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HIGH-ENERGY ASTROPHYSICS AND COSMOLOGY

The Influence of Star Surface Temperature on Inner Gap of Radio Pulsar J0901-4046

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Abstract—The influence of neutron star surface temperature outside polar cap on pulsar diode of radio pulsar J0901-4046 is considered. It is shown that the influence of the star surface temperature on the polar cap heating by backflowing reverse positrons is small, but number density of electron-positron pairs photoionized by thermal photons from star surface strongly depends on the star surface temperature outside polar cap.

Keywords: neutron star, radio pulsar

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1. INTRODUCTION

Radio pulsar J0901-4046 is the slowest known rotating-powered radio pulsar at present [1]. Its rotation period is $P = 75.89$ s [1, 2]. The period derivative is equal to $\dot{P} = 2.25 \times 10^{-13}$ [1, 2]. And hence its characteristic age estimated as $\tau = P/2\,\dot{P}$ is equal to $\tau \approx 5.3 \times 10^{6}$ years [1, 2]. The dipolar magnetic field strength at magnetic pole calculated by using $\dot{P}$ may be estimated as $B_{\rm dip} \approx 2.6 \times 10^{14}$ G [1, 2]. Using these parameters it easy to see that this pulsar is far beyond "death line" [3]. The explanation of its work has been proposed in [4]. In the paper [4] it is assumed that J0901-4046 radio pulsar is close to orthogonal, i.e., $\chi \approx 90°$, where χ is angle between magnetic dipolar momentum $\vec{m}$ and rotation axis, see Fig. 1, and has a strong dipolar magnetic field which is much stronger than dipolar magnetic field value $B_{\rm dip} \approx 2.6 \times 10^{14}$ G estimated by $\dot{P}$ [4, 5]. The similar explanation has been proposed in [6]. But in the paper [6] it has been shown by using radio and other observation data that this pulsar is almost aligned $\chi \approx 10°$ and that its dipolar magnetic field strength is $B_{\rm dip} \gtrsim 2.5 \times 10^{16}$ G. In this paper we use the alternative model, considered, for example, in [7]. Accordingly this model we assume that the estimation of dipolar magnetic field $B_{\rm dip} \approx 2.6 \times 10^{14}$ G by $\dot{P}$ is right, but the neutron star has a strong small scale surface magnetic field with characteristic scale length $\ell = 500$ m. Also we accept the result of [6] that the pulsar is close to aligned and $\chi = 10°$. Also it is worth to note that accordingly the used model the pulsar diode is considered as inner gap in steady state with space-charge limited flow [7].

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2. MODEL

In this paper we use the same model of small scale magnetic field as in [7] and, correspondingly, suppose that the surface magnetic field $\vec{B}$ nearby polar cap may be modeled by two-dipole model [8]:

$$\vec{B} = \frac{1}{r^3} \cdot \left(3\,\vec{x}\,(\vec{x}\cdot\vec{m}) - \vec{m}\,r^2\right) + \frac{1}{\rho^3} \cdot \left(3\,\vec{\rho}\,(\vec{\rho}\cdot\vec{m}_{\rm sc}) - \vec{m}_{\rm sc}\,\rho^2\right), \qquad (1)$$

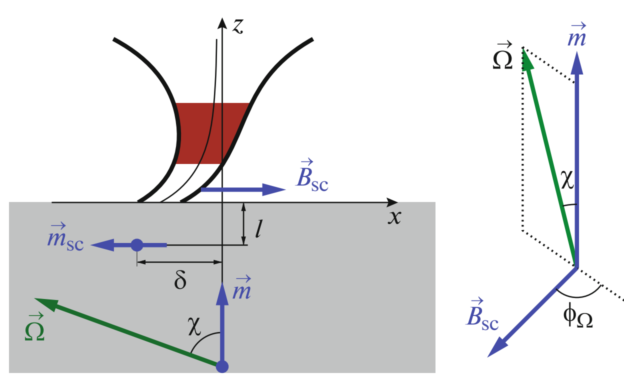

Fig. 1. A sketch of the vicinity of the polar cap. Neutron star is shown by gray area, pulsar tube boundaries are shown by black lines and the pulsar diode is shown by brown area.

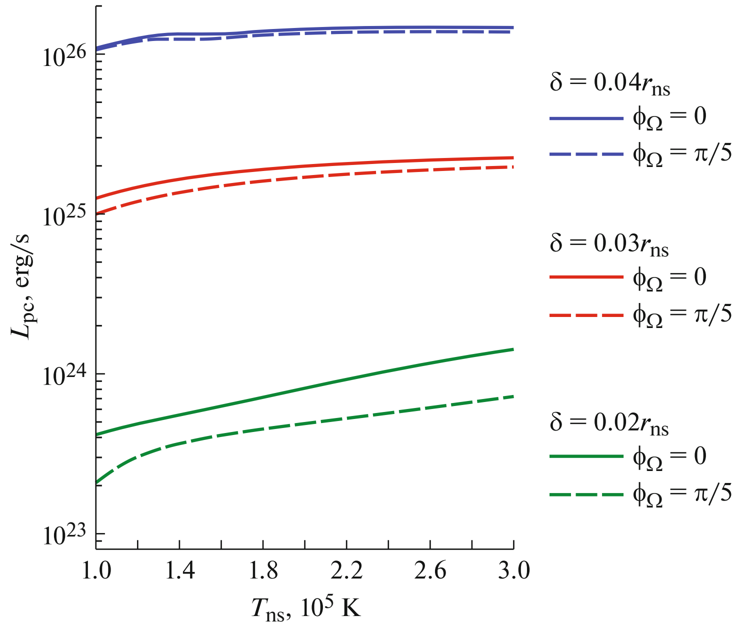

Fig. 2. The dependence of the polar cap heating L_{pc} on the surface neutron star temperature T_{ns} is shown. Green lines correspond to $\delta = 0.02r_{ns}$, red lines correspond to $\delta = 0.03r_{ns}$ and blue lines correspond to $\delta = 0.04r_{ns}$. The solid lines correspond to $\phi_\Omega = 0$ and dashed lines correspond to $\phi_\Omega = \pi/5 \approx 36°$, see Fig. 1.

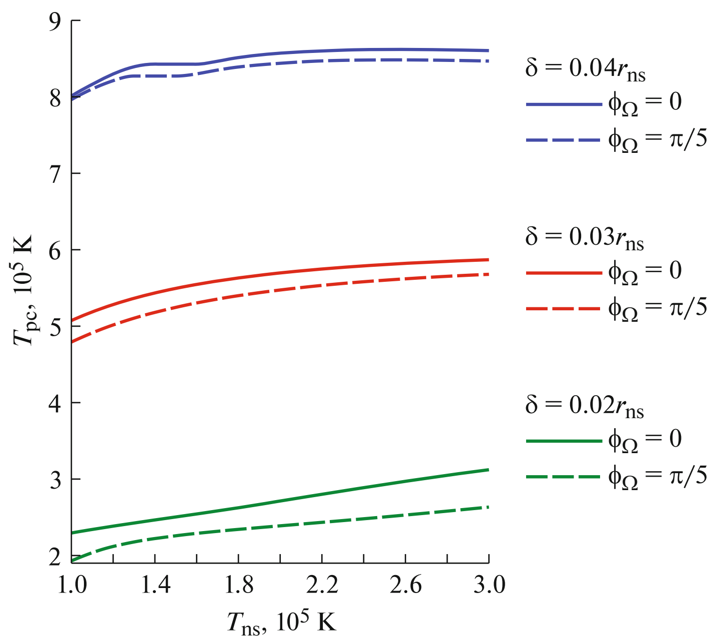

Fig. 3. The same as in figure but the dependence of "polar cap temperature" T_{pc} on surface neutron star temperature T_{ns} is shown.

where $r = |\vec{x}|$ is the distance from star center, the plane $z = 0$ corresponds to the star surface, $\vec{m} = m\,\vec{e}_z$ is dipolar magnetic moment of neutron star, $B_{dip} = 2m/r_{ns}^3$, r_{ns} is the neutron star radius, $\vec{\rho} = \vec{x} + \delta\,\vec{e}_x - (r_{ns} - \ell)\,\vec{e}_z$, $\rho = |\vec{\rho}|$, $\vec{m}_{sc} = -m_{sc}\,\vec{e}_x$, $B_{sc} = 2m_{sc}/\ell^3$ and ℓ is the characteristic length of the small scale magnetic field, see Fig. 1. In this paper we assume $\ell = 500$ m. Also the positron production is calculated by the same way as in [7]. In this paper we restrict self only the case of $B_{sc} = 0.7B_{dip}$. It seems the most optimal value in the case of considered model because of the decreasing or increasing of field B_{sc} decreases the range of other small scale magnetic field parameters used in our model at

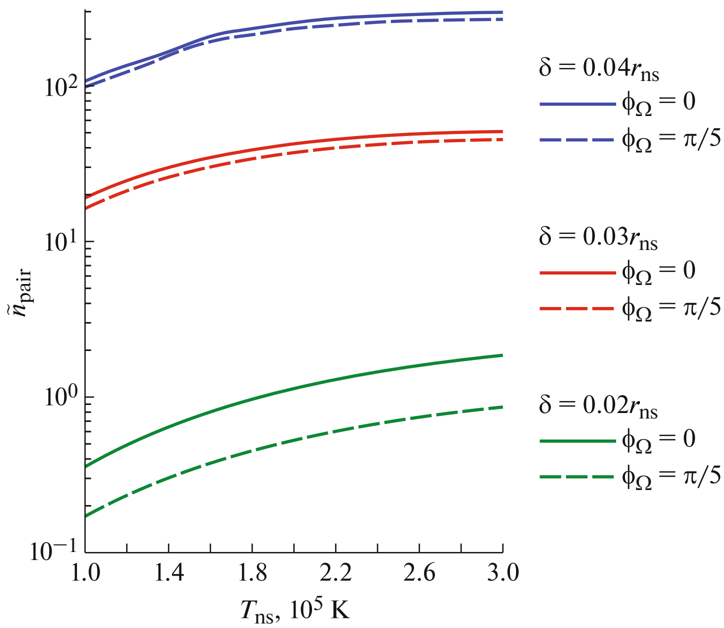

Fig. 4. The same as in Fig. 2 but the dependence of dimensionless photoionized positrons number density $\tilde{n}_{\text{pair}}$ on surface neutron star temperature T_{ns} is shown.

which radio pulsar works. It is necessary to note that the surface magnetic field B_{surf} is very strong $B_{\text{surf}} \sim 3 \times 10^{14}$ G, so all electron-positron pairs are produced in bound state (positronium). Accordingly to the used model the pulsar diode operates in regime of space-charge limited flow of electrons from polar cap surface. Consequently, the diode electric field is too weak to destroy positroniums. The polar cap radius is equal to $r_{\text{pc}} = r_{\text{ns}}\sqrt{\Omega\, r_{\text{ns}}/c}\,\sqrt{B_{\text{dip}}/B_{\text{surf}}} \approx$ 14 m, where $\Omega = 2\pi/P$ is angular velocity of neutron star, so hot polar cap is highly small and hence thermal photons from polar cap are too not enough to photoionize sufficient quantity of positroniums. So in this paper we assume that all positroniums are photoionized by thermal radiation from whole neutron star surface, as well as in [7]. Unfortunately, the neutron star surface temperature T_{ns} of radio pulsar J0901-4046 is not known at present. Only upper limit on its X-ray luminosity L_X is known: $L_X < 1.6 \times 10^{30}$ erg/s or $L_X < 3.2 \times 10^{30}$ erg/s [1]. So in this paper we assume that its surface temperature T_{ns} lies in interval $T_{\text{ns}} \approx (1-3) \times 10^5$ K. It is enough high surface temperature in the case of so old radio pulsar $\tau \approx 5.3 \times 10^6$ years. However, it is worth to note that radio pulsar B0950+08 has characteristic age $\tau \approx 17.5 \times 10^6$years [2] but its observed surface temperature is $T_{\text{ns}} \approx (1-3) \times 10^5$ K [9].

3. RESULTS

The dependence of the polar cap heating L_{pc} by reverse positron current on star surface temperature T_{ns} is shown in Fig. 2. The polar cap heating L_{pc} is calculated as simple total energy flux carried through the polar cap surface by backflowing positrons inside pulsar diode. The dependence of corresponding "polar cap surface temperature" T_{pc} on star surface temperature T_{ns} is shown in Fig. 3. The "'polar cap surface temperature" T_{pc} is calculated as $L_{\text{pc}} = \sigma_{\text{B}} T_{\text{pc}}^4 S_{\text{pc}}$, where σ_{B} is Boltzmann constant and S_{pc} is area of polar cap. The dependence of dimensionless photoionized pair number density $\tilde{n}_{\text{pair}}$ on star surface temperature T_{ns} is shown in Fig. 4. The number density n_{pair} of pair photoionized by thermal photon from star surface (with assumed temperature T_{ns}) is equal to $n_{\text{pair}} = \tilde{n}_{\text{pair}}(\Omega\, B)/(2\pi c e)$, where B is strength of magnetic field. The shown value $\tilde{n}_{\text{pair}}$ is calculated at enough large altitude above star surface where pairs are not already produced and positrons are not reversed by electric field. In this case the value $\tilde{n}_{\text{pair}}$ is constant along magnetic field lines and does not depend on altitude above star surface. Although, of course, the number density n_{pair} decreases with the increasing of the altitude due to the corresponding decreasing of magnetic field strength B. It is easy to see that the polar cap heating L_{pc} does almost not depend on star surface temperature T_{ns} at least the pulsar diode continues to work. But in contrast the pair number density n_{pair} highly depends on star surface temperature T_{ns}. Although it is worth to note that the decreasing of star surface temperature T_{ns} in 3 times from 3×10^5 K to 10^5 K leads to the decreasing of the pair number density n_{pair} only in 3 times although thermal photon number density nearby star surface decreases in 27 times. So we can conclude that "photoionization effectiveness" by thermal photons increases in 9 times. Also it worth to note that the total polar cap heating $L_{\rm pc}$ is small and $L_{\rm pc} < 2 \times 10^{26}$ erg/s in the best case $\delta = 0.04 r_{\rm ns}$. In the last case the polar cap surface temperature $T_{\rm pc}$ may achieve value $T_{\rm pc} \approx 8.5 \times 10^5$ K. But even in this best case due to very small polar cap radius photons from relatively hot polar cap give less than 10% of all photoionized electron–positron pairs. In the case of $\delta = 0.02 r_{\rm ns}$ the "polar cap temperature" $T_{\rm pc}$ is formally less than the surface star temperature $T_{\rm ns}$. It only means that the energy flux to polar cap surface from pulsar diode is less than the energy flux from star interior. And hence the input of photons from polar cap into positronium photoionization is negligible.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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