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The influence of inclination angle on J0901-4046 radiopulsar polar cap heating

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The influence of inclination angle on J0901-4046 radiopulsar polar cap heating by reverse positron current is considered.

Keywords: radiopulsars, neutron stars, positrons.

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Introduction

Radio pulsar J0901-4046 is currently the slowest rotating „normal" radiopulsar known [1]. Its rotation period is $P = 75.89$ s [1,2]. The rate of decrease of its period is $\dot{P} = 2.25 \cdot 10^{-13}$ [1,2], which gives an estimate of the strength of the dipole magnetic field on the surface of the neutron star near the magnetic pole $B_{dip} \approx 2.6 \cdot 10^{14}$ Gs [1,2]. Its characteristic age, estimated by the rate of deceleration, is $\tau \approx 5.3 \cdot 10^{6}$ year [1,2]. An explanation of the operation of the J0901-4046 radiopulsar was proposed in Ref. [3] with the assumption that the standard method for estimating the strength of the dipole field leads to a strong underestimation of its value. Within the framework of the proposed explanation, it was assumed (see Ref. [3,4]) that the radiopulsar is close to orthogonal, i.e., the angle of inclination $\chi \approx 90°$. A similar explanation of the operation of this radiopulsar was proposed in Ref. [5]. However, after a thorough analysis of the radio emission properties of this pulsar, it was shown in Ref. [5] that its tilt angle is actually very small $\chi \approx 10°$, i.e. the pulsar is close to coaxial. At the same time, it was shown in this paper that the strength of the dipole field exceeds the estimate obtained for the deceleration rate $B_{dip} \approx 2.6 \cdot 10^{14}$ Gs [1,2] by almost two orders of magnitude $B_{dip} \gtrsim 2.5 \cdot 10^{16}$ Gs [5]. It is also worth noting that estimating the angle of inclination of χ by the pulse width, when using the approximation of the minimum pulse width taken from Ref. [6], gives for this radiopulsar rather the value of $\chi \sim 40° - 60°$. However, it was recently shown in Ref. [7] that the radio emission properties of long-period radiopulsars have a number of features that significantly distinguish them from other normal radiopulsars. And therefore, it is possible that the use of standard methods for estimating the angle of inclination χ by pulse width, for example [6,8], may be incorrect. In this paper, we continue to develop an alternative model explaining the operation of the J0901-4046 radiopulsar. We assume that the magnitude of its dipole magnetic field corresponds to the value determined by the standard deceleration rate method $B_{diP} \approx 2.6 \cdot 10^{14}$Gs [1,4]. However, we assume that an extremely small-scale magnetic field with a characteristic scale of ~ 500 m and with a strength comparable to a dipole magnetic field is present on the surface of the neutron star.

1. Model

The parameterization of the small-scale field at the surface of a neutron star and the calculation of the heating of the polar cap by the reverse current of positrons, as well as the determination of the number of unbound positrons formed, are done exactly as in Ref. [9]. It is taken into account that in such a strong magnetic field, electron-positron pairs are born in a bound state (positronium). The magnitude of the small-scale field B_{sc} on the surface of a neutron star in the vicinity of the polar cap in this work was considered equal to $B_{sc} = 0.7 \cdot B_{dip}$. This choice of small-scale field strength for the configurations considered in this paper is optimal, providing the largest range of possible other small-scale field configuration parameters at which the pulsar diode operates. In the case of a decrease or increase in its intensity, this area narrows. The radius of the polar cap of pulsar J0901-4046 $r_{pc} = r_{ns} \cdot \sqrt{\Omega\, r_{ns}/c} \cdot \sqrt{B_{dip}/B_{surf}}$ it is only $r_{pc} \sim 14$ m for $B_{sc} = 0.7 \cdot B_{dip}$, where r_{ns} is the radius of the neutron star, B_{surf} is the magnetic field strength on the surface of the neutron star and $\Omega = 2\pi/P$ is its angular velocity of rotation. Even in the best considered case $\delta = 0.04 \cdot r_{ns}$ (for a description of this small-scale field configuration parameter, see [9]), photons from the hot polar cap produce less than 10 % of the total number of photoionized positronium. Therefore, in this paper, as in Ref. [9], we will neglect their contribution to the photoionization of positronium and assume that all positronium is ionized by thermal radiation from the surface of a neutron star. In this case, for simplicity, we neglect the possible annihilation of positronium, which corresponds to the case of $f = 1$ in Ref. [10] (for a description of the designation of f, see Ref. [10]). Unfortunately, the surface temperature

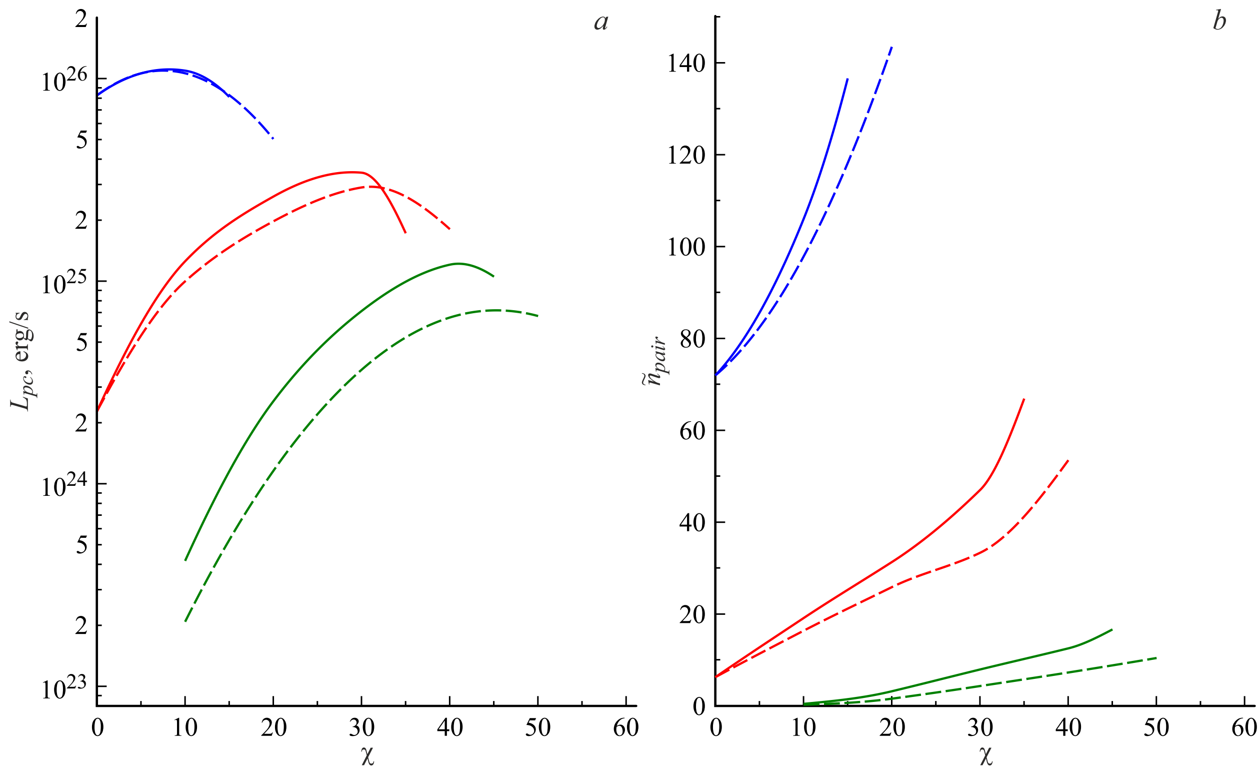

Figure 1. a — dependence of the rate of heating of the polar cap by the reverse current of positrons L_{pc} on the angle of inclination of the radiopulsar χ for the case of the temperature of the star $T_{surf} = 10^6$ K. b — a similar dependence for the concentration of formed unbound electron-positron pairs n_{pair}. The value L_{pc} is given in erg/s, the value n_{pair} in units of $(\Omega B)/(2\pi ce)$, the angle of inclination χ is in degrees. The green curves correspond to the configuration of the small-scale magnetic field, for the case $\delta = 0.02 \cdot r_{ns}$, red curves correspond to the case $\delta = 0.03 \cdot r_{ns}$ and blue curves correspond to the case $\delta = 0.04 \cdot r_{ns}$. The solid curves correspond to the case $\phi_\Omega = 0$, the dashed curves correspond to the case $\phi_\Omega = \pi/5$(for a description of the notation, see Ref. [9]).

T_{surf} of the neutron star of pulsar J0901-4046 has not been measured at present. Only the upper limit for the total X-ray luminosity is known $L_X \lesssim 3.2 \cdot 10^{30}$ erg/s [1]. Therefore, in this paper we consider $T_{surf} = (1{-}3) \cdot 10^5$ K as possible temperature values, which does not contradict this limit. This choice of temperature range was motivated by the fact that radiopulsar B0950+08 has a characteristic age of $\tau \approx 17.5 \cdot 10^6$ year [2], i.e. it can be expected that its actual age is comparable to that of pulsar J0901-4046. At the same time, the surface temperature of the neutron star $T_{surf} = (1-3) \cdot 10^5$ K is known for it [11]. Therefore, we can well expect a similar surface temperature for the neutron star pulsar J0901-4046. Based on this, in this paper we have considered 3 possible temperature values $T_{surf} = 1, 2$ and $3 \cdot 10^5$ K.

2. Results

Fig. 1–3 shows the dependences of the heating of the polar cap of the pulsar L_{pc} by the reverse current of positrons flowing through the diode of the inner gap and the concentration of the formed unbound electron-positron pairs n_{pair} on the angle of inclination of the radiopulsar χ. Fig. 1 corresponds to the case when the surface temperature of a neutron star is $T_{surf} = 1 \cdot 10^5$ K, Fig. 2 corresponds to the case $T_{surf} = 2 \cdot 10^5$ K, Fig. 3 corresponds to the case $T_{surf} = 3 \cdot 10^5$ K. The value L_{pc} is defined as the amount of energy per unit time that is transmitted to the polar cap by the reverse current positrons hitting its surface. The concentration of electron-positron pairs n_{pair} is calculated at high altitudes, where pair generation has already stopped and there is no reversal of positrons. It is shown in dimensionless units $\tilde{n}_{pair}$, where $n_{pair} = \tilde{n}_{pair} \cdot (\Omega B)/(2\pi ce)$ and B is the magnetic field strength. It is worth noting that in the region where pairs are no longer being born and the reversal of positrons has practically stopped, the value of $\tilde{n}_{pair}$ will be constant along the magnetic field lines. At the same time, of course, the concentration of n_{pair} pairs decreases with increasing altitude above the star's surface as the magnetic field strength decreases B. It can be seen from the drawings that while the inner gap is working, the heating of the polar cap by the reverse current of positrons is practically independent of the neutron star surface temperature T_{surf} . On the contrary, the number of unbound pairs formed n_{pair} depends very strongly on the surface temperature. So, for the case of $\delta = 0.04 \cdot r_{ns}$, a decrease in the temperature of the star from $T_{surf} = 3 \cdot 10^6$ to 10^6 K leads to a decrease in the number of pairs by 3 times (for

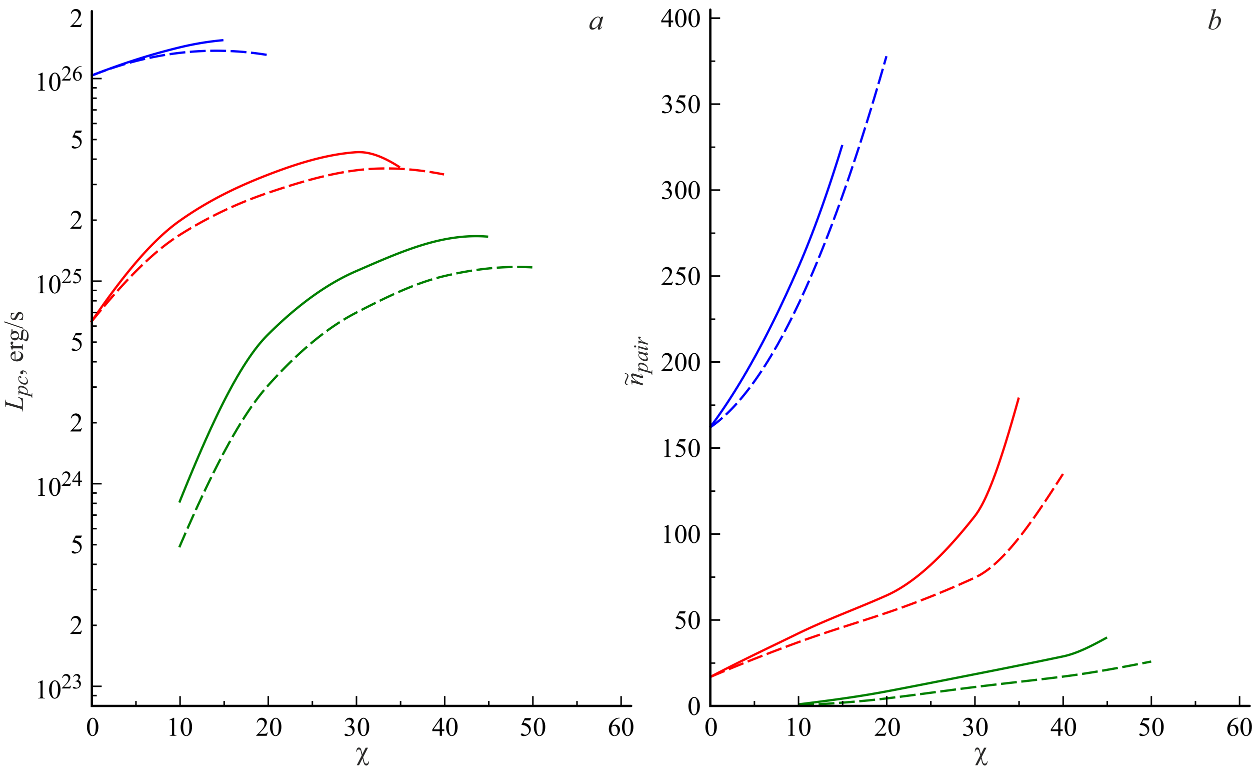

Figure 2. The same as in Fig. 1, but for the case $T_{surf} = 2 \cdot 10^6$ K.

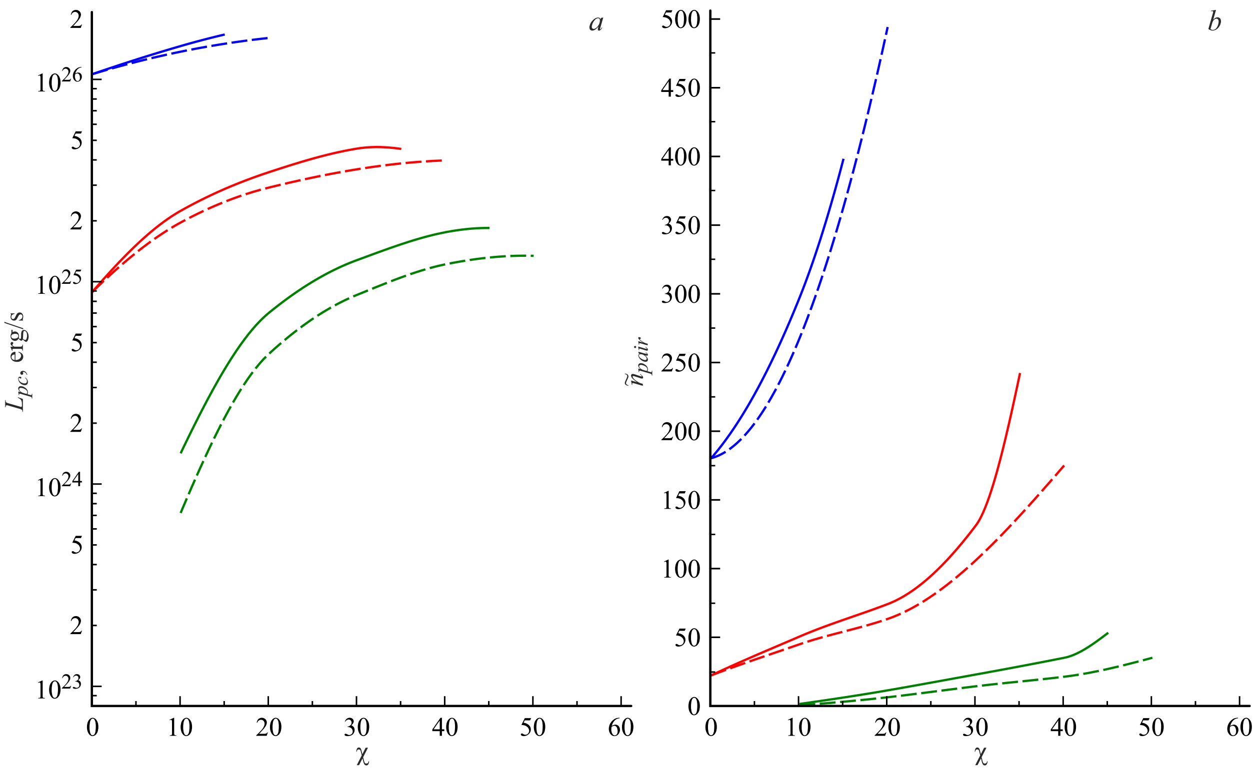

Figure 3. The same as in Fig. 1, but for the case $T_{surf} = 3 \cdot 10^6$ K.

a description of the designation δ, see Ref. [9]). However, it is worth noting that the concentration of thermal X-ray photons from the star near the surface of the polar cap drops by 27 times. And, therefore, we can say that

„the efficiency of photoionization" of pairs increases by almost an order of magnitude. It is also worth noting that the heating of the polar cap L_{pc} and the number of unbound pairs n_{pair} depend much more strongly on the configuration of the small-scale magnetic field than on the surface temperature (Fig. 1–3). At $\chi < 10^\circ$, $\delta = 0.02 \cdot r_{ns}$ and all the temperatures considered, the radiopulsar J0901-4046 is turned off because the intensity of pair generation is very low $\tilde{n}_{pair} \lesssim 10^{-2}$.

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Conflict of interest

The authors declare that they have no conflict of interest.

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