}.
\]

(21)

The spin period of the star during this time increases to a value of

\[
P_s \lesssim P_{\text{d,cd}}^{(0)} \approx 10^4 \left( \frac{\mu_3}{10^9} \right)^{7/10} \mu_{15}^{-11/14} \frac{V_8}{15} \text{ s}.
\]

(22)

As the star switches to the subsonic propeller stage its spin period increases on a time scale of

\[
\tau_{\text{d}} \sim 200 \mu_{15}^{7/10} I_{15}^{-1} \mu_{15}^{1/2} \frac{V_8}{15} \text{ yr},
\]

(23)

to a value of

\[
P_{\text{bh}} \approx 1.1 \times 10^4 \left( \frac{\mu_3}{10^9} \right)^{6/10} \mu_{15}^{5/10} \frac{V_8}{15} \text{ m}^{-1/2} \text{ s}.
\]

(24)

The above estimates suggest that the spin period of magnetars accreting material from a disc unlikely exceeds \( 500 L_{15}^{3/7} \) s, where \( L_{15} \) is the X-ray luminosity of the source expressed in units of \( 10^{38} \) erg s\(^{-1}\). If the time scale of the magnetic field decay of magnetars exceeds \( 3 \times 10^3 \) yr a probability of observational identification of these stars in the magnetar stage is not zero. On the other hand, it appears to be rather small as the magnetic field of an accreting star decays more rapidly than that of an isolated one (for a discussion, see, e.g., Urpin et al. 1998 and references therein). The spin period of magnetars in the accretor state evolves to the equilibrium period expressed by Eq. (17) and the time scale of its evolution is determined by the decay rate of the stellar magnetic field.

The magnetars undergoing spherical accretion can be spun-down to a period of \( \sim 2 \times 10^7 L_{15}^{-5/7} \) s. However, the spin-down time scale in this case proves to be comparable with the upper limits to the characteristic time of the magnetic field decay. Therefore, a possibility to observe an accretion-powered magnetar undergoing spherical accretion is almost negligible.

Finally, the appearance of close binaries containing magnetar descendants of an age \( \sim t_{\text{d,cd}} \) would be similar to that of close binaries in which the initial field of the neutron star was under the critical value. In contrast, the evolutionary tracks and appearance of neutron stars undergoing disc and spherical accretion differ significantly.

ACKNOWLEDGEMENTS

I would like to thank Malvin Ruderman and James E. Pringle for useful discussion and an anonymous referee for very stimulative comments. I acknowledge the support of the European Commission under the Marie Curie Incoming Fellowship Program. The work was partly supported by Russian Foundation of Basic Research.

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