Effect of the small-scale field on the heating of the polar cap of the radio pulsar J0901-4046

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The effect of a small-scale magnetic field on the heating of the polar cap of the pulsar J0901-4046 by the reverse current of positrons is considered. It is shown that under some configurations of a small-scale field, the luminosity of its polar cap can reach 10^{25} erg/s.

Keywords: Radio pulsars, neutron stars, positrons.

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Introduction

Radio pulsar J0901-4046 — the slowest known radio pulsar [1]. Its rotation period P is only $P = 75.89$ s [1]. Estimation of its magnetic field from $\dot{P} = 2.25 \cdot 10^{-13}$ gives the value of the dipole magnetic field B_{dip} at the magnetic pole $B_{dip} = 2.6 \cdot 10^{14}$ G [1], while its characteristic age $\tau = P/2\dot{P}$ is $\tau = 5.3 \cdot 10^6$ year, rotational energy loss $\dot{E} = 2.0 \cdot 10^{28}$ erg/s [1]. The distance D to it is either 328 pc or 467 pc [1]. Such pulsars lie below the „off line" and are usually explained by the presence of a small-scale component of the magnetic field on the surface of the neutron star, see e.g., [2–5]. In this paper, we consider the effect of a small-scale field on the heating of the polar cap of this pulsar.

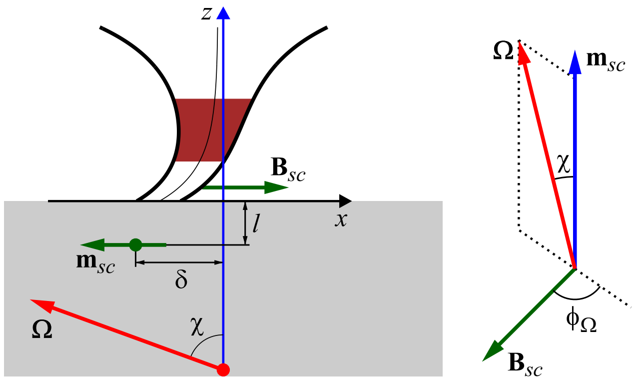

Figure 1. Schematic representation of a pulsar tube. The direction of angular velocity Ω is shown by a red arrow (in the online version), χ — the angle of the pulsar, the brown area (in the online version) shows the location of the pulsar diode.

1. Model

The magnetic field near the magnetic pole of the pulsar is modeled using a two-dipole model [3]:

$$B(x) = \frac{3x(x \cdot m) - mr^2}{r^5} + \frac{3r_{sc}(r_{sc} \cdot m_{sc}) - m_{sc} r_{sc}^2}{r_{sc}^5}, \quad (1)$$

where $r = |x|$ — is the distance from the center of the star, the plane $z = 0$ corresponds to the surface of the neutron star, z — the height above the surface of the star, $m = me_z$ — is the dipole magnetic moment of the star, $B_{dip} = 2m/r_{ns}^3$, $r_{sc} = x + \delta r_{ns} e_x - (r_{ns} - \ell)e_z$, $B_{sc} = 2m_{sc}/\ell^3$ is the strength of the small-scale magnetic field at the magnetic pole of the star, Fig. 1. In this paper we have limited ourselves to the case of $\ell = r_{ns}/20$. The angle of inclination of the radio pulsar χ Fig. 1 was assumed to be $\chi = 30°$. The pulsar was considered in a model of the polar cap with a steady state charge limited flow of electrons from the surface of the star. The generation of electron-positron pairs was calculated in the same way as in the paper [6]. At the same time, it was considered that the pairs are born in a bound state (positronium), which are then ionized by thermal radiation from the surface of the star. The photoionization rate parameter W_0 was assumed to be $W_0 = 6 \cdot 10^5\,\mathrm{s}^{-1}$, see [6,7]. In order to estimate the possible effects of photon splitting and positronium annihilation, we assumed that only a fraction of f pairs were photoionized, and the remaining $(1 - f)$ pairs were annihilated immediately after formation. The surface temperature of the star T_{surf} was thought to be $T_{surf} = 3 \cdot 10^5$ K.

2. Results

Fig. 2 shows the effect of a small-scale field on the luminosity of the polar cap L_{tot}. The heating of the polar cap was calculated in the scope of the „model of rapid screening", see the calculation details in [8]. Figure 3 shows the number of electron-positron pairs formed n_{pair} in units $(\Omega B_{dip})/(2\pi ce)$, where $\Omega = 2\pi/P$ is the angular velocity of rotation of the star. In the case $\phi_\Omega = 0$, $\delta = 0.01$ at $f = 1$ the pulsar is on the verge of shutting down

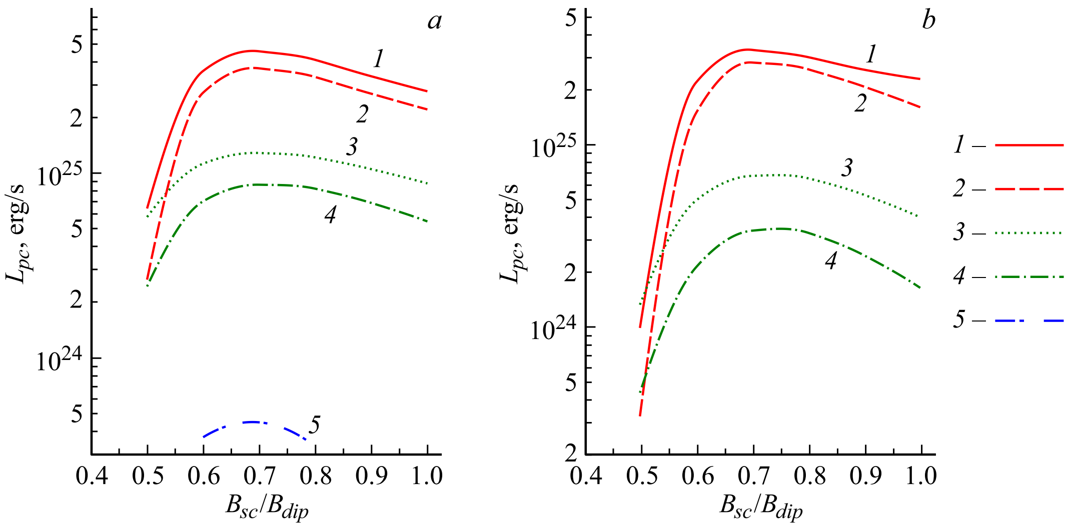

Figure 2. The luminosity L_{tot} of the polar cap is shown due to its heating by reverse current positrons for various small-scale field configurations. a — corresponds to the case $f = 1$, b — $f = 0.1$. *1* — $\delta = 0.03$, $\phi_\Omega = 0$, *2* — $\delta = 0.03$, $\phi_\Omega = 0.2\pi$, *3* — $\delta = 0.02$, $\phi_\Omega = 0$, *4* — $\delta = 0.02$, $\phi_\Omega = 0.2\pi$, *5* — $\delta = 0.01$, $\phi_\Omega = 0$.

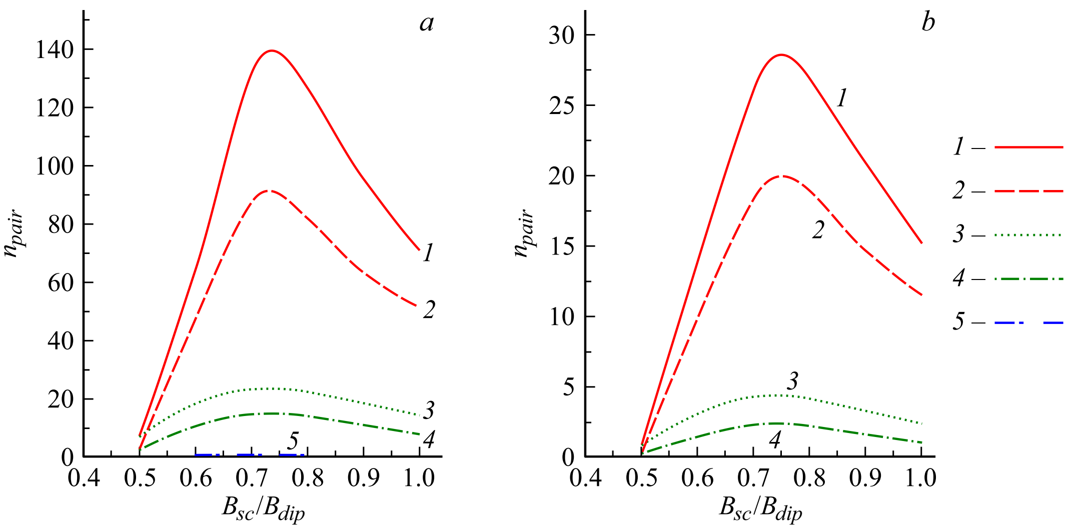

Figure 3. Same as Fig. 2, but for the number of electron-positron pairs formed n_{pair} in units $(\Omega B_{dip})/(2\pi ce)$. *1* — $\delta = 0.03$, $\phi_\Omega = 0$, *2* — $\delta = 0.03$, $\phi_\Omega = 0.2\pi$, *3* — $\delta = 0.02$, $\phi_\Omega = 0$, *4* — $\delta = 0.02$, $\phi_\Omega = 0.2\pi$, *5* — $\delta = 0.01$, $\phi_\Omega = 0$.

$n_{pair} \sim 0.2(\Omega B_{dip})/(2\pi ce)$, at $f = 0.1$ it is already off. In the present paper, we hypothesized that the neutron star has a surface temperature of $T_{surf} = 3 \cdot 10^5$ K and a noticeable small-scale field with a scale of $\ell \sim 1$ km, even though its age is $\tau = 5.3 \cdot 10^6$ year. First, it is worth noting that the older pulsar B0950+08 with an age of $\tau = 17.5 \cdot 10^6$ year has a star surface temperature of $T_{surf} = (1 - 3) \cdot 10^5$ K [9]. Second, the star may have been further heated by the rotochemical mechanism [10] or, like perhaps J0250+5854, the pulsar J0901-4046 has recently passed through the Hall attractor stage [11], during which, in particular, its small-scale field may have formed. In addition, it is possible that its real age is not so great, and is only $\sim 10^3 - 10^5$ year [12], so the star may simply not have had time to cool down, and the small-scale field may have noticeably disintegrated. In this paper, we assumed that the angle of inclination of the pulsar is $\chi = 30°$, which is not much different from the $\chi = 10°$ value used in the paper. However, if in the paper [5] it is assumed that the dipole magnetic field is 2 orders of magnitude higher than the estimate [1], reaching the values of $B_{dip} \sim 3 \cdot 10^{16}$ G on the surface of the star, then in this paper we were able to show that in order to preserve the work of J0901-4046, we can do with only doubling the surface field. At the same time, it should be noted that in our explanation, unlike the one proposed in the paper [5], there are still problems associated with the suppression of the generation of electron-positron pairs due to the splitting of photons in a strong magnetic field.

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Conflict of interest

The authors declare that they have no conflict of interest.

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