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ANOMALOUS PULSARS

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Abstract

Many astrophysicists believe that Anomalous X-Ray Pulsars (AXP), Soft Gamma-Ray Repeaters (SGR), Rotational Radio Transients (RRAT), Compact Central Objects (CCO) and X-Ray Dim Isolated Neutron Stars (XDINS) belong to different classes of anomalous objects with neutron stars as the central bodies inducing all their observable peculiarities. We have shown earlier [1] that AXPs and SGRs could be described by the drift model in the framework of the preposition on usual properties of the central neutron star (rotation periods P~ 0.01 − 1 sec and, surface magnetic fields B ~ 10^{11} –10^{13} G). Here we shall try to show that some differences of the sources under consideration will be explained by their geometry (particularly, by the angle β between their rotation and magnetic axes). If $\beta \lesssim 10^0$ (the aligned rotator) the drift waves at the outer layers of the neutron star magnetosphere should play a key role in the observable periodicity. For large values of β (the case of the nearly orthogonal rotator) an accretion from the surrounding medium (for example, from the relic disk) can cause some modulation and transient events in received radiation.

Recently Kramer et al. [2] and Camilo et al. [3] have shown that AXPs J1810-197 and 1E 1547.0 – 5408 have both small angles β, that is these sources are nearly aligned rotators, and the drift model should be used for their description.

On the other hand, Wang et al. [4] detected IR radiation from the cold disk around the isolated young X-ray pulsar 4U 0142+61. This was the first evidence of the disk-like matter around the neutron star.

Probably there is the bimodality of anomalous pulsars. AXPs, SGRs and some radio transients belong to the population of aligned rotators with the angle between the rotation axis and the magnetic moment $\beta < 20^0$. These objects are described by the drift model, and their observed periods are connected with a periodicity of drift waves. Other sources have $\beta \sim 90^0$, and switching on's and switching off's of their radiation are caused by accretion phenomena connected with a relic (debris) disc surrounding them.

XDINS and CCOs are probably neutron stars with rather low magnetic fields at the surface of neutron stars.

Other known models of "anomalous " pulsars are briefly discussed.

Key words: AXP, SGR, RRAT, radio pulsars: drift waves, relic disk, accretion

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I. INTRODUCTION

During the last decades the interest in some X-ray sources has grown significantly. These are first of all AXPs and SGRs, "magnetars" as many investigators believe. We showed in our paper [1] that these objects could be described by the drift model, and the usual neutron star lied in the base of both types of sources. The drift waves cause some changes of magnetic field

lines curvature and as the consequence the modulation of emission propagation directions (Fig.1). The calculations in the framework of this model have been carried out. As a result some parameters of neutron stars in the known AXPs and SGRs were obtained: the interval for the rotation periods is P = 11 – 737 msec, for their derivatives $dP/dt = 3.7 \times 10^{-16} – 5.5 \times 10^{-12}$, and for the surface magnetic fields $\log B_s = 11.22 – 13.24$. The main difference between AXPs / SGRs and normal radio pulsars is a small inclination of the magnetic moment to the rotation axis in the first group. The corresponding angle β must be of the order of (or less than) 10^0. We believe that all neutron stars with $\beta \lesssim 10^0$ must belong to the population with observed intervals between successive pulses (if they are seen) P_{obs} of order to several seconds. For example, The so-called high magnetic field pulsars are objects of this type. Real rotation periods and magnetic fields for pulsars with very long observed pulse periods are the same as for normal pulsars [5]: $P = 0.5 – 1.12$ sec, $B_s = (0.2 – 16)\ 10^{12}$ G.

Anomalous pulsars include besides AXPs and SGRs Rotating RAdio Transients (RRATs), Compact Central Objects in supernova remnants (CCOs), and X-ray Dim Isolated Neutron Stars (XDINSs). We believe all these objects have an isolated neutron star as the central body.

Let us consider some models of anomalous pulsars.

2. RADIO TRANSIENTS

Transients are sources emitting suddenly a few number of pulses and then switching off. Currently, about 20 RRATs are known.

To explain the transient character of emission from these objects some models were put forward during the last few years.

1. Precession of pulsars with long time nullings [6]. To achieve the agreement with observations it is necessary to suggest in this model large angles of precession ($\gamma > 15^0$). γ is the angle between the rotation axis and the angular moment. The estimations give for normal radio pulsars $\gamma < 10^0$. The required precession in neutron stars is possible for very large deformations only and can be realized at rotation periods of order to 1 msec. Moreover this precession must quickly damp (during $10^2 – 10^4$ periods of the precession). To avoid these difficulties the authors propose to use as the host object in such pulsars a solid quark star with possible large elastic deformations. However the existence of quark stars is rather problematic, and their corresponding models have not been worked out up to now.

2. Zhang et al. [7] considered the possibility of the location of a pulsar near and below the "death line" and irregular appearances of the pulsar above this line. Such appearances take place when the magnetic field of the solar spot type comes to the surface and induces the process of $e^{\pm}$ - pairs creation. What is the real equation of the death line is unclear yet. If we take the equation used by the authors some transients find themselves above this line, and other mechanism of switching off of their radiation must operate.

3. The same authors [7-8] considered another possibility to explain RRATs. They put forward the idea of so-called inward radiation, i.e. radiation directed opposite to usual "right" pulsar

radiation, and connected nullings with this emission directed inward. In this model the geometric effects play a role only and the breaking must be the same in "on" and "off" phases. So, some other mechanisms must operate at least in PSR B1931+24, where the frequency derivatives differ significantly (1.5 times) in these two phases [9]. Similar behavior shows PSR J1832+0031[10].

4. Drift model. In this model [11] the line of sight could find itself sometimes inside of an emission cone due to cataclysms at the surface of the neutron star. It is suggested that angle β between the rotation axis and the magnetic moment is small enough. A very narrow pulse is expected in this case. This pulse must contain an odd number of extremely narrow sub-pulses (1, 3, 5 or more with smoothly falling intensities) (Fig.2). To be seen during milliseconds such transients must have a very short rotation period.

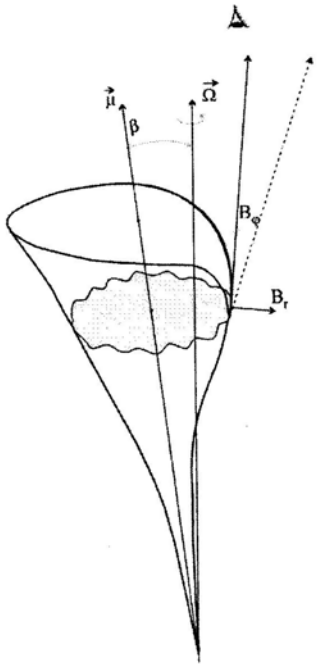


Fig.1. Scheme of the drift model. **μ** is the magnetic moment, **Ω** is the rotation axis.

5. Li [12] put forward the model of a relic disk retained after the supernova explosion or formed from the captured interstellar matter. The neutron star operates as a propeller when the disk penetrates inside the light cylinder and quenches the generation of $e^{\pm}$ - plasma. An emission is switched on if disk goes out the light cylinder. In one case the braking is caused by the magneto-dipole radiation, in another one an additional moment is taken away by the pulsar wind, and the pulsar is slowing down faster.

Wang et al. [4] detected IR radiation from the cold disk around the isolated young X-ray pulsar 4U 0142+61. This was the first evidence of the disk-like matter around the neutron star.

In the disk model the angle β is expected to be high.

3. ANGLES BETWEEN ROTATION AND MAGNETIC AXES

As we declared in the previous section, the angle β between the rotation axis of the given object and its magnetic moment is very important for the choosing of the adequate model.

Here we will discuss some possibilities of the evaluation of this angle for a number of sources under consideration.

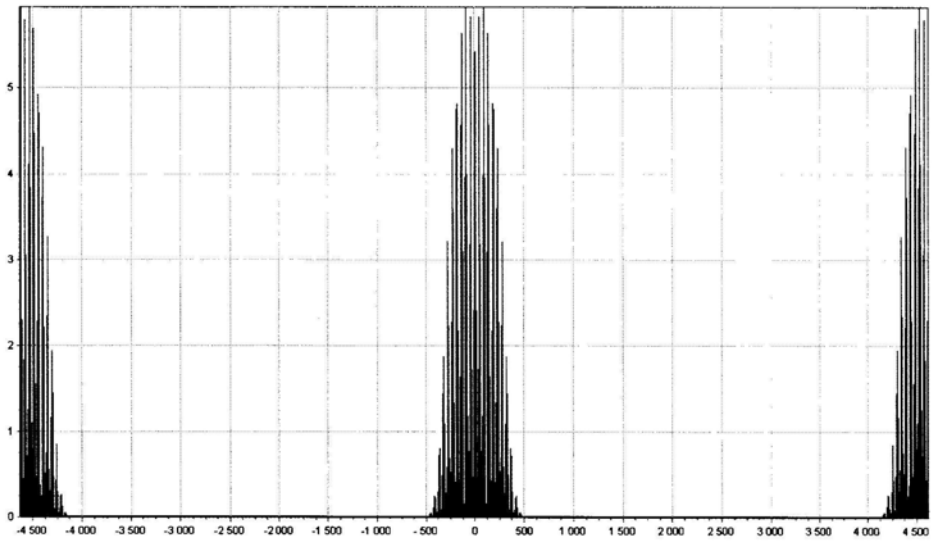


Fig.2. Simulated light curve of PSR J1819-1458 [11].

Using a schematic presentation of the radiation-cone geometry [13], we can write three following equations [14]:

$$\sin\beta = C\sin(\zeta - \beta),$$

$$\cos\theta = \cos\zeta\cos\beta + D\sin\beta\sin\zeta,, \qquad (1)$$

$$\theta = n(\zeta - \beta)$$

for three unknown quantities: the angle β between the rotation axis ($\mathbf{\Omega}$) and the magnetic moment $\boldsymbol{\mu}$, the angle ζ between the line of sight ($\mathbf{L}$) and $\mathbf{\Omega}$, and the angular radius θ of the radiation cone, assuming that it is connected to the last open magnetic-field lines.

In (1) n is the fraction of the angular radius of the cone where the line of sight passes and

$$C = |(d\psi/d\Phi)|_{\max} = \sin\beta/\sin(\zeta - \beta) \qquad (2)$$

is the maximum derivative of the linear-polarization position angle in the average profile, which is obtained from the relationship describing the position angle ψ as a function of longitude Φ [13]:

$$\tan\psi = \frac{\sin\beta\sin\Phi}{\sin\zeta\cos\beta - \cos\zeta\sin\beta\cos\Phi} \qquad (3)$$

The factor $D = \cos(W_{10}/2)$ is determined by the observed width W_{10} of the mean profile at the 10% level. The value of n can be estimated from the shape of the mean profile.

Now we consider some pulsars with measured polarization characteristics and known pulse profiles.

PSR B1931+24

The radio pulsar **PSR B1931+24** (J 1933+2421) emits pulses over five to ten days, then sharply switches off, remaining undetectable over the next 25–30 days [2].

We have for this pulsar at a frequency close to 400 MHz [10, 15]

$$C = 5.5,\ W_{10} = 37.5^0,\ D = 0.95,\ \text{and}\ n \approx 2.$$

Thus, the problem of finding the angles β, ξ, and θ in this case reduces to solving the system of equations

$$\begin{aligned} &\sin\beta = 5.5\sin(\zeta - \beta), \\ &\cos\theta = \cos\zeta\cos\beta + 0.95\sin\beta\sin\zeta, \\ &\theta = 2(\zeta - \beta). \end{aligned} \qquad (4)$$

This system has only one real-valued root, $\cos\zeta = -0.15$, which corresponds to $\zeta = 98^0.7$. We obtain from (6) the value $\beta = 88^0.2$, and from the last equation of system (4), $\theta = 21^0.0$.

Hence, this pulsar is nearly orthogonal rotator.

The calculated values of angles ($\zeta = 98^0.7^0$ and $\beta = 88^0.2$) correspond to the pulsar geometry presented in Fig.3.

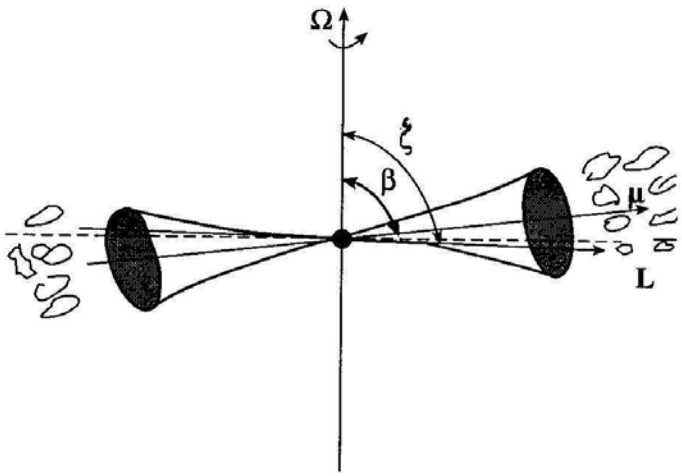


Fig.3. Radiation geometry for the pulsar PSR B1931+24.

As it was mentioned in the previous section, the possible cause of the switching on and off of radiation in PSR B1931+24 was the presence of a relic disk around the pulsar. In particular there may be precession with a period of about 30–40 days. If such a disk is in the equatorial region, it can occasionally "lock up" the pulsar radiation. Searches for traces of such a disk, e.g., of its infrared radiation, are necessary. The possible existence of relic disks around pulsars with transient radiation was also considered in [4, 12]. A decrease in dP/dt can also be related to the presence of plasma of the relic disk at the times of switching off. Partial or full blocking of the radiation inside the magnetosphere decreases the loss of angular momentum of the pulsar. Meanwhile, the escape of relativistic particles to the surrounding plasma partially persists, and this pulsar wind provides a spin-down in the periods of switching off of the observed radiation. A small amount of disk accretion also can spin up the neutron star, decreasing dP/dt somewhat. Generally speaking, the presence of precession is not a mandatory element in the proposed model. Locking and unlocking of the radiation cone could be due to inhomogeneity of the surrounding disk. In this case, due to differential disk rotation, dense inhomogeneities sometimes fall in the line of sight, hindering the propagation of the pulsar radiation. Essentially, this type of situation can be observed in some RRATs.

Beskin and Nochrina [16] discussed the role of current losses in the magnetosphere of PSR B1931+24. These losses could account for the observed jump $(d\Omega/dt)_{on} / (d\Omega/dt)_{off} = 1.5$. In "off" periods, the magnetosphere is not filled with plasma, and angular-momentum losses are due to magneto-dipole radiation. When the radiation is observed, braking of the neutron star is due to current losses; the ratio of these energy losses is then

$$\frac{W_{md}}{W_c} = \frac{B_s^2 R^6 \Omega^4 \sin^2\beta}{6c^3} : \frac{f_*^2 B_s^2 R^6 \Omega^4 \cos^2\beta}{4c^3} = \frac{2\tan^2\beta}{3 f_*^2} \qquad (10)$$

However, using $\beta = 88^0.2$ and the dimensionless area of the polar cap $f* = 1.96$, we obtain

$$(d\Omega/dt)_{on} /(d\Omega/dt)_{off} = W_{md} / W_c = 264.$$

Thus, magneto-dipole losses in the "on" state of PSR B1931+24 should be considerably greater than the current losses in the "off" state.

PSR B0656+14

Weltewrede et al. [17] proposed that the burst-like character of the radiation of **PSR B0656+14** is similar to the behavior of RRATs. In this connection, it is interesting to estimate the angles between its axes. We could use the system (1), but, in the case of PSR B0656+14, it is sufficient to obtain simpler estimates based on the profile shape and derivative of the polarization position angle. For this pulsar, the maximum derivative at frequencies near 400 MHz is $C = 1.28$ [15]. For such a small value of C, we can use the formula [14]:

$$C \geq 3.24 \sin \beta, \qquad (11)$$

which yields $\beta < 23^0.3$. This estimate demonstrates that the pulsar PSR B0656+14 is a "normal" pulsar and not a transient. The variations in its radiation (including outbursts) have intrinsic origins, related to the particulars of its radiation mechanism, not its specific geometry or the presence of a relic disk.

PSR J 1810-197

Kramer et al. [2] present polarization observations of the radio emitting magnetar AXP J1810−197. Its emission is nearly 80-95% polarized. The position angle swing has a low maximal slope $C \leq 1$. Using the first equation from the system (1) or the inequality (11), we conclude that $\beta < 20^0$. Hence, the main suggestion of the drift model is fulfilled for this object. It is nearly aligned rotator with the modulation of emission like presented in Fig. 2. The solution for all parameters by using profiles from [2] is rather uncertain because we don't know a real rotation period of this pulsar and can't calculate precisely the parameters D and C to use the system (1).

Probably there is the bimodality of anomalous pulsars. AXPs, SGRs and some radio transients belong to the population of aligned rotators with the angle between the rotation axis and the magnetic moment $\beta < 20^0$. These objects are described by the drift model, and their observed periods are connected with a periodicity of drift waves. Other sources have $\beta \sim 90^0$, and switching on's and switching off's of their radiation are caused by accretion phenomena connected with a relic (debris) disc surrounding them.

4. COMPACT CENTRAL OBJECTS

CCOs are characterized by stable X-ray fluxes, the typical luminosity $L_X \sim 10^{33}$ эрг/сек, thermal emission, the lack of optical counterparts and the lack of pulsar wind nebula (PWN). The detection of pulsed emission in X-ray from some CCOs shows that we observe the neutron star.

Pulsar J1852+0040 in the SNR Kes79

The period of this pulsar is $P = 0{,}105$ sec, and $dP/dt < 2\ 10^{-16}$ from data obtaining during 2.5 years. Thus the surface magnetic field is rather weak

$$B_s = 6{,}4\ 10^{19}\ (P\ dP/dt)^{1/2} < 3\ 10^{11}\ G$$

The losses of rotational energy

$$dE/dt = I\,\Omega\,d\,\Omega\,/dt < 710^{33}\ erg/sec$$

Using the relationships between radio and optical luminosities and magnetic fields at the light cylinder B_{LC} [18], we obtain the estimates $L_r < 2\ 10^{28}$ erg/sec, $L_{opt} < 10^{28}$ erg/sec.

The qualitative model of the pulsar PSR J1852+0040 can be described as follows. The hot surface of the young neutron star emits the thermal X-ray radiation. The known processes of the creation of electron-positron plasma are taken place higher in the magnetosphere, causing the generation of plasma oscillations and the development of plasma instabilities. The small size of the magnetosphere usual for short periodic pulsars is the reason why the radio emission is generated near the light cylinder only.

Pulsar 1E 1207.4+5209 in the SNR G296.5+10.0

We have for this pulsar $P = 424$ msec , $dP/dt = (6{,}6 \pm 9{,}0)\ 10^{-17}$, $B_s < 6{,}6\ 10^{11}$ G. Spectral lines detected nearly 0,7 and 1,4 keV and possibly at 2,1 and 2,8 keV give $B = 6\ 10^{10}$ G if we assume that they are electron cyclotron lines. So, this source has a small magnetic field at the surface like the PSR J1852+0040.

The small value of $dE/dt < 1{,}3\ 10^{32}$ erg/sec means that for the providing the X-ray luminosity $L_X \approx 2{,}1\ 10^{33}$ erg/sec it is necessary to take into account a neutron star cooling and an accretion from the relic disk.

The particle flux from a pulsar is

$$\frac{dN}{dt} = k\,\frac{\Omega^2\,B_s\,R_*^3}{e\,c}\ sec^{-1}, \qquad (12)$$

where k ~1. This flux will be small for weak magnetic fields B_s.

The wind dynamics and the possibility to observe PWN are determined by the following parameter (see, for example, [19])

$$\sigma = \frac{B^2}{4\ \pi\ m_e\,c^2\,n\,\Gamma}, \qquad (13)$$

where Γ is Lorentz-factor of the wind and n is the particle concentration in the wind. The parameter σ will be small for small values of B_s as well.

Data of catalogue [20] shows that 61 objects from 1511 radio pulsars have surface magnetic fields $B_s < 10^{11}$ G (Fig.4). The time of life for pulsars can be taken of order 10^6 years, for SNRs ~ 10^5 years, and we can expect about 10 CCOs. This estimate is in agreement with the observed number.

The three orders discrepancy between ages of SNRs and characteristic ages of pulsars means that these objects have been born with the modern rotation periods and that the magneto-dipole model of their slowing down is unacceptable.

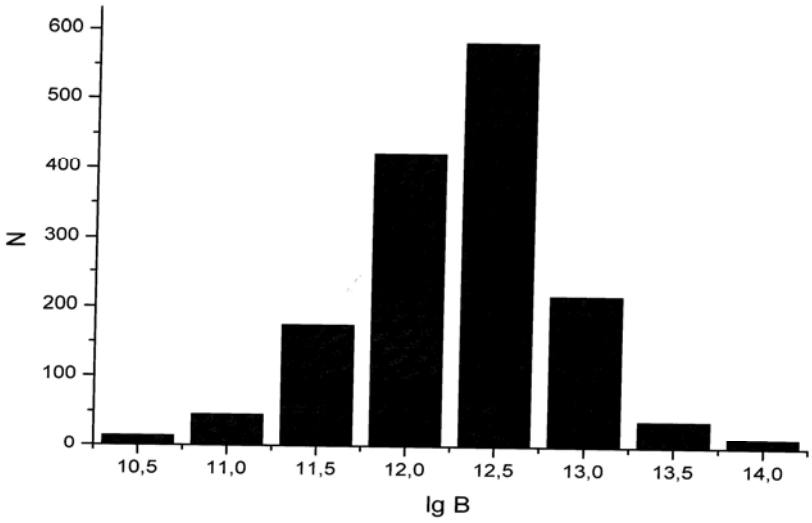


Fig. 4. Distribution of surface magnetic fields for 1511 normal pulsars.

5. XDINS

If a SNR dispersed and became unobservable a host neutron star could be seen as a radio source due to losses of its rotation energy or as an X-ray object due to cooling of this neutron star or accretion from a relic disk. Such an object with a weak magnetic field may be a candidate in XDINS.

Spectral features in the pulsar J214303.7+065419/RBS 1774 [21] and in other similar sources correspond to energies of order hundreds keV. If these features are electron cyclotron lines then magnetic field in the region of their generation is equal to 7,5 10^{10} G for RBS 1774.

Long periods of XDINSs as in the case of AXPs, SGRs and radio pulsars with large periods are explained probably by drift waves, and their rotation periods are much shorter. We believe

these objects must be described by the drift model. To test this expectation it is very important to show that XDINSs are aligned rotators.

6. CONCLUSIONS

1. Anomalous X-ray pulsars and soft gamma-ray repeaters are aligned rotators with rotation periods from milliseconds to 1 sec and surface magnetic fields $B_S \sim 10^{11} - 10^{13}$ G. The observable intervals between pulses in these objects are connected with periods of the drift waves at the periphery of their magnetospheres. In this case the regular modulation of emission is taken place.

2. Radio transients belong to two populations: 1) quasi-periodic emitters, which are probably orthogonal rotators with accretion from equatorial relic disks surrounding them, 2) sources showing episodic pulses with dispersion are aligned rotators which undergo to irregular cataclysms at the surface. They are described by the drift model.

3. Compact central objects in SNRs are sources with weak surface magnetic fields. They emit thermal X-ray radiation from the surface and non-thermal radio emission from the regions near the light cylinder.

4. XDINSs are neutron stars with weak surface magnetic fields. The drift model can be used probably for the description of these objects.

Acknowledgments

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