Period clustering of the anomalous X-ray pulsars

G.S. Bisnovatyi-Kogan* and N.R. Ikhsanov†

*Space Research Institute of RAS, 84/32 Profsoyuznaya Str, Moscow 117997, Russia, and
National Research Nuclear University “MEPhI”, Kashirskoye shosse 31, Moscow 115409, Russia
†Pulkovo Observatory, Pulkovskoe Shosse 65, Saint-Petersburg 196140, Russia, and
Saint Petersburg State University, Universitetsky pr., 28, Saint Petersburg 198504, Russia

Abstract. In this paper we address the question of why the observed periods of the Anomalous
X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) are clustered in the range 2–12 s. We
explore a possibility to answer this question assuming that AXPs and SGRs are the descendants of
High Mass X-ray Binaries (HMXBs) which have been disintegrated in the core-collapse supernova
explosion. The spin period of neutron stars in HMXBs evolves towards the equilibrium period, \( P_{eq} \).
For a wide range of relevant accretion parameters, its value falls in the interval of observed periods
of AXPs and SGRs. After the explosion of its massive companion, the neutron star turns out to
be embedded into a dense gaseous envelope, the accretion from which leads to the formation of a
residual magnetically levitating (ML) disk. We show that the expected mass of a disk in this case is
\( 10^{-7} – 10^{-8} \, M_\odot \), which is sufficient to maintain the process of accretion at the rate \( 10^{14} – 10^{15} \, g/s \)
over a time span of a few thousand years. During this period the star manifests itself as an isolated X-
ray pulsar with parameters close to those observed from AXPs and SGRs. Period clustering of such
pulsars can be provided if the lifetime of the residual disk does not exceed the spindown timescale
of the neutron star.

Keywords: Accretion and accretion disks, X-ray binaries, neutron star, pulsars, magnetic field,
anomalous X-ray pulsars, Soft gamma-ray repeaters

PACS: 97.10.Gz, 97.80.Jp, 95.30.Qd

1. INTRODUCTION

In the previous paper [1] we have shown that the spin evolution and X-ray emission
of Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) can be
explained in a scenario of magnetic-levitation accretion [2] without an assumption about
super-strong magnetic field of these neutron stars. Within our approach these objects
are described in terms of isolated neutron stars accreting material from a residual non-
Keplerian magnetic disk. This notion is based on the results of modeling in which a
compact star accretes material from a magnetized stellar wind, presented in [3, 4, 5,
6, 8, 7, 9]. The magnetic field strength on the surface of AXPs and SGRs, evaluated
within this approach to fit their observed spindown rates, is in the range \( B_s \sim (0.01 – 10) \times 10^{12} \, G \), while the expected blackbody temperature of the pulsar X-ray radiation
is \( kT \sim 0.3 – 1.4 \, keV \) [1]. We explained flaring activity of these objects in gamma-
rays assuming a spontaneous release of energy accumulated in a non-equilibrium layer
of super-heavy nuclei located at the lower boundary of the upper crust of a low- or
moderate-mass neutron star [10, 11, 12].

In this paper we discuss a period clustering of AXPs and SGRs in a relatively narrow interval from 2 to 12 seconds. Analysis of this phenomenon is traditionally performed under assumption that the age of these objects, \( \tau_s \), does not exceed their spindown timescale, \( \tau_{sd} \sim P_s/2\dot{P} \), and/or the age of supernova remnants associated with them. Here \( P_s \) is the spin period of a pulsar and \( \dot{P} = dP_s/dt \) is its current spindown rate. In this case AXPs and SGRs are relatively young \((10^{2} - 10^{5})\) years) neutron stars with initial spin period of a few fractions of a second which had increased by \(3 - 4\) orders of magnitude following the exponential law according to the canonical model of a radio-pulsar. In this context it seems rather difficult to understand why the stars of different ages undergoing rapid spindown manifest themselves as AXPs and SGRs only and exclusively at the moment when their spin period attains a value from the observed narrow range.

We suggest a radically new approach to solving this problem, in which AXPs and SGRs are considered as descendants of X-ray pulsars in High Mass X-ray Binaries (HMXBs). A suggested scenario is based on the hypothesis that these objects are neutron stars which had been born in the first supernova explosion in the high-mass binary system, and became accretion-powered X-ray pulsars. The spin period of a star in this state evolves towards the equilibrium period, \( P_{eq} \), whose value falls into the interval of observed periods of AXPs and SGRs for a wide range of relevant accretion parameters. (see Section 2). After the second supernova outburst caused by core-collapse of the massive component, the system is very likely to be disintegrated with the old neutron star being embedded into a dense gaseous medium from which it captures material at a rather high rate. In Section 3 we show that this process can under certain conditions result in the formation of a residual magnetically levitating disk (ML-disk). Accreting from such a disk, the star acts as an isolated X-ray pulsar with parameters fitting the observed parameters of AXPs and SGRs. If the lifetime of a residual disk does not exceed the spindown timescale of the neutron star, \( \tau_{sd} \), the periods of such pulsars will be clustered around the value of \( P_{eq} \). Hence, in the frame of our approach AXPs and SGRs turn out to be old rather than young neutron stars. At the same time, physical conditions in their crusts can essentially differ from those in a neutron star of the same age but not having undergone accretion onto its surface, since the mass of gas being accreted onto these stars during the epoch of their evolution as a part of a HMXB is compatible with the mass of a non-equilibrium layer of super-heavy nuclei located in their crust. Spontaneous release of energy accumulated in this layer can trigger flaring activity of AXPs and SGRs in gamma-rays. Our basic conclusions are summarized in Section 4.

2. PULSAR PERIOD IN A HIGH-MASS X-RAY BINARY

The majority of presently known X-ray pulsars are the members of HMXBs, which are close pairs consisting of a massive O/B-star and a neutron star with strong magnetic field. Their X-ray emission is generated due to accretion of matter onto the neutron star surface in the magnetic polar regions. The period of a pulsar corresponds to the spin period of a neutron star, \( P_s \), and its luminosity, \( L = \dot{M}GM_{ns}/R_{ns} \), is determined by the rate of mass accretion onto the stellar surface, \( \dot{M} \), where \( M_{ns} \) is the mass and \( R_{ns} \) is the
radius of a neutron star. The period of such a pulsar evolves according to the equation

\[ 2\pi I \dot{\nu} = K_{su} - K_{sd} \]  

(1)
towards the equilibrium period, \( P_{eq} \), whose value is defined by the balance of a spin-up, \( K_{su} \), and spin-down, \( K_{sd} \), torques, exerted on the star by the accretion flow. Here \( I \) is the moment of inertia of a neutron star, \( \nu = 1/P_s \) is the frequency of its axial rotation and \( \dot{\nu} = d\nu/dt \).

According to modern views, HMXBs are the descendants of high-mass binaries, which survived a supernova explosion caused by a core-collapse of their more massive component. A neutron star born in the course of this event (the first supernova explosion) possesses strong magnetic field and rotates with a period of a fraction of a second. Then it is spinning down because of magneto-dipole losses (the ejector state) and later on due to interaction between its magnetic field and the surrounding plasma (the propeller state). When its spin period reaches the critical value determined by the equality of its corotation radius, \( r_{cor} = \left( \frac{GM_{ns}}{\omega_s^2} \right)^{1/3} \), and the magnetosphere radius, \( r_m \), the star passes to the accretor state and manifests itself as an X-ray pulsar. Here \( \omega_s = 2\pi/P_s \) is the angular velocity of its axial rotation.

Numerical simulations of this scenario [13] indicate that a neutron star with a sufficiently strong initial magnetic field at the final stage of its evolution in a HMXB undergoes accretion from a Keplerian disk and its spin period evolves towards the equilibrium period whose value can be estimated as

\[ P_{eq}^{(Kd)} \simeq 3 \times 10^6 \left( \frac{M_{opt}}{20M_{\odot}} \right)^{-5/2} \text{Ms} \]  

(2)
Here \( k_i \) is a dimensionless parameter of the order of unity, \( \mu_{30} \) is the dipole magnetic moment of the neutron star in units of \( 10^{30} \text{G} \cdot \text{cm}^3 \), \( m \) is the neutron star mass in units of \( 1.4M_{\odot} \) and \( \dot{\mathcal{M}}_{17} \) is the mass accretion rate onto the stellar surface in units of \( 10^{17} \text{g/s} \). The age of the neutron star by this moment is

\[ t_{ms} \simeq 6 \times 10^6 \left( \frac{M_{opt}}{20M_{\odot}} \right)^{-5/2} \text{yr}, \]  

(3)
that corresponds to the average time of its massive component (of the mass \( M_{opt} \)) evolution on the main sequence [14]. As the massive star begins to evolve off of the main sequence, its radius increases and it fills its Roche lobe. In this case the mass exchange between the system components proceeds on the thermal timescale, \( t_{th} = GM_{opt}^2/(R_{opt}L_{opt}) \sim 3 \times 10^7 \text{m}^2 \text{yr} \), in the form of a stream through the Lagrangian point L1 at the rate \( \dot{\mathcal{M}} \sim M_{opt}/t_{th} \sim 10^{17} (M_{opt}/20M_{\odot})^{-1} \text{g/s} \). Here \( R_{opt} \) and \( L_{opt} \) are the radius and the luminosity of the massive component determined in general case by its mass (see [15] and references therein). For the stars with the mass \( M_{opt} \sim 15 - 30M_{\odot} \), the rate of mass exchange between the system components falls in a relatively narrow interval \( \dot{\mathcal{M}} \sim (0.6 - 2) \times 10^{17} \text{g/s} \).

The magnetic field strength of the neutron star manifesting itself as an X-ray pulsar at the end of evolutionary history of the HMXB is very likely to be in the range \( \sim 10^{12} - \)
10^{13} \text{ G}. The lower boundary of this interval is defined by the condition \(\tau_{ej} + \tau_{pr} \leq t_{ms}\), where \(\tau_{ej} \simeq 8 \times 10^5 f_m^{-1/2} I_{45} \mu_{30}^{-1} \Omega_{15}^{-1/2} v_8^{-1/2} \text{ yr}\) is a characteristic evolutionary time of a neutron star in the ejector (spin-powered pulsar) state, and
\[
\tau_{pr}^{(sp)} \simeq 6 \times 10^6 \text{ yr} \times k_t^{-1} f_m^{-1/4} I_{45} \mu_{30}^{7/6} m^{1/3} \Omega_{15}^{-5/12} v_8^{-13/12}
\]
determines the duration of the propeller phase in the scenario of quasi-spherical accretion (the state of super-sonic propeller in the classification proposed by Davis and Pringle [17]). Here \(I_{45} = I/10^{45} \text{ g cm}^2\), \(v_8 = v_{\text{rel}}/10^8 \text{ cm/s}\) is the neutron star velocity relative to the wind of its massive component and \(f_m\) is a dimensionless parameter ranging as \(1 \leq f_m \leq 4\) [18, 19]. The parameter \(\Omega_{15} = \dot{M}_c/10^{15} \text{ g/s}\) in these expressions denotes the mass of gas with which a neutron star interacts in a unit time moving through the wind of its massive companion,
\[
\dot{M}_c \sim 3 \times 10^{14} \text{ g/s} \times m^2 v_8^{-4} a_{13}^{-2} M_{-6},
\]
where \(a_{13} = a/10^{13} \text{ cm}\) is the orbital separation and \(M_{-6} = M_{\text{out}}/10^{-6} M_\odot/\text{year}\) is the mass-loss rate of the optical component during its evolution on the main sequence. The upper limit of the most probable values of the magnetic field strength on the surface of X-ray pulsars is evaluated through observations of cyclotron lines in their spectra (see [20, 21] and references therein).

Dependence \(P_{eq}^{(Kd)} = P_{eq}^{(Kd)}(\Omega)\) for different values of the dipole magnetic moment of the neutron star is presented in Fig. 1. Dashed region shows a parameter domain for which the equilibrium period of a neutron star accreting material from a Keplerian disk falls into the observed period range of AXPs and SGRs. As can be seen in this figure, the periods of X-ray pulsars at the final stage of HMXB evolution are clustered in a relatively narrow interval. Accreting material from a residual ML-disk, these stars (after disintegration of the binary system caused by the second supernova explosion) can manifest themselves as isolated X-ray pulsars with the period \(P_{eq}^{(Kd)}\).

3. FORMATION OF A RESIDUAL DISK

Evolution of the binary system at the phase of HMXB ends up with a core-collapse of its massive component accompanied with a supernova explosion and ejection of a massive shell \((1 - 3 M_\odot)\). As a result, the second neutron star or a black hole is born. Depending on the energetics and geometry of the explosion, a HMXB can either become a system of two degenerate objects or disintegrate into two isolated compact stars with the latter case being more probable [22]. The characteristic time of system disintegration, \(\tau_{\text{dec}} \sim a/v_{\text{kick}}\), is determined by the initial orbital separation, \(a\), and the value of kick-velocity, \(v_{\text{kick}}\), whose average value is about \(\sim 100 \text{ km/s}\) [23].

Because of the envelope ejection in the supernova explosion, both stars appear to be embedded into a dense gaseous medium. The expansion velocity of the ejecta at the...
initial phase reaches the value of $10\,000\text{ km/s}$ and almost all this material leaves the region of explosion and disperses in space forming a nebulous supernova remnant. The only exception are the innermost layers of the ejecta with initial velocity of the order of or even smaller than the parabolic velocity in the gravitational field of the young compact star which is born in the process of core-collapse of the massive component. The expansion velocity of this part of the envelope is rapidly decreasing due to the strong gravitational attraction of the new-born compact star and becomes comparable to the sound speed at its Bondi radius. Studies of this process which is called fall-back accretion [24, 25] have shown that the mass of gas concentrated in this part of the envelope constitutes $M_0 \sim 10^{-4} - 10^{-5} M_\odot$. A portion of this matter with initial expansion speed below the parabolic velocity returns to the young compact star forming a fall-back accretion flow, while the remaining part with initial expansion velocity of the order or slightly in excess of the parabolic velocity forms a slowly expanding shell. In this Section we show that interaction between the old neutron star and slowly expanding shell can lead to formation of an ML-disk. Accreting from this disk, the star shows itself
as an isolated X-ray pulsar with the period \( P_{\text{eq}}^{(Kd)} \) and the life-time up to a few thousand years provided its luminosity is \( 10^{34} - 10^{35} \) erg/s.

The amount of mass with which an old neutron star interacts in a unit time moving with a relative velocity \( v_{\text{rel}} \) can be estimated as follows

\[
\dot{M}_{\text{cap}} = \frac{4\pi (GM_{\text{ns}})^2 \rho_{\text{env}}}{v_{\text{rel}}^3}.
\]  

(7)

Here \( \rho_{\text{env}} \sim 3M_0/(4\pi a^3) \) is the mean density of the material in the inner part of the envelope with the mass \( M_0 \) contained inside radius \( a \). The total amount of matter which can under favorable conditions be captured by the neutron star over the time span \( \tau_{\text{dec}} \) from this part of the envelope is

\[
M_{\text{cap}} \simeq 3 \times 10^{-7} M_{\odot} \times m^2 a_{13}^{-2} \left( \frac{M_0}{10^{-5} M_{\odot}} \right) \left( \frac{v_{\text{rel}}}{100 \text{ km/s}} \right)^{-3} \left( \frac{v_{\text{kick}}}{100 \text{ km/s}} \right)^{-1}. \quad (8)
\]

The structure of an accretion flow forming by the captured material inside Bondi radius is determined by the relative velocity of the star, \( v_{\text{rel}} \), as well as by physical parameters of the gas and magnetic field strength in the surrounding envelope. As has been recently shown by Ikhsanov et al. (see [26] and references therein), a scenario of quasi-spherical accretion can be realized under the condition \( v_{\text{rel}} > v_{\text{ma}} \), where

\[
v_{\text{ma}} \simeq 1700 \beta_0^{-1/5} \mu_{30}^{-6/35} m_{17}^{-3/35} m_{12}^{12/35} \left( \frac{c_s(r_G)}{100 \text{ km/s}} \right)^{2/5} \text{ km/s}. \quad (9)
\]

Here \( \beta_0 = E_{\text{th}}(r_G)/E_{\text{m}}(r_G) \) is the ratio of the thermal, \( E_{\text{th}} \sim \rho c_s^2 \), to magnetic, \( E_{\text{m}} = B_f^2/8\pi \), energy in the material captured by the star at its Bondi radius. Parameters \( \rho \), \( B_f \) and \( c_s \) denote the density, the magnetic field strength and the sound speed in the accretion flow, respectively. If \( v_{\text{rel}} < v_{\text{kd}} \), where

\[
v_{\text{kd}} \simeq 60 \text{ km/s} \times \xi_{0.2}^{3/7} \beta_0^{1/7} m_{17}^{3/7} m_{12}^{-2/7} \left( \frac{P_{\text{orb}}}{100 \text{ days}} \right)^{-3/7}, \quad (10)
\]

the material captured by the star is accumulated in a Keplerian accretion disk [1]. Here \( P_{\text{orb}} \) is the orbital period of the HMXB and \( \xi_{0.2} = \xi/0.2 \) is a parameter accounting for the angular momentum dissipation in the quasi-spherical non-magnetic flow, normalized on its average value obtained in [27].

Finally, in the intermediate case \( v_{\text{kd}} \leq v_{\text{rel}} < v_{\text{ma}} \), we expect realization of magnetic-levitation accretion scenario in which the matter captured by the neutron star is accumulated around its magnetosphere in a form of non-Keplerian magnetically levitating disk and moves towards the star in the diffusion regime. The outer radius of the ML-disk is determined by the Shvartsman radius [3],

\[
R_{\text{sh}} = \beta_0^{-2/3} r_G \left( \frac{c_s(r_G)}{v_{\text{rel}}} \right)^{4/3}, \quad (11)
\]
at which the magnetic pressure in the free-falling gas reaches its ram pressure. In the presence of large-scale magnetic field with the inhomogeneity scale in excess of Bondi radius, the initially quasi-spherical flow rapidly decelerates and transforms its geometry into a ML-disk [4, 5]. Here \( r_G = \frac{2GM_{\text{ns}}}{v_{\text{rel}}^2} \) is the Bondi radius of the neutron star.

The inner radius of a ML-disk corresponds to the magnetosphere radius of the neutron star and equals \([9, 2]\)

\[
r_{\text{ma}} = \left( \frac{c m_p^2}{16 \sqrt{2 e} k_B} \right)^{2/13} \alpha_B \mu^{6/13} \left( \frac{GM_{\text{ns}}}{T_0} \right)^{5/13} L_X^{4/13} R_{\text{ns}}^{4/13}.
\]

(12)

Here \( m_p \) and \( e \) are the proton mass and the electron charge, and \( k_B \) is the Boltzmann constant. \( T_0 \) is the gas temperature in the diffusion layer at the magnetosphere boundary (magnetopause), and \( \alpha_B = D_{\text{eff}}/D_B \) is a dimensionless parameter, expressing the ratio of the effective coefficient of the accretion flow diffusion into the magnetic field of the star, \( D_{\text{eff}} \), to the Bohm diffusion coefficient.

The mass of an ML-disk forming in this scenario is

\[
M_d = 4\pi \int_{r_{\text{ma}}}^{R_{\text{sh}}} \rho(h_z(r)) r dr,
\]

(13)

where \( \rho(r) \) is the density of the disk, and \( h_z(r) \) is its half-thickness. These parameters can be estimated taking into account that the gaseous (as well as the magnetic) pressure in the ML-disk reaches its maximum,

\[
\rho(r_{\text{ma}}) c_s^2(r_{\text{ma}}) = \frac{\mu^2}{2\pi r_{\text{ma}}^6},
\]

(14)

at the inner radius of the disk and decreases with distance from the star as \( \rho(r) c_s^2(r) \propto r^{-5/2} \) [4, 5]. Taking into account that the gas temperature in the disk is

\[
T(r) = \left( \frac{91GM_{\text{ns}}}{4\pi r^3 \sigma_{\text{SB}}} \right)^{1/4},
\]

(15)

and, correspondingly, the sound speed is \( c_s \sim (k_B T/m_p)^{1/2} \propto r^{-3/8} \), the density distribution in the radial direction is

\[
\rho(r) = \rho(r_{\text{ma}}) \left( \frac{r}{r_{\text{ma}}} \right)^{-7/4},
\]

(16)

where \( \sigma_{\text{SB}} \) is the Stefan-Boltzmann constant. Finally, the half-thickness of the disk can be estimated as [4, 5]

\[
h_z(r) = \left( \frac{k_B T(r) r^3}{m_p GM_{\text{ns}}} \right)^{1/2}.
\]

(17)
FIGURE 2. Dependence of the mass of the residual ML-disk, $M_d$, on the neutron star velocity relative to the slowly expanding part of the envelope, $v_{\text{rel}}$, for different values of the mass capture rate during the epoch of disk formation. Dashed region shows the values of $M_d$ allowing a neutron star to behave as an isolated X-ray pulsar with a luminosity of $10^{34} - 10^{35}$ erg/s over a time span of a few thousand years.

Substituting (12), (11) and (15–17) to (13) and taking into account that under the conditions of interest $R_{\text{sh}} \gg r_{\text{ma}}$, we find

$$M_d \simeq 7 \times 10^{-6} M_\odot \times \alpha_0^{-7/3} \beta_0^{-11/12} \mu_30^{5/13} \dot{M}_{17}^{99/104} \dot{m}^{25/52} c_7^{11/6} \gamma_7^{-55/12},$$

(18)

where parameter $\alpha_0 = \alpha_B/0.1$ is normalized following [28], $c_7$ is the sound speed in the envelope around the neutron star in units of $10^7$ cm/s and $\dot{M}_{17} = \dot{M}_{\text{cap}}/10^{17}$ g/s is the capture rate by the neutron star from the surrounding envelope during the phase of disk formation.

The function $M_d = M_d(v_{\text{rel}})$ is shown in Fig. 2 for different values of $\dot{M}_{\text{cap}}$. As can be seen in this figure, a ML-disk with the mass sufficient to provide the process of accretion at the rate $10^{14} - 10^{15}$ g/s over a time span of a few thousand years can be formed if the value of $v_{\text{rel}}$ is comparable to the average value of spatial velocity of isolated radio-pulsars, $v_{\text{kick}} \sim 100$ km/s, determined from observations [23].
4. CONCLUSIONS

We show that isolated X-ray pulsars with the periods of a few seconds can be formed in a supernova explosion at the final stage of evolution of the High Mass X-ray Binary accompanied by its disruption. The old neutron star captures material from the expanding envelope ejected by its exploding companion that results in the formation of a residual ML-disk, from which the star accretes matter onto its surface. The spin period of an isolated X-ray pulsar forming in the frame of this scenario is close to the equilibrium period of the neutron star rotation at the final evolutionary stage of the binary system. For a wide range of relevant accretion parameters, its value falls in the interval of observed periods of AXPs and SGRs. In this situation the neutron star is spinning down at the rate which is consistent with that measured in AXPs and SGRs if the surface magnetic field of these objects is $10^{10} - 10^{13}$ G. The period clustering of AXPs and SGRs is expected within this picture provided the lifetime of a residual disk does not exceed the spindown timescale of the neutron star.

In the frame of this scenario the supernova remnants associated with AXPs and SGRs were produced by explosion of their massive companions with which they had composed a HMXB in the previous epoch. This allows to understand why the majority of AXPs and SGRs are situated away from the central parts of corresponding nebulosities. Moreover, significant rate of mass loss from the binary system expected during the final stage of its evolution could result in density enhancement in the vicinity of AXPs and SGRs in comparison with an average gas density in the circumstellar medium. The supernova remnant in this case should be distinguished by enhanced compactness that is consistent with the results presented in [29].

ACKNOWLEDGMENTS

The authors thank N.G. Beskrovnaya and V.Yu. Kim for useful discussions and help in preparation of this manuscript. The work was partly supported by RFBR under the grants No. 13-02-00077 and No. 14-02-00728, SPbSU under the grant No. 6.38.669.2013, the President Support Program for Leading Scientific Schools NSH-261.2014.2, and the RAS Presidium Program No. 21 “Non-stationary phenomena in the Universe”.

REFERENCES

1. G.S. Bisnovaty-Kogan, N.R. Ikhsanov, Astronomy Reports 58, 217 (2014).
2. N.R. Ikhsanov, N.G. Beskrovnaya, Yu.S. Likh, Int. J. Mod. Phys.: Conf. Ser. 28, 1460187 (2014).
3. V.F. Shvartsman, Soviet Astronomy 15, 377 (1971)
4. G.S. Bisnovaty-Kogan, A.A. Ruzmaikin, Astrophys. and Space Sci., 28, 45 (1974).
5. G.S. Bisnovaty-Kogan, A.A. Ruzmaikin, Astrophys. and Space Sci., 42, 401 (1976).
6. I.V. Igumenshchev, R. Narayan, M.A. Abramowicz, Astrophys. J. 592, 1042 (2003).
7. N.R. Ikhsanov, M.H. Finger, Astrophys. J. 753, 1 (2012).
8. N.R. Ikhsanov, N.G. Beskrovnaya, Astronomy Reports 56, 589 (2012)
9. N.R. Ikhsanov, V.Y. Kim, N.G. Beskrovnaya, L.A. Pustil’nik, Astrophys. and Space Sci. 346, 105 (2013).
10. G.S. Bisnovaty-Kogan, V.M. Chechetkin V.M., Astrophys. and Space Sci., 26, 25 (1974).
11. G.S. Bisnovatyi-Kogan, V.S. Imshennik, D.K. Nadyozhin, V.M. Chechetkin V.M., Astrophys. and Space Sci., 35, 23 (1975).
12. G.S. Bisnovatyi-Kogan, V.M. Chechetkin, Soviet Physics - Uspekhi 22, 89 (1979).
13. V. Urpin, A. Konnenkov, U. Geppert, Mon. Not. R. Astron. Soc. 299, 73 (1998).
14. D. Bhattacharya, E.P.J. van den Heuvel, 1991, Phys. Rep. 203, 1 (1991).
15. A.G. Masevich, A.V. Tutukov, Stellar evolution: Theory and observations, M: Nauka, 1988.
16. N.R. Ikhsanov, Monthly. Not. Roy. Astron. Soc. 375, 698 (2007).
17. R.E. Davies, J.E. Pringle, Monthly. Not. Roy. Astron. Soc. 196, 209 (1981).
18. A. Spitkovsky, Astrophys. J. 648, L51 (2006).
19. V.S. Beskin, Phys. Uspekhi, 53, 1199 (2010).
20. I. Caballero, J. Wilms, Mem. Soc. Astron. Italiana, 83, 230 (2012).
21. A.N. Baushev, G.S. Bisnovatyi-Kogan, Astronomy Reports, 43, 241 (1999).
22. S.B. Popov, M.E. Prokhorov, Monthly. Not. Roy. Astron. Soc. 367, 732 (2006).
23. Z. Arzoumanian, D.F. Chernoff, J.M. Cordes, Astrophys. J. 568, 289 (2002).
24. F.C. Michel, Nature 333, 644 (1988).
25. R.A. Chevalier, Astrophys. J. 346, 847 (1989).
26. N.R. Ikhsanov, Yu.S. Likh, N.G. Beskrovnaya, Astronomy Reports, 58, 376 (2014).
27. M. Ruffert, Astron. and Astrophys. 346, 861 (1999).
28. J.T. Gosling, M.F. Thomsen, S.J. Bame, et al. 1991, J. Geophys. Res., 96, 14097 (1991).
29. D. Marsden, R.E. Lingenfelter, R.E. Rothschild, J.C. Higdon, Astrophys. J. 550, 397 (2001).