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MODELING OF THE SURFACE MAGNETIC FIELD IN PULSARS

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RESUMEN

Proponemos un modelo que explica la emisión térmica de rayos X observada en la superficie de las estrellas de neutrones (pulsares). Las características de tal radiación nos permite obtener una gran cantidad de información acerca de la region polar de los pulsares, donde se cree que se genera la radiación térmica de rayos X. El modelo requiere de la existencia de un campo magnético fuerte, superficial y no dipolar. Proveemos de un formalismo numérico para modelar tales estructuras en la superficie estelar y para calcular los parámetros básicos que pueden ser ajustados a los datos de las observaciones. Se supone que la fuente de actividad del pulsar está asociada con la región justo por encima de la zona polar donde el campo eléctrico tiene una componente a lo largo de las líneas del campo magnético. Las partículas (electrones y positrones) son aceleradas en ambas direcciones: hacia afuera y hacia la superficie estelar. Las partículas que fluyen de regreso calientan la superficie y proveen la energía necesaria para la emisión térmica. Se discuten varias configuraciones posibles del campo magnético superficial y se demuestra que el modelo permite, naturalmente, interpretar las observaciones.

ABSTRACT

We propose a model that explains the observed thermal X-ray emission from the surface of neutron stars (pulsars). Characteristics of such radiation allow us to get a lot of in-formation about the polar cap region of the pulsars, where the thermal X-ray radiation is believed to be generated. The model requires existence of a strong and non-dipolar surface magnetic field. We provide a numerical formalism for modeling such structures at the stellar surface and calculating the basic parameters that can be fitted to the observational data. We assume that the source of the pulsar activity is associated with the region just above the polar cap where the electric field has a component along the magnetic field lines. The particles (electrons and positrons) are accelerated in both directions: outward and toward the stellar surface. The back-streaming particles heat the surface and provide necessary energy for the thermal emission. We discuss various possible configurations of the surface magnetic field and demonstrate that the model naturally allows interpretation of observations.

Key Words: pulsars: general — stars: neutron — X-rays: stars

1. INTRODUCTION

Thermal X-ray emission seems to be a quite common feature of the radio pulsars. On the other hand characteristics of such radiation allow us to get a lot of information about the polar cap region of the pulsars. The standard model of the radio pulsars assumes that there exists the Inner Acceleration Region (IAR) above the polar cap where the electric field has a component along the magnetic field lines. The bundle of magnetic field lines that originate from the polar cap crosses the light cylinder and leaves the magnetosphere. The magnetospheric emission (both high energy and radio) should be generated in the region of open field lines, while the thermal emission should be radiated from the polar cap surface. The particles (electrons and positrons) are accelerated in both directions: outward and to-ward the stellar surface. Consequently, out-streaming particles generate the magnetospheric (radio and high-frequency) emission while the back-streaming particles heat the surface and provide necessary energy for the thermal emission. In such a scenario X-ray diagnostics seems to be an excellent method to get insight into the most intriguing region of the neutron star

2. THE MODEL

As soon as we can fit the X-ray spectrum of the pulsar to the black body spectra, we can estimate the temperature $T_{\rm BB}$ of the hot spot and its area $A_{\rm BB}$, as the distance to the pulsar is usually known. It is natural to assume that the hot spot coincides with the polar cap, rather than only a small part of it contributes to the bolometric emissivity. Assuming that the pulsar magnetic field is dipolar we can easily estimate the polar cap size as $A_{\rm pc} = 6.6 \times 10^8 P^{-1}$ cm^2 (P is a pulsar period in s) and the magnetic field strength as $B_d = 2 \times 10^6 (P\dot{P}_{15})^{0.5}$ G ($\dot{P}_{-15} =$

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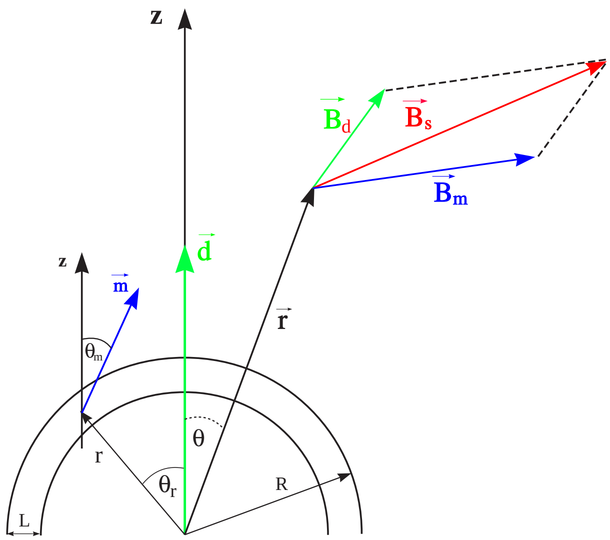

Fig. 1. Superposition of the star centered global magnetic dipole $\vec{b}$ and crust anchored local dipole $\vec{m}$ placed at $r_s = (r_s \sim R; \theta = \theta_r)$ and inclined to the z-axis by an angle θ_m. The actual surface magnetic field at the variable point described by the radius vector $\vec{r} = (r; \theta)$ is $\vec{B}_s = \vec{B}_d + \vec{B}_m$, where $\vec{B}_d = 2\vec{d}/r^3$, $\vec{B}_m = 2\vec{m}/|\vec{r} - \vec{r}_s|$, r is the radius (altitude) and θ is the polar angle (magnetic co-latitude). R is the radius of the neutron star and L is the crust thickness.

$\dot{P}\times 10^{15}$ is the time derivative of the period in 10^{-15}). However, observations suggest that in most cases $A_{\rm BB}$ is much less than the conventional polar cap area $A_{\rm pc}$. It can be easily explained by assuming that the surface magnetic field of pulsars differs significantly from the pure dipole one. Then, one can estimate an actual surface magnetic field by the magnetic flux conservation law $b = A_{\rm BB}/A_{\rm pc} = B_d/B_s$ as

$$B_s \simeq 1.3 \times 10^{21} A_{\rm BB}^{-1} \left(\frac{\dot{P}_{-15}}{P}\right)^{0.5} \;[\mathrm{G}]\,. \qquad (1)$$

In most cases $b \sim 10 - 60$, which implies $B_s \sim (2-6)\times 10^{13} \gg B_d$, while $T_{\rm BB} \sim (2-4)\times 10^6$ K (Zhang, Sanwal, & Pavlov 2005; Kargaltsev, Pavlov, & Garmire 2006). Therefore it seems to be well-founded that the surface magnetic field differs essentially from the dipolar one. The stronger magnetic field implies also stronger curvature of the filed lines, which is a very important factor for the pair creation process.

In order to sketch configuration of the field lines and estimate their curvature radius we use the following model. We assume that the actual surface magnetic field is a composition of the star centered dipole field and a few arbitrary oriented crust anchored local dipoles (see Gil, Melikidze, & Mitra 2002). The model is schematically illustrated on Figure 1.

3. THE PARTIALLY SCREENED GAP

The rotating neutron star with such a huge magnetic field also generates a huge electric field in the vicinity of the object. If there is no charge just above the polar cap the parallel (with respect to the magnetic field) component of the electric field can be estimated as $E_{||}| \sim 10^{-3}(B_s/P)$ V/m. At the polar cap region there is a thin inner acceleration region, with an acceleration length scale much shorter than the polar cap size. The accelerating potential drop discharges via a number sparks. So called primary particles are accelerated in the gap and while moving along the curved field lines they radiate high energy photons. The photons are absorbed by the strong magnetic field creating the secondary particles electrons and positrons. Back-streaming relativistic charges deposit their kinetic energy in the polar cap surface and heat it. For such a scenario Gil, Melikidze, & Geppert (2003) have suggested the model for the inner acceleration region, which assumes that the gap operates in such a way that surface temperature always stays near the certain, unambiguously defined by the surface magnetic field, value, near the so called critical temperature Ti. The model is called as the Partially Screened Gap (PSG) model, be-cause it assumes that the potential drop near the stellar surface is partially screened by the positive ions. In order to estimate Ti we need to know the cohesive properties of the surface matter. This problem has been recently examined by Medin & Lai (2006, 2007). They have estimated the critical temperature of the neutron star's iron crust and derived the dependence of $T_i = T_i(B_s)$. Let us stress once more that according to the PSG model the hot spot temperature always should be very near to the critical temperature $T_{\rm BB} = T_i$. Therefore while fitting the hot spot BB spectra $A_{\rm BB}$ and $T_{\rm BB}$ should not be treated as an independent parameters. The pulsars, which X-ray spectra can be fitted to the black body emission from the hot spot should obey the $T_i = T_i(B_s)$ dependence. Assuming $T_i = T_{\rm BB}$ we can demonstrate this dependence for a given pulsar if we rewrite the function $T_i = T_i(B_s)$ as

$$T_{\rm BB} \simeq F\left(P, \dot{P}_{-15}, A_{\rm BB}\right)\,. \qquad (2)$$

In Figure 2 the dependance described by equation (2) is plotted by the solid red line for the following pulsars: PSRs B1133+16, B0943+10, B0628-28,

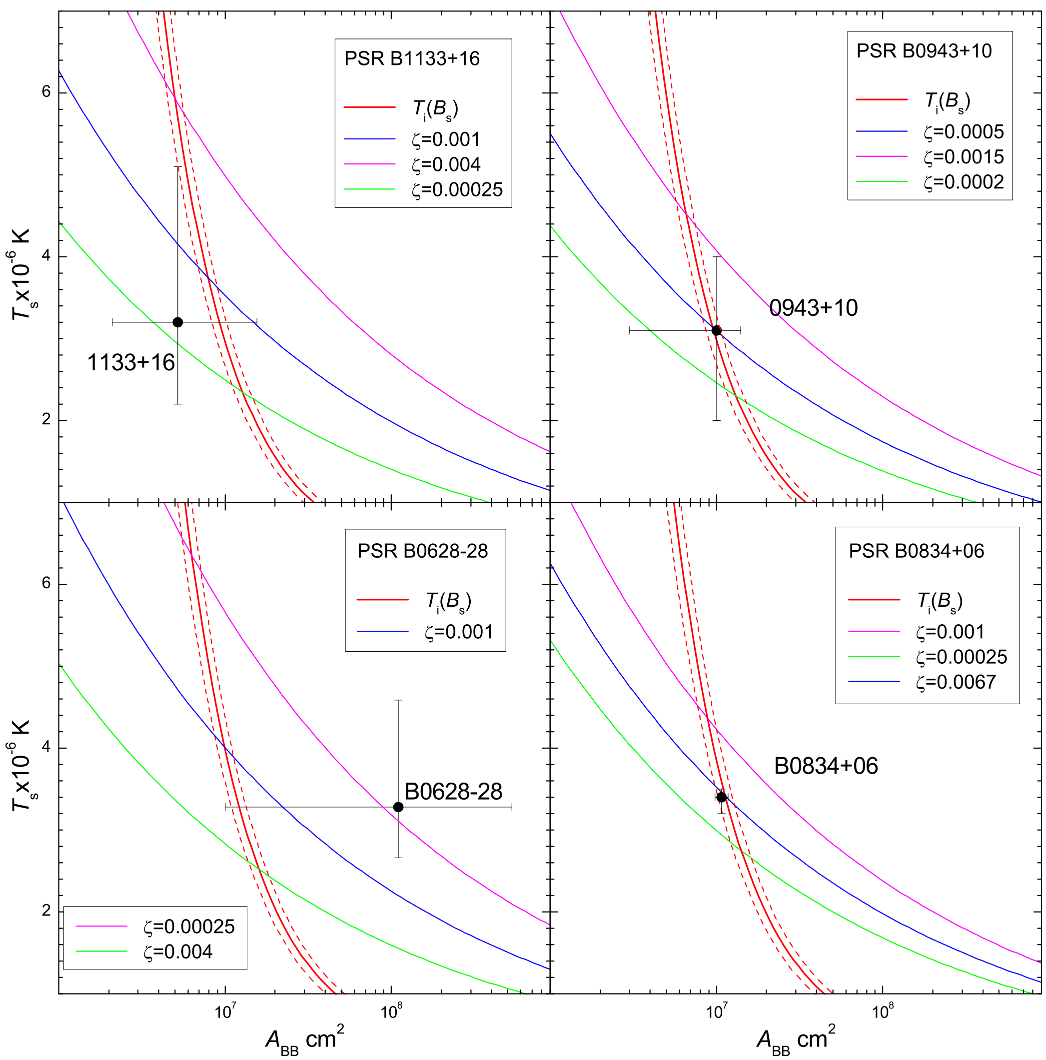

Fig. 2. The dependence of $T_{\rm BB} = T_{\rm BB}(A_{\rm BB})$ for 4 pulsars is shown (the solid red lines). The lines of the constant bolometric luminosity are plotted as blue, magenta and green lines. The black circles with error bars show the observed (for PSRs B1133+16, B0943+10 and B0628-28) and predicted (for PSR B0834+06) black body spectra fitting parameters.

B0834+06. The dashed red lines corre-spond to uncertainty in estimation of the critical temperature. We can also estimate the X-ray luminosity that follows from our model as

$$L_X \simeq a A_{\rm BB} \sigma T_{\rm BB}^4 \,, \qquad (3)$$

and its efficiency as

$$\zeta = \frac{L_X}{L_{\rm SD}} \,. \qquad (4)$$

$L_{\rm SD} = 3.9 \times 10^{31} P^{-3} \dot{P}_{-15}$ erg s^{-1} is called pulsar spin-down energy loss rate. One can see from Figure 2 that observations are in satisfactory agreement with the model.

The model can also explain the case of PSR J1119-6127. The X-ray observations of this pulsar showed quite unusual features of this pulsar. As it was demonstrated by Gonzalez et al. (2005) the XMM-Newton observations denote the thermal feature of the pulsed X-ray emission from this pulsar. The derived characteristics of the black body fit are as follows: $A_{\rm BB} = 3.6^{+4.9}_{-0.6} \times 10^{13}$ cm^2 and $T_{\rm BB} = 2.4^{+0.3}_{-0.2} \times 10^6$ K. The X-ray flux is estimated as $L_X = 2.0^{+2.5}_{-0.4} \times 10^{33}$ erg s^{-1}. Let us note that both $A_{\rm BB}$ and L_x depend on the distance estimation, which for this pulsar is estimated as $D = (8.4 \pm 0.4)$ kpc, while Cordes-Lazio NE2001 (2002) Electron Density Model suggests the distance

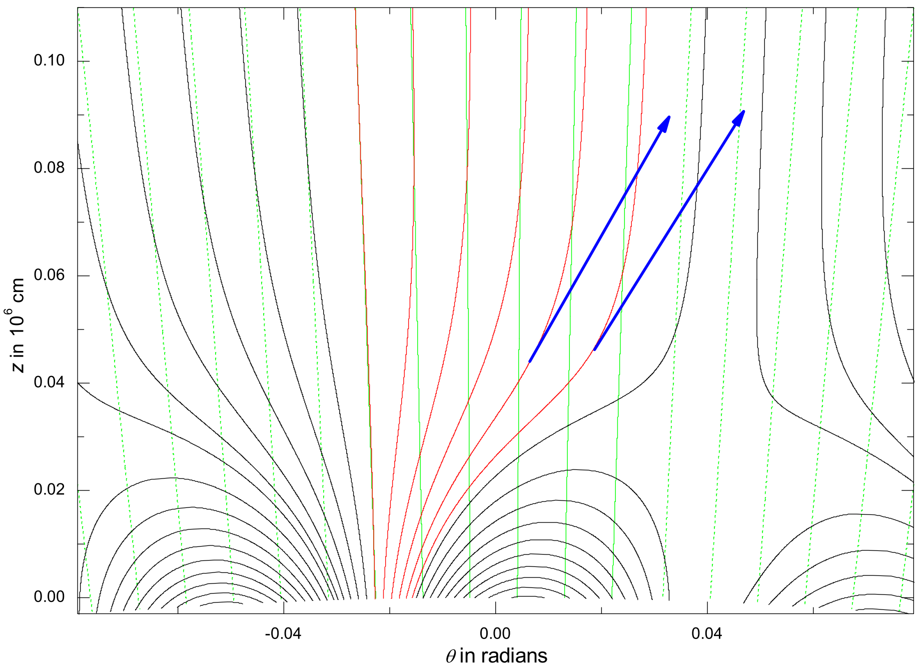

Fig. 3. Cartoon of the magnetic field lines in the polar cap region. There are three crust anchored magnetic anomalies in this case: the central one is aligned with the global dipole, while two others are directed to the opposite direction. Distances between the local dipoles are about 500 meters. The green lines represent open (solid) and closed (dashed) field lines the pure dipole filed. The red lines correspond to the open field lines, which at high altitudes coincide with the dipole field lines. θ is the magnetic co-latitude in radians.

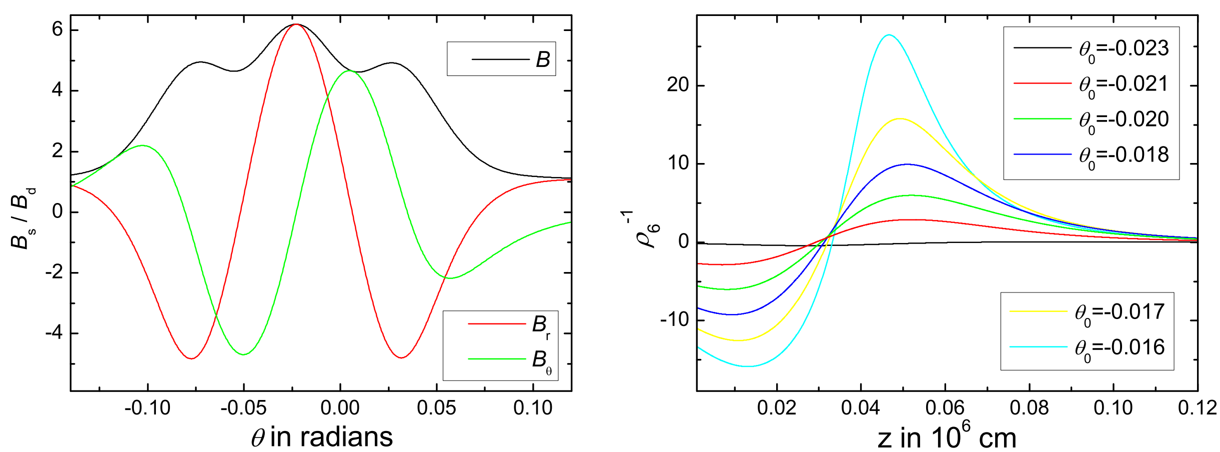

Fig. 4. The surface magnetic field components (left panel) and curvature of the field lines (right panel) at the stellar surface. The curvature is measured in units of 10^6 cm^{-1}.

estimate as $D = 17$ kpc, $(10 < D < 50)$. Therefore, if the distance is underestimated the flux as well as $A_{\rm BB}$ is even larger. The spin-down energy loss of this pulsar is $L_{\rm SD} = 2.3 \times 10^{35}$ erg s^{-1} and the conventional polar cap area is about $A_{\rm pc} = 1.6 \times 10^9$ cm^2. As we see the efficiency of X-ray emission defined as $\xi = L_x/L_{\rm SD} \sim 0.009$ is of the same order of magnitude as it is for other pulsars, while the hot spot area $A_{\rm BB}$ exceeds $A_{\rm pc}$ about 2×10^3 times.

4. CONCLUSION

We propose the following scenario. The Figures 3 and 4 (right panel) show, that the curvature can change its direction in such a way, that the curvature photons are radiated towards the closed field line region. This is not a particular case but demonstrates quite a general feature of the crust anchored magnetic anomalies. It can be easily understood as the local field has a significant B_θ component, while the dipole field is directed almost along the radius vector. Then in a region where the dipole field becomes significant, the curvature has to be strong and positive (see Figures 3 and 4). When the primary particles reach a region where the curvature of the magnetic field lines is large they radiate curvature photons (in the direction of the blue arrows in Figure 3) which can propagate in the relatively low magnetic field and create pairs in the closed field line region. The localization of the pair creation region depends strongly on the Lorentz factors of the primary particles. Even a small alteration of the Lorentz factor can significantly change the photon free path. In the non-stationary sparking scenario the particles energy changes stochastically, (which is observed as a microstructure of the radio emission). Therefore, in the closed field line region, there can stochastically appear favorable conditions for two-stream instability. Consequently, the resulting radio emission can be directed in different directions. This kind of radio emission can naturally explain existence of RRAT-s.

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