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X-ray pulsar radiation from polar caps heated by back-flow bombardment

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ABSTRACT

We consider the problem of the thermal X-ray radiation from the hot polar caps of radio pulsars that show evidence of $\boldsymbol{E} \times \boldsymbol{B}$ subpulse drift in radio band. In our recent Paper I, using the partially screened gap (PSG) model of 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 back-flow particle bombardment. This relationship can be tested for pulsars in which the so-called carousel rotation time P_4, reflecting the $\boldsymbol{E} \times \boldsymbol{B}$ plasma drift, and the thermal X-ray luminosity $L_{\rm x}$ from the hot polar cap are known. To test the model we used only two available pulsars: PSRs B0943+10 and B1133+16. They both satisfied the model prediction, although due to low photon statistics the thermal component could not be firmly identified from the X-ray data. Nevertheless, these pulsars were at least consistent with PSG pulsar model.

In this Letter we consider two more pulsars: PSRs B0656+14 and B0628−28, the data for which have recently become available. In PSR B0656+14 the thermal radiation from the hot polar cap was clearly detected, and PSR B0628−28 also seems to have such a component.

In all cases for which both P_4 and $L_{\rm x}$ are presently known, the PSG pulsar model seems to be fully confirmed. Other available models of inner acceleration region fail to explain the observed relationship between radio and X-ray data. The pure vacuum gap model predicts too high $L_{\rm x}$ and too low P_4, while the space charge limited model predicts too low $L_{\rm x}$ and the origin of the subpulse drift has no natural explanation.

Key words: pulsars: general – pulsars: individual: B0628−28 – pulsars: individual: B0656+14 – pulsars: individual: 0943+10 – pulsars: individual: B1133+16 – X-rays: thermal.

1 INTRODUCTION

Although almost 40 years have passed since the discovery of pulsars, the mechanism of their coherent radio emission is still not known. The theory of pulsating X-ray emission also demands further development. The puzzling phenomenon of drifting subpulses is widely regarded as a powerful tool for the investigation of the pulsar radiation mechanism. Recently, this phenomenon received a lot of attention, mostly owing to the newly developed techniques for the analysis of the pulsar radio emission fluctuations (Edwards & Stappers 2002, 2003). Using these techniques, Weltevrede, Edwards & Stappers (2006a, WES06 henceforth) presented the results of the systematic, unbiased search for the drifting subpulses and/or phase stationary intensity modulations in single pulses of a large sample of pulsars. They found that the fraction of pulsars showing evidence of drifting subpulses is at least 55 per cent and concluded that the conditions for the drifting mechanism to work cannot be very different from the emission mechanism of radio pulsars.

It is therefore likely that the drifting subpulse phenomenon originates from the so-called inner acceleration region right above the polar cap, which powers the pulsar radiation. In the classical model of Ruderman & Sutherland (1975, RS75 henceforth) the subpulse-associated spark filaments of plasma circulate in the pure Vacuum Gap (VG) around the magnetic axis due to the $\boldsymbol{E} \times \boldsymbol{B}$ plasma drift. This model is widely regarded as a natural and plausible explanation of the drifting subpulse phenomenon, at least qualitatively. On the quantitative level, this model predicts too high a drifting rate, or too short a period P_4($\hat{P}_3$ in the nomenclature introduced by RS75), of the sparks' circulation around the polar cap, as compared with the observations (e.g. Deshpande & Rankin 1999; DR99 henceforth). Also, the predicted heating rate of the polar cap surface due to the spark-associated back-flow bombardment is too high. The alternative model, namely the space charge limited model (SCLF; e.g. Arons & Sharleman 1979), predicts too low a heating rate and has no natural explanation for the phenomenon of drifting subpulses

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Table 1. The observed and the model parameters for the four pulsars.

Name	a	P_4/P		P_3/P	η		N		$L_x \times 10^{-28}$ (erg s $^{-1}$)	
PSR B		Obs.	Pred.		$P/2\pi P_3$	$aP/2P_4$	$\lfloor P_4/P_3 \rfloor$	$\lfloor \pi a \rfloor$	Obs.	Pred.
$0628-28^a$	7.61	7^{+1}_{-1}	6^{+1}_{-1}	$0.29^{+0.04}_{-0.04}$		$0.54^{+0.09}_{-0.07}$	24^{+8}_{-6}	23	287^{+152}_{-82}	189^{+100}_{-54}
$0656+14^a$	29.1	20^{+1}_{-1}	18^{+2}_{-2}	$0.22^{+0.01}_{-0.01}$		$0.73^{+0.04}_{-0.03}$	90^{+10}_{-8}	91	5700^{+652}_{-561}	6037^{+652}_{-561}
$0943+10$	6.73	$37.4^{+0.4}_{-1.4}$	36^{+8}_{-6}	1.87	0.085	0.09	20^{+1}_{-1}	21	$5.1^{+0.6}_{-1.7}$	$4.7^{+2.0}_{-1.3}$
$1133+16$	6.52	33^{+3}_{-3}	27^{+5}_{-2}	3^{+2}_{-2}	$0.05^{+0.11}_{-0.02}$	$0.10^{+0.01}_{-0.01}$	11^{+25}_{-5}	20	$6.8^{+1.1}_{-1.3}$	$5.3^{+1.1}_{-0.8}$

Note: ^{a}as P_3 was not measured for these two pulsars we used the estimate of η to calculate P_3/P.

(Zhang & Harding 2000; Harding & Muslimov 2002). However, this model has an advantage over the VG model, namely it is free of the so-called binding energy problem, to avoid which the VG model requires an ad hoc assumption of the strong, non-dipolar surface magnetic field (for review and more detailed discussion see Gil & Melikidze 2002).

Motivated by these observational discrepancies of the otherwise attractive VG model, Gil, Melikidze & Geppert (2003; GMG03 henceforth) further developed the idea of the inner acceleration region above the polar cap by including the partial screening caused by the thermionic ions flow from the surface heated by sparks. We call this kind of the inner acceleration region the 'partially screened gap' (PSG henceforth).[1] Because the PSG potential drop is much lower than that in the RS75 model, the intrinsic drift rate P_4 is compatible with the observations. This is a consequence of the reduced potential drop, partially screened by the thermionic ion flow from the polar cap surface. In the pure vacuum RS75 gap, the heating of the polar cap is definitely too intense (e.g. Zhang, Harding & Muslimov 2000; Zhang, Sanwal & Pavlov 2005; ZSP05 henceforth). On the other hand, the SCLF model predicts too low a heating rate as compared with observations (Zhang & Harding 2000; Harding & Muslimov 2002). Thus, by measuring the thermal X-ray luminosity from heated polar caps one can potentially reveal the nature of the inner acceleration region in pulsars. This can also help one to understand a mechanism of drifting subpulses, which appears to be a common phenomenon in radio pulsars.

ZSP05 were the first to attempt to test different available models of the inner acceleration region in pulsars, using a concept of the polar cap heated by the back-flow particle bombardment. They observed the best-studied drifting subpulse radio pulsar PSR B0943+10 with the *XMM–Newton* observatory and argued that the detected X-ray photons were consistent with PSG formed in the strong, non-dipolar magnetic field just above the surface of a very small and hot polar cap. Recently Gil, Melikidze & Zhang (2006a,b; hereafter Papers I and II, respectively) developed a detailed model for the thermal X-ray emission from radio drifting pulsars. They applied their model to PSR B0943+10 as well as to PSR B1133+16, which was observed in X-rays with the *Chandra* observatory by Kargaltsev, Pavlov & Garmire (2006, KPG06 henceforth). These authors found that this case is also consistent with the thermal radiation from a small hotspot, much smaller than the canonical polar cap. PSR B1133+16 is almost a twin of PSR B0943+10 in terms of P and $\dot{P}$ values and, interestingly, both pulsars have very similar X-ray signatures, in agreement with the PSG model (see Table 1 and Fig. 1).

The PSG model can be tested if two observational quantities are known: (i) the circulational period P_4 for drifting subpulses observed in the radio band (also called the pulsar carousel time) and (ii) the X-ray luminosity L_x of thermal black-body (BB) radiation from the hot polar cap (see equations 2 and 3 below). The above mentioned observations of PSRs B0943+10 and B1133+16 are not decisive. Indeed, due to poor photon statistics, their spectra can be described by either a thermal model, a non-thermal model, or a combination of the both. In any case, one can pose the upper limits for the thermal radiation from the hot polar cap from these data, so that the PSG model could be tested at least in the order of magnitude approximation.

In this Letter we include two more pulsars for which values of both P_4 and L_x are currently known: PSRs B0656+14 and B0628−28. The former case was a real breakthrough for our considerations and testing. Indeed, while in the other cases the character of the spectrum was not certain, in this pulsar (one of the Three Musketeers) the thermal radiation from the hot polar cap was clearly detected (De Luca et al. 2005). PSR B0628−28 was observed with *Chandra* and *XMM–Newton* observatories by Tepedelenlioğlu & Ögelman (2005; hereafter TÖ05). We show that both pulsars comply with the PSG model, increasing the number of pulsars that pass the model test expressed by equations (2) and (3) from two to four. At the moment, PSRs B0943+10, B1133+16, B0656+14 and B0628−28 are the only pulsars for which both P_4 and L_x are known. It is important to show that all of them follow the theoretical prediction curve in Fig. 1.

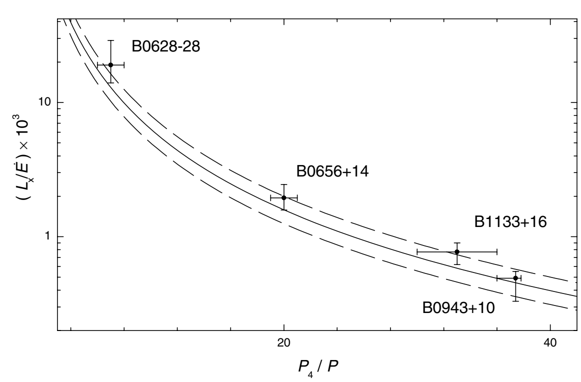

Figure 1. The efficiency of thermal X-ray emission from hot polar cap L_x versus circulation period P_4 of drifting subpulses in the radio band. The solid curve represents the prediction of the PSG model (equation 3) with $I_{45} = 1$, while the dotted curves correspond to uncertainties in determining of the moment of inertia. Error bars on P_4 and L_x were given by the authors mentioned in the text.

[1] Cheng & Ruderman (1980) were the first to consider the PSG model. However, they argued that even with partial screening included, the conditions above the polar cap are close to pure VG as in RS75. GMG03 demonstrated that the actual thermostatic self-regulation establishes the accelerating potential drop that may be as low as few per cent of that of RS75 value.

2 PSG MODEL OF THE INNER ACCELERATION REGION

The charge-depleted inner acceleration region above the polar cap results from the deviation of a local charge density ρ from the corotational charge density (Goldreich & Julian 1969) $\rho_{\rm GJ} = -\Omega \cdot \boldsymbol{B}_{\rm s}/2\pi c \approx B_{\rm s}/cP$. For isolated neutron stars one might expect the surface to consist mainly of iron formed at the neutron star's birth (e.g. Lai 2001). Therefore, the charge depletion above the polar cap can result from the binding of the positive $^{56}_{26}$Fe ions (at least partially) in the neutron star surface. If this is really possible (see Medin & Lai 2006 and Paper II for details), then the positive charges cannot be supplied at the rate that would compensate the inertial outflow through the light cylinder. As a result, a significant part of the unipolar potential drop develops above the polar cap, which can accelerate charged particles to relativistic energies and power the pulsar radiation mechanism.

The ignition of cascading production of the electron-positron plasma is crucial for limitation of the growing potential drop across the gap. The accelerated positrons will leave the acceleration region, while the electrons bombard the polar cap surface, causing a thermal ejection of ions. This thermal ejection will cause partial screening of the acceleration potential drop ΔV corresponding to a shielding factor $\eta = 1 - \rho_i/\rho_{\rm GJ}$ (see GMG03 for details), where ρ_i is the charge density of the ejected ions, $\Delta V = \eta(2\pi/cP)B_{\rm s}h^2$ is the potential drop and h is the height of the acceleration region. The gap potential drop is completely screened when the total charge density $\rho = \rho_i + \rho_+$ reaches the co-rotational value $\rho_{\rm GJ}$.

GMG03 argued that the actual potential drop ΔV should be thermostatically regulated and a 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 $Q_{\rm cool} = Q_{\rm heat}$, where $Q_{\rm cool} = \sigma T_{\rm s}^4$ is the cooling power surface density by thermal radiation from the polar cap surface and $Q_{\rm heat} = \gamma m_e c^3 n$ is the heating power surface density due to back-flow bombardment, $\gamma = e\Delta V/m_e c^2$ is the Lorentz factor, $n = n_{\rm GJ} - n_i = \eta n_{\rm GJ}$ is the number density of the back-flowing particles that deposit their kinetic energy at the polar cap surface, η is the shielding factor, n_i is the charge number density of the thermionic ions and $n_{\rm GJ} = \rho_{\rm GJ}/e = 1.4 \times 10^{11} b \dot{P}_{-15}^{0.5} P^{-0.5}$ cm^{-3} is the corotational charge number density. It is straightforward to obtain an expression for the quasi-equilibrium surface temperature in the form $T_{\rm s} = (6.2 \times 10^4\,{\rm K})(\dot{P}_{-15}/P)^{1/4}\eta^{1/2}b^{1/2}h^{1/2}$, where the parameter $b = B_{\rm s}/B_{\rm d} = A_{\rm pc}/A_{\rm bol}$ describes the domination of the local actual surface magnetic field over the canonical dipolar component at the polar cap, and $\dot{P}_{-15}$ is the normalized period derivative. Here $A_{\rm pc} = \pi r_{\rm pc}^2$ and $A_{\rm bol} = A_{\rm p} = \pi r_{\rm p}^2$ is the actual (bolometric) emitting surface area, with $r_{\rm pc}$ and $r_{\rm p}$ being the canonical (RS75) and the actual polar cap radius, respectively. Because the typical polar cap temperature is $T_{\rm s} \sim 10^6$ K (Paper II), the actual value of b must be much larger than unity, as expected for the highly non-dipolar surface magnetic fields.

The accelerating potential drop ΔV and the perpendicular (with respect of the magnetic field lines) electric field ΔE, which causes $\boldsymbol{E} \times \boldsymbol{B}$ drift, must be related to each other, and this relationship should be reflected in combined radio and X-ray data of pulsars showing drifting subpulses. This is basically a conal phenomenon (Rankin 1986), so we can restrict ourselves to the periphery of the polar cap, where these two potential drops are numerically equal to each other. Moreover, following the original 'pillbox' method of RS75 we can argue that the tangent electric field is strong only at the polar cap boundary where $\Delta E = 0.5\ \Delta V/h = \eta(\pi/cP)B_{\rm s}h$ (see appendix A in GMG03 for details). Due to the $\boldsymbol{E} \times \boldsymbol{B}$ drift the discharge plasma performs a slow circumferential motion with velocity $v_{\rm d} = c\Delta E/B_{\rm s} = \eta\pi h/P$. The time-interval to make one full revolution around the polar cap boundary is $P_4 \approx 2\pi r_{\rm p}/v_{\rm d}$. One then has

$$\frac{P_4}{P} = \frac{r_{\rm p}}{2\eta h}. \tag{1}$$

If the plasma above the polar cap is fragmented into filaments (sparks), which determine the intensity structure of the instantaneous pulsar radio beam, then in principle, the circulational periodicity P_4 can be measured/estimated from the pattern of the observed drifting subpulses (Deshpande & Rankin 1999; Gil & Sendyk 2003). According to RS75, $P_4 = NP_3$, where N is the number of sparks contributing to the drifting subpulse pattern observed in a given pulsar and P_3 is the primary drift periodicity (distance between the observed subpulse drift bands). On the other hand, $N \approx 2\pi r_{\rm p}/2h = \pi a$, where the complexity parameter can be estimated from the approximate formula $a = 5\dot{P}_{-15}^{0.29} P^{-0.64}$ (Gil & Sendyk 2000; GS00 henceforth). One has to realize that this approximation was derived under a specific assumption concerning the actual surface magnetic field (see discussion below equation 11 in GS00), and it can give misleading values of a for some untypical pulsars (see discussion in Section 4). However, using this concept we can write the shielding factor in the form $\eta \approx (1/2\pi)(P/P_3)$, which depends only on a relatively easy-to-measure primary drift periodicity P_3. Note also that $P_4/P = a/(2\eta)$. We show the values of the model parameters obtained from these equations in Table 1.

The X-ray thermal luminosity from the polar cap with a temperature $T_{\rm s}$ is $L_{\rm x} = \sigma T_{\rm s}^4 \pi r_{\rm p}^2 = 1.2 \times 10^{32}(\dot{P}_{-15}/P^3)(\eta h/r_{\rm p})^2$ erg s^{-1}, 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^{-1}, where $I = I_{45}\ 10^{45}$ g cm^2 is the neutron star moment of inertia[2] and $I_{45} = 1^{+1.25}_{-0.22}$. Using equation (1) we can derive the formula for bolometric X-ray luminosity as

$$L_{\rm x} = 2.5 \times 10^{31}\left(\dot{P}_{-15}/P^3\right)(P_4/P)^{-2}, \tag{2}$$

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

$$\frac{L_{\rm x}}{\dot{E}} = \left(\frac{0.63}{I_{45}}\right)\left(\frac{P_4}{P}\right)^{-2}. \tag{3}$$

This equation is very useful for a direct comparison with the observations, as it contains only the observed quantities (although it is subject to a small uncertainty factor related to the unknown moment of inertia), and it does not depend on any details of the sparking gap model. It reflects the fact that both the subpulse drifting rate (due to $\boldsymbol{E} \times \boldsymbol{B}$ plasma drift) and the polar cap heating rate (due to back-flow bombardment) are determined by the same physical quantity, which is the potential drop across the inner acceleration region just above the polar cap.

The microscopic properties of the PSG model require a more sophisticated analysis, such as the one presented in Paper II. Here we can give simplified but more intuitive estimate of the screening factor $\eta = (a/2)(P/P_4) = (1/2\pi)/(P/P_3)$ and the number of sparks

[2] Considering general relativity, the moment of inertia of a neutron star can be written as $I = 0.21\ MR^2/(1 - 2GM/(c^2R))$, where M and R are the neutron star mass and radius, respectively (Ravenhall & Pethick 1994). Taking $M = 1.4$ solar masses and R ranging from 8×10^5 to 1.7×10^6 cm, for the softest and stiffest equations of state, respectively, one obtains the moment of inertia ranging from 7.82×10^{44} to 2.25×10^{45} g cm ^{2}, respectively.

$N = (P4/P3) = \pi a$, using arguments based on the complexity parameter $a = r_p/h$ presented in the paragraph below equation (1).

3 OBSERVATIONAL VERIFICATION

Table 1 presents the observational data and the predicted values of a number of quantities for four pulsars, which we believe to show clear evidence of thermal X-ray emission from the spark-heated polar caps as well as having known values of the circulational subpulse drifting periodicity. The predicted values of P_4 and/or L_x are computed from equation (3). Errors in L_x is taken from the observational papers or derived from the distance uncertainty (taken from Cordes & Lazio (2002), except the case of B0656+14, for which it was obtained by Brisken et al. (2003) using the pulsar parallax), whichever is greater. The relationship expressed by equation (3) is represented by the solid curve in Fig. 1, with two dashed curves describing the uncertainty in determining of the neutron star moment of inertia. To save space in Table 1, we give the basic pulsar parameters (P, $\dot{P}_{-15}$, $\dot{E} \times 10^{-32}$, D) next to the pulsar name in the paragraphs describing each case below.

PSR B0943+10 ($P = 1.099$ s, $\dot{P}_{-15} = 3.49$, $\dot{E} = 1.04 \times 10^{32}$ erg s^{-1}, $D = 0.631^{+0.113}_{-0.104}$ kps) is the best-studied drifting subpulse radio pulsar. As this case, along with PSR B1133+16, was discussed earlier in Papers I and II, we do not find it necessary to review it again (see Table 1 and Fig. 1). Error bars for P_4 were given by Rankin & Suleymanova (2006), while errors for L_x were given by ZSP05. See Section 4 for discussion.

PSR B1133+16 ($P = 1.188$ s, $\dot{P}_{-15} = 3.73$, $\dot{E} = 0.88 \times 10^{32}$ erg s^{-1}, $D = 0.35^{+0.02}_{-0.02}$ kps) is almost a twin of PSR B0943+10, in both radio and X-ray bands, as was demonstrated in Papers I and II (see Table 1 and Fig. 1). Error bars for P_4 were given by WES06, while errors for L_x were given by KPG06. See Section 4 for discussion.

PSR B0656+14 ($P = 0.385$ s, $\dot{P}_{-15} = 55.0$, $\dot{E} = 381 \times 10^{32}$ erg s^{-1}, $D = 0.288^{+0.033}_{-0.027}$ kps) is one of the famous Three Musketeers, in which the thermal X-ray emission from the hot polar cap was clearly detected (De Luca et al. 2005). This pulsar is very bright, so the photon statistics are good enough to allow identification of the BB component in the spectrum. As indicated in Table 1, the X-ray luminosity of this hot-spot BB component is $L_x \sim 5.7 \times 10^{31}$ erg s^{-1}. This value, when inserted into equation (2), returns the predicted value of $P_4 = 20.6\,P$. Amazingly, Weltevrede et al. (2006b) reported recently the periodicity of $(20 \pm 1)P$ associated with the quasi-periodic amplitude modulation of erratic and strong emission from this pulsar. Thus, it is tempting to interpret this period as the circulation time P_4. As there is no doubt about the thermal polar cap emission component, this case greatly strengthens our arguments given for PSRs B0943+10 and B1133+16, and the equation (3) receives a spectacular confirmation. It is interesting to note that the erratic radio emission detected by Weltevrede et al. (2006b) is similar to the so-called Q-mode in PSR B0943+10. The low-frequency feature in the fluctuation spectra, identical to the one in the organized B-mode, was found by Rankin & Suleymanova (2006; see their fig. 6). Asgekar & Deshpande (2001, AD01 hereafter) also detected this feature in the 35-MHz observations of PSR B0943+10 (see their figs 1 and 2). This simply means that the $\boldsymbol{E} \times \boldsymbol{B}$ plasma drift is maintained in both regular (with drifting subpulses observed) and erratic (no drifting subpulses) pulsar emission modes. See some additional discussion in Section 4.

PSR B0628−28 ($P = 1.244$ s, $\dot{P}_{-15} = 7.12$, $\dot{E} = 1.46 \times 10^{32}$ erg s^{-1}, $D = 1.444^{+0.265}_{-0.277}$ kps) is an exceptional pulsar according to TÖ05 (see also Becker et al. 2005). 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 (ZSP05, TÖ05). The BB efficiency $L_x/\dot{E} \sim 1.9 \times 10^{-2}$ gives the predicted value of $P_4 \sim (6 \pm 1)P$ from equation (2). It is very interesting that WES06 report the periodicity of $(7 \pm 1)\ P$ (see Table 1 and 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.

4 CONCLUSIONS AND DISCUSSION

Within the partially screened gap (PSG) model of the inner acceleration region in pulsars developed by GMG03, we derived a simple relationship between the X-ray luminosity L_x from the polar cap heated by sparks and the circulation time P_4 of the spark-associated drift detected in the radio band, not necessarily in the form of regularly drifting subpulses. This relationship expresses the fact that both $\boldsymbol{E} \times \boldsymbol{B}$ drifting rate and polar cap heating rate are determined by the same value of the available potential drop. In PSRs B0943+10, B1133+16, B0628−20 and B0654+14, which are the only pulsars for which both L_x and P_4 are known at the moment, the predicted relationship between observational quantities holds very well (Fig. 1 and Table 1). This suggests that the PSG model may indeed be a reasonable description of the inner accelerator near the polar cap region. With the abundant radio drifting data (WES06) and the growing number of old pulsars detected in X-rays by *XMM–Newton* and *Chandra*, the clean prediction from this model (equation 3) will be unambiguously further tested with more pulsars in the future. PSR B0826−34 with P_4 about 14 or 7.5 P (Gupta et al. 2004) and PSR B0834+06 with P_4 about 15 P, will be examined in the near future.

For the carousel circulation time P_4 to be measurable at all, it requires a strong unevenness in the circulating system, maybe a distinguished group of adjacent sparks or even just a single spark (see also scenario discussed by Gil & Sendyk (2003). Moreover, it requires this feature to persist much longer than the circulation time. Such favourable conditions do not occur frequently in pulsars and therefore direct measurements of P_4 are very rare. In principle, in a clean case and using the fluctuation spectra analysis, one should be able to detect the primary feature P_3, reflecting the phase modulation of regularly drifting subpulses, flanked by two symmetrical features corresponding to slower amplitude modulation associated with carousel circulation. PSR B0943+10 was the first pulsar to show such a model behavior (DR99) and PSR B0834+06 was the second one, as demonstrated by Asgekar & Deshpande (2005). The latter authors have also found a direct long-period circulational feature in both pulsars. For the B0943+10 they found it in their 35-MHz observations (AD01). In the case of B0834+06, Asgekar & Deshpande (2005) found an occasional sequence of 64 pulses with much weaker frequency modulation (present in the rest of their data) but with a strong long-period feature associated with the amplitude modulation due to the circulation of one or few sparks (see their fig. 3).[3] Most interestingly, however, Rankin & Suleymanova (2006) were able to detect a long-period circulational feature P_4 in the so called Q-mode erratic emission mode in B0943+10. This apparently first detection of the Q-mode circulation time is very important. Indeed, this fact and other cases discussed in this paragraph strongly suggest that no matter the degree of the organization of spark plasma filaments at the polar cap, the $\boldsymbol{E} \times \boldsymbol{B}$ drift motion is always performed at the same rate in a given pulsar. The problem is how to reveal this motion.

Different methods of analysis of pulsar intensity fluctuations are sensitive to different effects. The method used by WES06 has an obvious advantage of finding periodicities even in very weak pulsars, so it resulted in a large increase of pulsars with drifting subpulses and/or periodic intensity modulation. Generally, WES06 can find only one period and they denote all the periods they find by P_3, suggesting that these are primary drift periodicities. It does not have to be this way at all. In fact, we suggest that in at least three cases their reported values correspond to carousel circulation times P_4. We base our argument mainly on the fact that they satisfy nicely our empirical relationship (equation 3 and Fig. 1), without any obvious selection effect involved. Moreover, in B1133+16 the value of $P_4 = (33 \pm 3)$ P is close to $(37.4^{+0.4}_{-1.4})$ P detected in the twin pulsar B0943+10 (see Paper I for a more detailed discussion). In B0656+14 the periodicity of about $20\,P$ results from intensity modulation of erratic spiky emission, similar to the case of Q-mode in B0943+10.

Using a concept of the complexity parameter a (GS00) corresponding to the ratio of the polar cap size to the spark characteristic dimension, we estimated a number of sparks, N, operating in the inner accelerating regions, as well as values of the screening parameter η for the pulsars discussed in this Letter. In the two twin pulsars both N and η are almost the same. Is seems trivial since in the approximation we used a depends only on the P and $\dot{P}$ values, which are close to each other for these two pulsars. However, N can also be found from the ratio of observed values of P_4 and P_3, and both estimates are consistent with each other. PSR B0628-28 seems quite similar to the twin pulsars, while in PSR B0656+14 the number of sparks is four times greater, and the screening parameter is quite high (corresponding to about 75 per cent of the vacuum potential drop). This is a result of relatively low P (large polar cap) and unusually high $\dot{P}$. Thus, either the actual number of sparks is really that big in this pulsar, or the approximation of GS00 is not good for such a non-typical pulsar. It is not difficult to lower the value of the complexity parameter and a corresponding number of sparks ($N = \pi a$) by a factor of 2–3, by considering larger radii of curvature of the actual surface magnetic field lines, or even the inverse Compton scattering instead of curvature radiation as seed photons for the sparking discharges (see Zhang et al. 2000; Gil & Melikidze 2002, for some details).

[3] A close inspection of this sequence of 64 pulses shows also a presence of even–odd modulation corresponding to the value of $P_3/2$ close to 2. However, the slope of the secondary drift-bands changes sign, meaning that P_3/P oscillates around the value of 2 every P_4 periods. Thus, at least in this sequence, the subpulse drift in PSR B0834+06 seems aliased.

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