How young the accretion-powered pulsars could be?

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Abstract. A question about the age of accretion-powered X-ray pulsars has recently been reopened by a discovery of the X-ray pulsar SXP1062 in the SMC. This High Mass X-ray Binary (HMXB) contains a neutron star rotating with the period of 1062s and is associated with a supernova remnant of the age $\sim 10^4$ yr. An attempt to explain the origin of this young long-period X-ray pulsar within the traditional scenario of three basic states (ejector, propeller and accretor) encounters difficulties. Even if this pulsar were born as a magnetar the spin-down time during the propeller stage would exceed $10^4$ yr. Here we explore a more circuitous way of the pulsar spin evolution in HMXBs, in which the propeller stage in the evolutionary track is avoided. We find this way to be possible if the stellar wind of the massive companion to the neutron star is magnetized. The geometry of plasma flow captured by the neutron star in this case differs from spherically symmetrical and the magnetospheric radius of the neutron star is smaller than that evaluated in the convention accretion scenarios. We show that the age of an accretion-powered pulsar in this case can be as small as $\sim 10^4$ years without the need of invoking initial magnetic field in excess of $10^{13}$ G.

1. Introduction

The age of neutron stars (NSs) identified with accretion-powered pulsars in High Mass X-ray Binaries (HMXBs) is expected to exceed $10^5$ yr [13]. A newly formed NS needs this time to spin-down from its initially short period up to a critical period, $P_{cr}$, at which the accretion of material onto its surface starts. Observations, however, suggest that the accretion-powered NS in HMXBs can be significantly younger. In particular, the 1062s X-ray pulsar SXP 1062 has recently been identified with a Supernova Remnant of the age $\sim 10^4$ yr [2, 3, 12]. This discrepancy cannot be resolved within the framework of traditional scenario without invoking additional assumptions about properties of the NS itself [1, 11], or its environment [7]. In this paper, we show that under certain conditions evolution of a NS can follow a simplified scenario, skipping the propeller stage. The time required for a NS to come into accretor stage this way is significantly smaller than that expected in traditional scenarios.

2. Spin-down phase

A newly formed NS is presumed to rotate rapidly and be strongly magnetized. Initially it appears to be a powerful ejector of relativistic wind which prevents the surrounding material from penetrating to within the Bondi radius of the NS and, correspondingly, from reaching the stellar surface. The NS, therefore, starts its evolution with a non-accreting spin-down phase at which its spin period monotonically increases. As the spin period of the NS reaches
a critical value, $P_{\text{cr}}$, the accretion of material onto its surface starts and the star switches on as an accretion-powered pulsar. The critical period, $P_{\text{cr}}$, is usually defined by equating the magnetospheric radius, $r_m$, with the corotation radius, $r_{\text{cor}} = (G M_{\text{NS}}/\omega_s^2)^{1/3}$, where $M_{\text{NS}}$ is the mass and $\omega_s$ is the angular velocity of the NS. The initial spin-down phase in the general case can be divided into ejector and propeller states (see e.g. [6] and references therein).

### 2.1. Ejector state

The rotational rate of NS in the ejector state decreases by the conventional spin-powered pulsar energy-loss mechanism expressed by equation for the magneto-dipole radiation. The spin-down power in this case can be limited to its magnetosphere and surrounding matter. The mechanism of this interaction is rather complicated. However, the spin-down power of NS in this state can be evaluated as (see e.g. [7] and references therein)

$$\tau_{\text{ej}} \simeq 8 \times 10^5 \text{ yr} \times f_m^{-1/2} I_{45}^{-1/2} M_{16}^{-1/2} v_7^{-1/2} \mu_{30}^{-1}, \quad (1)$$

where $f_m$ is a dimensionless parameter of order unity which is according for plasma contribution into the processes of energy release in the magnetosphere of NS, $I_{45}$ is the moment of inertia of the NS in units $10^{45}$ g cm$^2$, $M_{16}$ is the mass transfer rate between the system components in units $10^{16}$ g s$^{-1}$, $v_7$ is the velocity of NS in the frame of surrounding material in units $10^7$ cm s$^{-1}$ and $\mu_{30}$ is the dipole magnetic moment of NS in units $10^{30}$ G cm$^3$. This indicates that the spin-down time of a strongly magnetized ($\mu \gg 10^{30}$ G cm$^3$) NS, which moves through a relatively fast stellar wind of its massive companion can be significantly shorter than a million years.

### 2.2. Propeller state

The ejector spin-down ceases as the pressure of relativistic wind at the Bondi radius decreases up to the ram pressure of surrounding material. The surrounding gas under these conditions penetrates to within the Bondi radius and moves towards the NS forming the accretion flow. The interaction between the flow and the magnetic field of the NS leads to formation of the magnetosphere. The radius of the magnetosphere, $r_m$, depends on the parameters of the NS, the mass accretion rate and on the geometry and parameters of the accretion flow itself. If $r_m < r_{\text{cor}}$ the star switches on as an accretion-powered pulsar. Otherwise, it remains to spin-down in the propeller state up to a moment when the corotation radius reaches the radius of the magnetosphere.

The NS in the propeller state is spinning-down due to the interaction between its magnetosphere and surrounding matter. The mechanism of this interaction is rather complicated. However, the spin-down power of NS in this state can be limited to $L_{\text{ns}} \leq L_{\text{pr}}^{\text{max}}$, where

$$L_{\text{pr}}^{\text{max}} = \frac{GM_{\text{ns}}}{r_m} = \dot{M} \omega_s^2 r_m \left( \frac{\omega_k(r_m)}{\omega_s} \right)^2 = \omega_s K_{\text{sd}} \left( \frac{\omega_k(r_m)}{\omega_s} \right)^2, \quad (2)$$

$\omega_k(r_m) = (G M_{\text{ns}}/r_m^3)^{1/2}$ is the Keplerian angular velocity at the magnetospheric radius of NS and $K_{\text{sd}} = I \omega_s$ is the spin-down torque exerted to NS from matter surrounding its magnetospheric boundary (note, that the spin-down power of a star with the moment of inertia $I$ which rotates with the angular velocity $\omega_s$ and brakes at the rate $\dot{\omega}_s$ is $L_{\text{sd}} = I \omega_s \dot{\omega}_s$).

The spin-down timescale of the NS in the propeller state can be evaluated as $\tau_{\text{pr}} \geq E_{\text{rot}}(\omega_s)/L_{\text{pr}}^{\text{max}}$, where $E_{\text{rot}} = I \omega_s^2/2$ is the rotational energy of the NS and $\omega_{\text{ej}}$ is the angular velocity of the NS at the moment when it switches into the propeller state. Hence,

$$\tau_{\text{pr}} \geq 10^6 \text{ yr} \times I_{45} M_{16}^{-11/14} \mu_{30}^{-3/7} v_7^{1/2} m^{-8/7}, \quad (3)$$
where \( m \) is the mass of the NS in units \( 1.4 M_\odot \). Thus, the spin-down time of the NS under the conditions of interest significantly exceeds recently evaluated age of SXP 1062.

### 3. The direct ejector to accretor state transition

For a NS to switch its state directly from ejector to accretor the spin period at which the matter starts to penetrate to within the Bondi radius should be equal the critical period \( P_{cr} \). In the conventional quasi-spherical or Keplerian disk accretion scenarios in which the magnetospheric radius of the NS is close to the Alfvén radius \( r_A \), the situation can unlikely be realized (see fig. 1). It could occur only if the mass accretion rate onto the NS were in excess of \( 10^{24} \text{ g s}^{-1} \) (see eq. (10) in [6]), which significantly exceeds the typical mass-loss rate of O/B-type stars.

The direct transition of a NS from the ejector to accretor state could be also expected if accretion onto a NS were realized according to a scenario in which the magnetospheric radius of the NS is smaller than the Alfvén radius. Such a scenario has recently been proposed for wind-fed HMXBs in which the stellar wind of massive component is magnetized. As recently shown in [9], the structure of the accretion flow onto a NS would significantly deviate from the traditional quasi-spherical and Keplerian disk if the magnetic field in the stellar wind of optical companion at the Bondi radius is \( B \geq B_{min} \), where

\[
B_{min} \approx 10^{-3} G \times \xi^{5/8} \frac{1}{m^{1/4}} \frac{P_{100}^{-5/8}}{M_{16}^{3/8}} \left( \frac{v_7}{\mu} \right)^{3/2} . \tag{4}
\]

Here \( \xi_{0.2} = \xi/0.2 \) is a dimensionless parameter accounting for density and velocity gradient in the material which the NS captures at its Bondi radius and \( P_{100} \) is the orbital period of the binary system in units 100 days. If this condition is satisfied the NS would accrete matter from a non-keplerian magnetic disk which is referred to as Magnetic self-Levitating Disk (see e.g. [7, 8, 9] and references therein). Numerical study of such accretion flow has been made in [5] (see also references therein). The magnetospheric radius of the NS in this case is [9]

\[
r_{ma} = \left( \frac{c m_p^2}{16 \sqrt{2} e k_B} \right)^{2/13} \alpha_B^{2/13} \frac{\mu^{6/13} (GM_{ns})^{1/13}}{T_0^{2/13} M^{4/13}} , \tag{5}
\]

where \( m_p \) is the proton mass, \( k_B \) is the Boltzmann constant and \( T_0 \) is the temperature of the matter at the inner radius of the ML-disk. The parameter \( \alpha_B = D_{eff}/D_B \) is the ratio of the effective diffusion coefficient at the magnetospheric boundary, \( D_{eff} \), to the Bohm diffusion coefficient. Under the conditions of interest the interchange instabilities of the magnetospheric boundary are suppressed by the magnetic field shear [10] and the value of \( \alpha_B \) does not exceed unity.

Evaluating the ratio

\[
\frac{r_{ma}}{r_A} = 0.16 \cdot \alpha_B^{2/13} \frac{m^{20/91}}{\\mu^{10/91}} \frac{1}{T_6^{2/13}} \frac{M_{16}^{-2/91}}{M_{ns}} \tag{6}
\]

one finds that the magnetospheric radius of a NS accreting from the ML-disk under the conditions of interest is significantly small than the Alfvén radius. Here \( T_6 = T_0/10^6 \) K [4].

Thereby, within the framework of the MLA scenario, the direct ejector to accretor transition of a NS can be realized at substantially lower values of \( \dot{M} \) (see fig. 2)

\[
\dot{M} \gtrsim 9 \times 10^{16} \frac{\text{g s}^{-1}}{f_m^{13/11}} \frac{\text{g s}^{-1}}{\mu_3^{10/11}} \frac{v_7^{13/11}}{T_6^{12/13}} m^{-20/11} \tag{7}
\]

For \( \alpha_B \sim 0.01 \) (which is a typical case of the Earth magnetosphere, see [8] and references therein) the mass accretion rate at which the direct ejector to accretor state transition is expected lies in the range \( \dot{M} \sim 10^{15} \div 10^{16} \text{ g s}^{-1} \), which is typical for HMXBs.
Figure 1. Three possible states of a NS in a HMXB with a non-magnetic optical companion (i.e. $B < B_{\text{min}}$) for the quasi-spherical or Keplerian disk accretion scenarios. The dipole magnetic moment of the NS is $\mu = 10^{31} \text{ G cm}^3$.

Figure 2. Three possible states of a NS in a HMXB with a magnetic optical companion (i.e. $B \geq B_{\text{min}}$) for the Magnetic Levitation Accretion (MLA) scenario. The dipole magnetic moment of the NS is $\mu = 10^{31} \text{ G cm}^3$.

4. Conclusions

Our basic conclusion is that the direct transition of a NS from the ejector to accretor state can be realized if the NS accretes matter from the ML-disk. In this case the spin-down time of the NS to a moment when its switches as an accretion-powered pulsar is comparable to the spin-down time in the ejector state (for a discussion see also [7, 8, 9]). It, therefore, appears that the age of accretion-powered pulsars in HMXBs can be as young as $\tau_{\text{ej}}$ provided the magnetic field in their plasma environment exceeds $B_{\text{min}}$ expressed by Eq. (4).

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