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

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We examine the Partially Screened Gap model of the inner acceleration region, in which ions ejected from the surface by the back-flow bombardment co-exist with the electron-positron plasma produced by sparks discharging the acceleration potential drop. The subpulse drifting phenomenon and the thermal radiation from hot spot associated with the polar cap are naturally accounted for in such model. The partial screening by thermionic ions slows down the drift rate and lowers the heating rate as compared with the pure vacuum gap model. We found the simple relationship between the polar cap 'carousel' time $\hat{P}_3$ and thermal x-ray luminosity from the hot spot, reflecting the fact that both the E×B drift rate and the back-flow heating rate are related to the same electric field. We test our model on PSRs B0943+10, 1133+16 and 0656+14, the only three cases for which measurements/estimates of both $\hat{P}_3$ in radio-band and L_x in X-rays exist. The latter case is particularly important, as there is no doubt about thermal BB character of the hot spot emission. Due to poor photon statistics the radiation detected from the two former cases is consistent with both thermal BB and power law spectra. Most likely, both components are present.

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 $\hat{P}_3$ 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 $N=\hat{P}_3/P_3$. 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 $T_s=(6.2\times10^4\,\mathrm{K})(\dot{P}_{-15}/P)^{1/4}\eta^{1/2}b^{1/2}h^{1/2}$. 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 $\Delta E=0.5\Delta V/h=\eta(\pi/cP)B_s h$. Due to the **E**×**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 $\hat{P}_3\approx 2\pi r_p/v_d$. Therefore, the polar cap "carousel" periodicity in units of basic pulsar period is

$$\hat{P}_3/P=r_p/2\eta h. \qquad (1)$$

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 (see Table 1).

The X-ray thermal luminosity is $L_x=\sigma T_s^4/\pi r_p^2=1.2\times10^{32}(\dot{P}_{-15}/P^3)(\eta h/r_p^2)$ erg/s, which can be compared with the spin-down power $\dot{E}=I\Omega\dot{\Omega}=3.95 I_{45}\times10^{31}\,\dot{P}_{-15}/P^3$ erg/s. Using equation (1) we can derive the thermal X-ray luminosity as

$$L_x=2.5\times10^{31}(\dot{P}_{-15}/P^3)(P/\hat{P}_{-3})^2, \qquad (2)$$

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

$$L_x/\dot{E}=0.63\left(P/\hat{P}_3\right)^2, \qquad (3)$$

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

$$T_s=(5.1\times10^6\,\mathrm{K})\mathrm{b}^{1/4}\,\dot{P}_{-15}^{1/4}\,P^{-1/2}\left(\hat{P}_3/P\right)^{-1/2}, \qquad (4)$$

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 $\hat{P}_3$ 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 radio pulsar showing drifting subpulses, with $\dot{E}=10^{32}$ erg/s, $P_3=1.86P$, $\hat{P}_3=37.4P$ and $N=\hat{P}_3/P_3=20$ (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 the bolometric luminosity $L_x=5^{+0.6}_{-1.6}\times10^{28}$ erg/s, thus $L_x/\dot{E}=0.49^{+0.06}_{-0.16}\times10^{-3}$. The bolometric surface $A_{\rm bol}=10^7\ [T_s/3\times10^6\ \mathrm{K}]^{-4}\ \mathrm{cm}^2\sim 1^{+0.4}_{-0.4}\times10^7\,\mathrm{cm}^2$ is much smaller than the conventional polar cap area $A_{\rm pc}=6\times10^8$ cm^2. This all correspond to the best fit temperature $T_s\sim3.1\times10^2$ 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 $b=A_{\rm pc}/A_{\rm bol}$ 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, weakening slightly our conclusions.

PSR B1133+16. This pulsar with $\dot{E}=9\times10^{31}\,\mathrm{erg\cdot s^{-1}}$ 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 $L_x/\dot{E}=0.77^{+0.13}_{-0.15}\times10^{-3}$, $A_{bol}=0.5^{+0.5}_{-0.3}\times10^7\,\mathrm{cm}^2$ and $T_s\approx 2.8\times10^6$ 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 $\hat{P}_3/P=27^{+5}_{-2}$ for B1133+16. Recently, Weltevrede et al. (2006a, A&A, 445, 243) found $P_3/P=3\pm2$ and a long period feature corresponding to $(33\pm3)P$ 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 $L_x=5.7\cdot10^{31}\,\mathrm{erg\cdot s^{-1}}$. This value, when inserted to eq. (2) or (3) returns predicted value of the carousel rotation period $\hat{P}_3=20.6\,P$. Amazingly, Weltevrede et al. (2006b, astro-ph/0608023) reported recently the periodicity of just $20P$ associated with quasi-periodic amplitude modulation of erratic and strong emission from this pulsar (resembling Q-mode in PSR B0943+10). 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. Of course, all other parameters of the BB fit agree with the observationally deduced values very well.

Name	P	$\dot{P}_{-15}\times10^{15}$	P_3/P	$\hat{P}_3/P$		$L_x/\dot{E}\times10^{-3}$		$L_x\times10^{28}$ erg s^{-1}		b	$T_s\times10^{-6}$		B_d	B_s	d
PSR B	s	s s^{-1}	Obs.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	A_{pc}/A_{bol}	Obs.	Pred	10^{12} G	10^{14} G	kpc
0943+10	1.0997	3.49	1.86	37.4	36	$0.49^{+0.06}_{-0.16}$	0.45	$5.1^{+0.6}_{-1.7}$	4.7	60^{+140}_{-48}	$3.1^{+0.9}_{-1.1}$	$3.3^{+1.2}_{-1.1}$	3.95	$2.37^{+5.53}_{-1.90}$	0.631
1133+16	1.188	3.73	3^{+3}_{-2}	33^{+3}_{-3}	27^{+5}_{-2}	$0.77^{+0.13}_{-0.15}$	$0.58^{+0.12}_{-0.09}$	$6.8^{+1.1}_{-1.3}$	$5.1^{+1.0}_{-0.8}$	$11^{+16.6}_{-5.6}$	$2.8^{+1.2}_{-1.2}$	$2.1^{+0.5}_{-0.4}$	4.25	$0.47^{+0.71}_{-0.24}$	0.350
0656+14	0.285	55.0		20	20.6	1.5	1.6	570	600	0.017	$1.25^{+0.03}_{-0.03}$		9.29		0.288