A Model for Pulsed X-Ray Emission from Radio Pulsars

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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. Observations suggest the assumption that the pulsar magnetic field at the stellar surface essentially differs from the pure dipole field. The model assumes that the source of the pulsar activity is associated with the Partially Screened Gap operated in the Inner Acceleration Region 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. Consequently, outstreaming particles generate the magnetospheric X-ray emission while the backstreaming particles heat the surface and provide necessary energy for the thermal emission. We model various possible configurations of the surface magnetic field and demonstrate that the curvature and structure of the field lines can be of the kind that naturally allows interpretation of observations. In some cases the curvature photons can be absorbed in the region of the closed field lines. The created pairs propagate along the closed field lines and heat the stellar surface near the local poles. Then the estimated area of the X-ray emitting hot spot can be even bigger then the conventional dipolar polar cap surface, which are the cases of PSRs J1119-6127 and B0656+14

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 particles (electrons and positrons) are accelerated in both directions: outward and toward the stellar surface. Consequently, outstreaming particles generate the magnetospheric (radio and high-frequency) emission while the backstreaming 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.

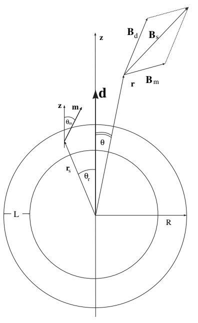

Fig.1. Superposition of the star centered global magnetic dipole ***b*** and crust anchored local dipole ***m*** placed at $\boldsymbol{r}_s=(r_s\sim R;\ \theta=\theta_r)$ and inclined to the z-axis by an angle θ_m. The actual surface magnetic field at radius vector $\boldsymbol{r}=(r;\ \theta)$ is $\boldsymbol{B}_s=\boldsymbol{B}_d+\boldsymbol{B}_m$,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

The black body fit allows us to obtain directly the bolometric size $A_{\rm bol}$ and temperature T_s of the polar cap. In most cases $A_{\rm bol}$ is much less than the conventional polar cap area. 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 as $b=A_{\rm bol}/A_{\rm pc}=B_d/B_s$. Here $B_d=2\times10^{12}\left(P\dot{P}_{15}\right)^{1/2}$, P is the pulsar period in seconds and $\dot{P}_{15}=\dot{P}\times10^{15}$ is the period derivative. In most cases $b\sim10-60$, which implies $B_s\gg B_d$, while $T_s\sim(2-4)\times10^6$ K.

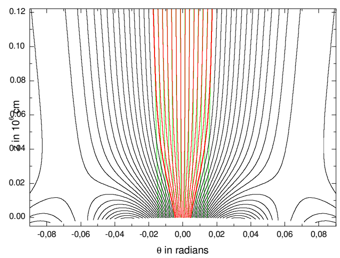

Fig.2 Cartoon of the magnetic field lines in the polar cap region. There are three crust anchored magnetic anomalies in this case: the central one is aligned with the global dipole, while two others are directed to the opposite direction. Distance between the local dipoles is 500 meters. The green lines represent the pure dipole filed. The red lines correspond to the last open field lines, which at high altitudes coincide with the dipole field lines. θ is the magnetic co-latitude in radians.

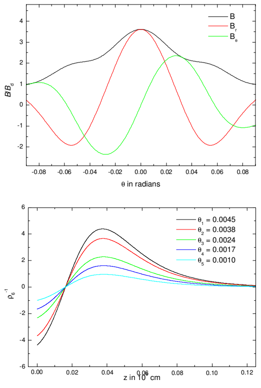

Fig.3 The surface magnetic field components (left panel) and curvature of the field lines (right panel) at the stellar surface. The field is measured in units of the

The X-ray observations of PSR J1119-6127 showed quite unusual features of this pulsar. As it was demonstrated by Gonzalez et al. (2005, ApJ, 630, 489) 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: $A_{\rm bol}=3.6^{+4.9}_{-0.6}\times10^{13}$ cm^2 and $T_s=2.4^{+0.3}_{-0.2}\times10^6$ K. The X-ray flux is estimated as $L_x=2.0^{+2.5}_{-0.4}\times10^{33}$ erg/s. Let us note that both $A_{\rm bol}$ and L_x depend on the distance estimation, which for this pulsar is estimated as $D=(8.4\pm0.4)$ kpc, while Cordes-Lazio NE2001 (2002) Electron Density Model suggests the distance estimate as $D=17$ kpc, $(10<D<50)$. Therefore, if the distance is underestimated the flux as well as $A_{\rm bol}$ are even larger. The spin-down energy loss of this pulsar is $L_{\rm sd}=2.3\times10^{35}$ erg/s and the conventional polar cap area is about $A_{\rm pc}=1.6\times10^9$ cm^2. As we see the efficiency of X-ray emission defined as $\xi=L_x/L_{\rm sd}\sim0.009$ is of the same order of magnitude as it is for other pulsars, while the bolometric area $A_{\rm bol}$ exceeds $A_{\rm pc}$ 2×10^3 times.

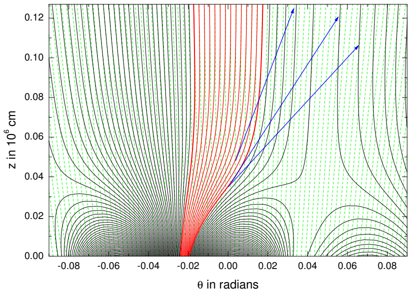

Fig.4 Cartoon of the magnetic field lines in the polar cap region in the asymmetric case. Red lines are open field lines and green dotted lines correspond to the dipole field. The blue lines show direction of the curvature photons emission.

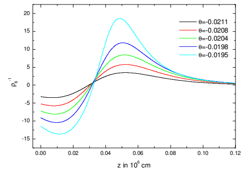

Fig. 5 The curvature of the open field lines at the altitude about 600 m from the stellar surface (see Fig.4).

The figs. 2 and 4 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 Fig. 5).

We propose the following scenario. At the polar cap region there 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. These sparks produce columns of electron-positron plasma, penetrated by the energetic particles, so called primary particles. When the primary particles reach a region where the curvature of the magnetic field lines is large they radiate curvature photons 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 γ 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.