Non-Dipolar Surface Magnetic Field of Neutron Stars: General Approach and Observational Consequences

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It is widely accepted that the magnetic field structure near the surface of neutron stars may significantly differ from the pure star centered dipole structure. We have modeled different possible configurations and found out that for some configurations the pair creation is possible not only along the open field lines, but also in the region of closed field lines. Therefore, in this case, we can naturally explain some peculiarities of pulsar activities, such as unusual thermal x-ray emission, reversible radio emission and rotating radio transients.

The pairs created along the closed field lines can easily reach the stellar surface near the polar cap at the opposite side of the neutron star and heat the surface area that can even exceed than the shrunk polar cap size.

In the frame of this model, we can easily realize the configuration, which allows the pair creation near both polar caps (along the same field). In this case, two streams of the pair plasma penetrate each other creating a favorable condition for the two-stream instability to be developed. Such a process can lead to the radio emission generation, either in quasi-stationary or stochastic process. Consequently, either quasi-stationary reversible radiation, or stochastic emission of the transients can be observed

Thermal X-ray emission seems to be a quite common feature of the radio pulsars. On the other hand characteristics of such radiation allows us to get a lot of information about the polar cap region of the pulsars. 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.

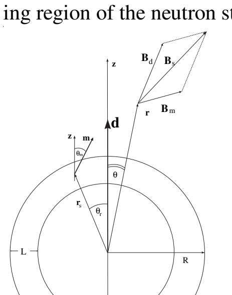

Fig.1. Superposition of the star centered global magnetic dipole $\boldsymbol{b}$ and crust anchored local dipole $\boldsymbol{m}$ placed at $r_s=(r_s\sim R;\ \theta=\theta_l)$ and inclined to the z-axis by an angle θ_m. The actual surface magnetic field at radius vector $\boldsymbol{r}=(r;\ \theta)$ 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 colatitude). R is the radius of the neutron star and L is the crust thickness.

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The black body fit allows us to obtain directly the bolometric size A_{bol} and temperature T_s of the polar cap. In most cases A_{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 $b=A_{bol}/A_{pc}=B_d/B_s$. 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. Recently Gil, Melikidze & Zhang (arXiv:astro-ph/0512653, arXiv:astro-ph/0601613) have shown that the model of the Partially Screened Gap (PSG) can interpret the observational data not only qualitatively but also quantitatively.

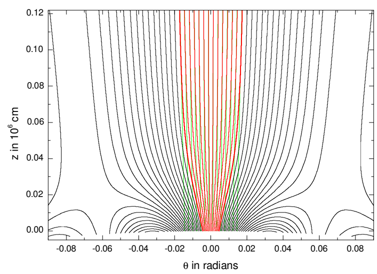

Fig.2 Cartoon of the magnetic field lines in the polar cap region. There are three crust anchored magnetic anomalies in this case: the central one is aligned with the global dipole, while two others are directed to the opposite direction. Distance between the local dipoles is 500 meters. The green lines 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 colatitude in radians.

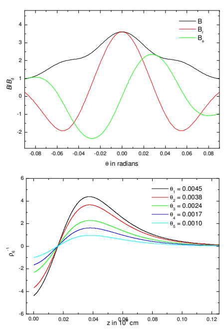

Fig.3 The surface magnetic field components (upper panel) and curvature of the field lines (lower panel) at the stellar surface. the field is measured in units of the

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: $A_{bol}=3.6^{+4.9}_{-0.6}\times10^{13}$ 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_{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_{bol} are even larger. The spin-down energy loss of this pulsar is $L_{sd}=2.3\times10^{35}$ erg/s and the conventional polar cap area is about $A_{pc}=1.6\times10^9$ cm^2. As we see the efficiency of X-ray emission defined as $\xi=L_x/L_{sd}\sim0.009$ is of the same order of magnitude as it is for other pulsars, while the bolometric area A_{bol} exceeds A_{pc} 2×10^3 times.

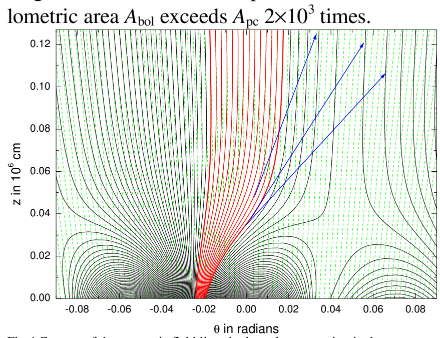

Fig.4 Cartoon of the magnetic field lines in the polar cap region in the asymmetric case. Red lines are open field lines and green dotted lines correspond to the dipole field. The blue lines show direction of the curvature photons emission.

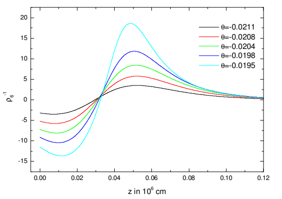

Fig. 5 The curvature of the open field lines at the altitude about 600 m from the stellar surface (see Fig.4).

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).

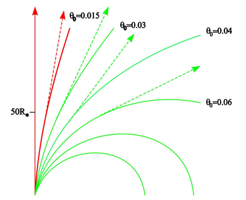

Fig. 6 Cartoon of the field lines in the radio wave generation region. The red line shows the last open field line. θ_0 indicates the magnetic colatitude of the corresponding filed lines at the stellar surface. The dotted lines show the direction of the radio wave emission (red lines correspond to the normal direction, while green lines show direction of the stochastic emission)

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 a different directions (see Fig.6). This kind of radio emission can naturally explain existence of RRAT-s.