Thermal X-ray Emission from Hot Spot in Radio Pulsars with Drifting Subpulses

Janusz Gil and George I. Melikidze,

Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265, Zielona Góra, Poland.

We consider the problem of the thermal X-ray radiation from the hot polar cap of radio pulsars showing evidence of ExB subpulse drift in radio band. Using the partially screened gap (PSG) model of the inner acceleration region we derived a simple relationship between the drift rate of subpulses observed in a radio-band and the thermal X-ray luminosity from polar caps heated by the spark-associated back-flow particle bombardment. This relationship reflects the fact that both the drift rate and the polar cap heating rate are determined by the same value of the gap electric field. The theoretical formula can be tested for pulsars in which the so-called carousel rotation time P_4 of the ExB plasma drift (time interval after which sparks complete one full revolution around the polar cap), and the thermal X-ray bolometric luminosity L_x from the hot polar cap are known. They are currently four pulsars in which both quantities P_4 and L_x are measured or at least estimated: PSRs B0943+10, B1133+16, B0656+14 and B0628-28. They all seem to fully confirm the predictions of the PSG model.

It is widely believed that drifting subpulses and/or phase stationary amplitude modulation correspond to circulation of the radiation sub-beams around the pulsar beam axis. Indeed, in some cases one can identify low frequency features corresponding to the time interval P_4 after which the non-corotating plasma completes one full circulation. This period (called carousel rotation time) is of the order of ten pulsar periods. Shorter periodicities P_3 of the order of few to several pulsar periods correspond to vertical drift-band separation. The number of sub-beams on the wheel is $N = P_4 / P_3$. If the subpulse associated subbeams are produced by sparking discharges of the inner accelerator potential drop, then one should expect an intense thermal radiation from hot polar cap. Indeed, the cascading production of electron-positron plasma is crucial for limitation of growing gap potential drop above the polar cap. The accelerated positrons will leave the acceleration region, while the electrons will bombard the polar cap surface, causing heating of the polar cap surface to MK temperatures as well as thermal ejection of ions. These ions will cause a partial screening of the potential drop, which can be described as $\Delta V = \eta(2\pi)/cP)B_s h^2$, where h is the height of the acceleration region, $\eta = 1 - \rho_i / \rho_{GJ}$ is a shielding factor and ρ_i is charge density of ejected ions.

The actual potential drop ΔV above the polar cap should be thermostatically regulated and the quasi-equilibrium state should be established, in which heating due to electron bombardment is balanced by cooling due to thermal radiation. The quasi-equilibrium condition is $Q_{cool} = Q_{heat}$, where $Q_{cool} = \sigma T_s^4$ is a cooling power surface density by thermal radiation from the polar cap surface and $Q_{heat} = \gamma m_e c^3 n$ is heating power surface density due to back-flow bombardment, $\gamma = e\Delta V / m_e c^2$ is the Lorentz factor, $n = n_{GJ} - n_i = \eta n_{GJ}$ is the number density of back-flowing plasma particles depositing their kinetic energy at the polar cap surface, n_i is the charge number density of thermionic ions. It is straightforward to obtain an expression for the quasi-equilibrium surface temperature in the form $T_s = (6.2 \times 10^4\,\mathrm{K})(\dot{P}_{-15}/P)^{1/4}\eta^{1/2}b^{1/2}h^{1/2}$. The parameter b is described below. Following Ruderman & Sutherland (1975, ApJ 196, 51) one can calculate the tangent electric field at the polar cap boundary, where $\Delta E = 0.5\Delta V / h = \eta(\pi / cP)B_s h$. Due to the $\mathbf{E}\times\mathbf{B}$ drift the discharge plasma performs a slow circumferential motion with the velocity $v_d = c\Delta E / B_s = \eta\pi h / P$. The time interval to make one full revolution around the polar cap boundary is $P_4 \approx 2\pi r_p / v_d$. Therefore, the "carousel" periodicity in units of basic pulsar period is

$$P_4 / P = r_p / 2\eta h. \tag{1}$$

Since the screening factor is of the order of 0.1 (Gil, Melikidze & Geppert, 2003, A&A 407, 315), then the carousel periodicity is of the order of tens of pulsar periods, as observed. The X-ray thermal luminosity is

$$L_x = \sigma T_s^4 \times \pi r_p^2 = 1.2 \times 10^{32}(\dot{P}_{-15}/P^3)(\eta h / r_p^2) \text{ erg/s},$$

which can be compared with the spin-down power

$\dot{E} = I\Omega\dot{\Omega} = 3.95 I_{45} \times 10^{31}\,\dot{P}_{-15}/P^3$ erg/s. Using equation (1) we can derive the thermal X-ray luminosity as

$$L_x = 2.5 \times 10^{31}(\dot{P}_{-15}/P^3)(P/P_4)^2, \tag{2}$$

or in the simpler form representing the efficiency with respect to the spin-down power

$$L_x / \dot{E} = 0.63(P/P_4)^2, \tag{3}$$

which is useful for comparison with observations. The above equations express the fact that both the drifting rate and the heating rate are caused by the same electric field. They contain only radio and X-ray data. It is particularly interesting that they do not depend on any details of the acceleration region like, polar cap radius, gap height, screening factor or properties of the surface magnetic field. Using eq. (1) we can write T_s as

$$T_s = (5.1 \times 10^6\,\mathrm{K})\mathrm{b}^{1/4}\,\dot{P}_{-15}^{1/4}\,P^{-1/2}(P_4/P)^{-1/2}, \tag{4}$$

where $A_{pc} = \pi r_{pc}^2$ and $A_{bol} = A_p$ is the actual emitting surface area (bolometric), the enhancement coefficient $b = B_s/B_d \approx A_{pc}/A_{bol}$. Since A_{bol} can be determined from the black-body fit to the spectrum of the observed hot-spot thermal X-ray emission, the above equation, similarly to eq. (3), depends only on combined radio and X-ray data.

Table 1 presents the data for three pulsars, which we believe show clear evidence of thermal X-ray emission from the polar caps as well as they have known values of tertiary subpulse drift periodicity. The predicted value of P_4 and/or L_x were computed from eqs. (2) and (3), while the predicted values of T_s were computed from eq. (4), with $b = A_{pc}/A_{bol}$ determined observationally.

PSR B0943+10. This is the best studied drifting subpulse radio pulsars with $\dot{E} = 10^{32}$ erg/s, $P_3 = 1.86P$, $P_4 = 37.4P$ and $N = P_4/P_3 = 20$ (Deshpande & Rankin 1999, ApJ 524,1008). It was observed by Zhang et al. (2005, ApJ, 624, L109) using *XMM-Newton*, who obtained an acceptable thermal BB fit with bolometric luminosity $L_x = 5^{+0.6}_{-1.6} \times 10^{28}$ erg/s, thus $L_x/\dot{E} = 0.49^{+0.06}_{-0.16} \times 10^{-3}$. The bolometric surface $A_{bol} = 10^7\,[T_s/3 \times 10^6\,\mathrm{K}]^{-4}$ cm^2 ~ $1^{+0.4}_{-0.4} \times 10^7$ cm^2 is much smaller than the conventional polar cap area $A_{pc} = 6 \times 10^8$ cm^2. This all correspond to the best fit temperature T_s~3.1×10^2 K. The predicted value of $L_x/\dot{E}$ calculated from eq.(3) agrees very well with the observational data. The surface temperature T_s calculated from eq. (4) with $b = A_{pc}/A_{bol}$ is also in good agreement with the best fit. Unfortunately, due to poor photon statistics, the spectrum could be equally well represented by the power law model.

PSR B1133+16. This pulsar with $\dot{E} = 9 \times 10^{31}$ erg·s^{-1} is almost a twin of PSR B0943+10. Kargaltsev et al (2006, ApJ, 636, 406) observed this pulsar with *Chandra* and found an acceptable BB fit $L_x/\dot{E} = 0.77^{+0.13}_{-0.15} \times 10^{-3}$, $A_{bol} = 0.5^{+0.5}_{-0.3} \times 10^7$ cm^2 and $T_s \approx 2.8 \times 10^6$ K. These values are also very close to those of PSR B0943+10, as should be expected for twins. Using eq. (3) we can predict $P_4/P = 27^{+5}_{-2}$ for B1133+16. Interestingly, Nowakowski (1996, ApJ 457, 868) obtained fluctuation spectrum for this pulsar with clearly detected long period feature corresponding to about 32*P*. Most recently, Weltevrede et al. (2006a, A&A, 445, 243) found $P_3/P = 3 \pm 2$ and a long period feature corresponding to $(33 \pm 3)P$ in the fluctuation spectrum of PSR B1133+16. We therefore claim that this is the actual tertiary "carousel" periodicity in PSR B1133+16 and show it in Table 1. Again, the small number of photon counts does not allow to differentiate between alternative spectral models, but most likely both thermal and non-thermal components are present.

PSR B0656+14. This is one of the Three Musketeers, in which thermal X-ray emission from hot spot was clearly detected (De Luca et al. 2005, ApJ 623,1051). This is a very bright pulsar with and thus photon statistics is very good. As indicated in Table 1 $L_x = 5.7 \cdot 10^{31}$ erg·s^{-1}. This value, when inserted to eq. (2) or (3) returns predicted value of the carousel rotation period $P_4 = 20.6\,P$. Amazingly, Weltevrede et al. (2006b, astro-ph/0608023) reported recently the periodicity of just 20*P* associated with quasi-periodic amplitude modulation of erratic and strong emission from this pulsar. This must be naturally interpreted as the carousel rotation time. Since there is no doubt about the thermal nature of the X-ray emission as well, we can conclude that our eqs. (2) and (3) received a spectacularly strong confirmation.

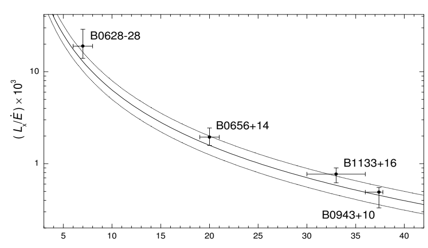

Fig.1. The efficiency of thermal X-ray emission from hot polar cap L_x versus circulation period P_4 of drifting subpulses in the radio band. The solid curve represents the prediction of the PSG model with I_{45} =1, while the dotted curves correspond to uncertainties in determining of the moment of inertia.

PSR B0628-28. This is an exceptional pulsar. Its X-ray luminosity exceeds the maximum efficiency line derived by Possenti et al. (2002) by a large factor. However, one should note that PSR B0943+10, with its luminosity derived from the PL fit, also exceeds this maximum efficiency. The BB efficiency L_X/E~$1.9 \times 10{-}2$ gives the predicted value of $P_4 = (6 \pm 1)P$. It is very interesting that WES06 report the periodicity of (7 ± 1) *P* (see Fig. 1). According to the model expressed by equation (3) this relatively low modulation periodicity (i.e. high modulational frequency) can be interpreted as the circulation time P_4. If this is true then PSR B0628-28 is not an exceptional pulsar at all. It lies on the theoretical curve in Fig. 1 at exactly the right place. This also means that the observed drift is highly aliased in this pulsar, with P_3/P being considerably lower than 2. As concluded by WES06, this might be the case for most pulsars. Therefore, all or most features in modulation spectrum frequencies below about 0.2 cycle/*P* may in fact represent directly the $\boldsymbol{E} \times \boldsymbol{B}$ plasma circulation around the pole rather than the apparent subpulse drift periodicity.