XMM-NEWTON OBSERVATIONS OF RADIO PULSARS B0834+06 AND B0826−34 AND IMPLICATIONS FOR THE PULSAR INNER ACCELERATOR

J. Gil,1 F. Haberl,2 G. Melikidze,1,3 U. Geppert,4 B. Zhang,5 and G. Melikidze, Jr.1

Received 2008 April 2; accepted 2008 May 31

ABSTRACT

We report the X-ray observations of two radio pulsars with drifting subpulses, B0834+06 and B0826−34, using XMM-Newton. PSR B0834+06 was detected with a total of 70 counts from the three EPIC instruments over 50 ks exposure time. Its spectrum is best described as that of a blackbody (BB), with temperature $T_x = (2.0^{+2.5}_{-1.0}) \times 10^6$ K and bolometric luminosity $L_B = (8.6^{+14.2}_{-4.7}) \times 10^{28}$ erg s$^{-1}$. As is typical in pulsars with BB thermal components in their X-ray spectra, the hot-spot surface area is much smaller than that of the canonical polar cap, implying a non-dipolar surface magnetic field much stronger than the dipolar component derived from the pulsar spin-down (in this case about 50 times smaller and stronger, respectively). The second pulsar, PSR B0826−34, was not detected over the 50 ks exposure time, giving an upper limit for the bolometric luminosity $L_B \leq 1.4 \times 10^{29}$ erg s$^{-1}$. We use these data, as well as the radio emission data concerned with drifting subpulses, to test the partially screened gap (PSG) model of the inner accelerator in pulsars. This model predicts a simple and very intuitive relationship between the polar cap thermal X-ray luminosity ($L_B$) and the “carousel” period ($P_4$) for drifting subpulses detected in the radio band. The PSG model has been previously successfully tested with four radio pulsars whose $L_B$ and $P_4$ were both measured: PSR B0943+10, PSR B1133+16, PSR B0656+14, and PSR B0628−28. The XMM-Newton X-ray data of PSR B0834+16 reported here are also in agreement with the model prediction, and the upper limit derived from the PSR B0826−34 observation does not contradict it. We also include two other pulsars, PSR B1929+10 and B1055−52, whose $L_B$ and/or $P_4$ data became available just recently. These pulsars also follow the prediction of the PSG model. The clear prediction of the PSG model is now supported by all pulsars whose $L_B$ and $P_4$ are measured and/or estimated.

Subject headings: pulsars: individual (B0834+06, B0826−34) — radiation mechanisms: thermal — stars: neutron — X-rays: stars

1. INTRODUCTION

More than 40 years after the discovery of radio pulsars, the mechanism by which they emit coherent radio beams is still not fully understood. Also, many properties of this radiation remain a mystery, especially the phenomenon of drifting subpulses, which is widely regarded as a powerful tool for the investigation of the pulsar radiation mechanism. Recently, this phenomenon has received renewed attention, mostly owing to newly developed techniques for the analysis of pulsar radio emission fluctuations (Edwards & Stappers 2002, 2003). Using these techniques, Weltevrede et al. (2006a, 2006b, hereafter W06a, W06b) presented results of a 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 60%, and concluded that the conditions necessary 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), the subpulse-associated spark filaments of plasma circulate in the pure vacuum gap (VG) around the magnetic axis due to the well-known drift of plasma with non-corotational charge density (see the Appendix for more details).

There are a few periodicities characteristic for this model, also called the pulsar carousel: the primary period $P_3$, which can be measured as a distance between the observed subpulse drift bands, the secondary period (apparent when drifting is aliased; see Gil & Sendyk 2003 for a detailed description), and the tertiary period $P_4$ (also called the carousel time; as it is the time interval during which the gap plasma completes one full circulation around the magnetic pole). The carousel model is widely regarded as a natural and qualitative explanation of the drifting-subpulse phenomenon. However, its original version, published by Ruderman & Sutherland (1975, hereafter RS75), predicts too high a drifting rate for the sparks around the polar cap, as compared with the observations of drifting subpulses (e.g., Deshpande & Rankin 1999, 2001), and too high a heating rate of the polar cap (PC) surface due to the spark-associated back-flow bombardment, as compared with X-ray observations (e.g., Zhang et al. 2000). Another difficulty of the RS75 model is that recent calculations strongly suggest that the surface binding energies of both ions and electrons are too low to allow the development of a vacuum gap. Indeed, when the surface magnetic field is purely dipolar, then the gap can develop only in magnetars and several of the highest $B$-field pulsars (Medin & Lai 2007, hereafter ML07). Another type of inner accelerator model, called space-charge limited flow (SCLF; Arons & Scharlemann 1979; Harding & Muslimov 1998), has been discussed in the literature, and assumes that both ions and electrons can be freely stripped off the neutron star surface. Although this approximation is valid for most pulsars assuming a pure dipolar field at the polar cap region, a stronger,...

1 J. Kepler Institute of Astronomy, University of Zielona Góra, Poland.
2 Max Planck Institute for Extraterrestrial Physics, Garching, Germany.
3 E. Kharadze Georgian National Astrophysical Observatory, Tbilisi, Georgia.
4 German Aerospace Center, Institute for Space Systems, Berlin, Germany.
5 Department of Physics, University of Nevada, Las Vegas, NV 89154.

$^6$ Designated as $\dot{P}_3$ in RS75. Although this symbol is still in use, we advocate to replace it by $P_4$. 
The drift rate and PC heating rate are compatible with measurements around the pole (where $T_s$ is the basic pulsar period). These properties also could not be accounted for by the conventional theory, and some radical modification of the RS75 model was required. It appears that the PSG model not only resolves all the problems of the RS75 model, but also offers a clean prediction that can be used to test theories of the inner pulsar accelerator.

2. PREVIOUS WORK

Gil et al. (2006, hereafter Paper I) reanalyzed the B0943+10 case within the PSG model. They derived a very useful formula directly connecting the drifting rate of plasma sparks (measured by the circulation period $P_d$) and the polar cap heating rate by back-flow spark bombardment (measured by the bolometric thermal luminosity $L_b$). By assuming that both measured quantities are determined by the same value of electric field in the PSG, they obtained a simple formula relating the so-called efficiency of thermal radiation from the hot polar cap to the circulation time:

$$L_b / \dot{E} = 0.63 (P_d / P)^{-2},$$

where $\dot{E}$ is the pulsar spin-down (see eq. [A3] with $I_{55} = c = 1$ in the Appendix). PSR B0943+10 (see data in Table 1) fitted this observational curve quite well (Fig. 1). When one observable parameter in equation (1) is known ($L_b$ or $P_d$), the other one can be predicted without any free parameters. In Paper I, we included B1133+16, the twin pulsar to B0943+10 (at least in the sense of their kinematical properties; see Table 1). In this second case, we speculated that the long periodicity of about 30$^4$ before they had conducted a detailed study of the properties of this source. However, they concluded that the BB model was acceptable as well. Within a BB model, they inferred a bolometric luminosity $L_b \sim 5 \times 10^{28}$ erg s$^{-1}$ emitted from the hot spot (a few MK) with a surface area much smaller (by about 60 times) than the conventional polar cap area as defined by the bundle of last-closed dipolar field lines. This radio pulsar was well studied by Deshpande & Rankin (1999), who described the number of sparks and the circulation time $P_d = 37.4 P$ needed for one full revolution around the pole (where $P$ is the basic pulsar period). These properties also could not be accounted for by the conventional theory, and some radical modification of the RS75 model was required. It appears that the PSG model not only resolves all the problems of the RS75 model, but also offers a clean prediction that can be used to test theories of the inner pulsar accelerator.

### TABLE 1

| PSR       | $P$ (s) | $\dot{P}$ | $E$ (erg s$^{-1}$) | $P_d/P$ | $L_b$ (erg s$^{-1}$) | $L_b/\dot{E}$ | $T_s$ (10$^5$ K) |
|-----------|--------|----------|-------------------|---------|----------------------|----------------|-----------------|
| B0943+10  | 1.09   | 3.49     | $1.0 \times 10^{32}$ | $37.4 \pm 1.4$ | $5.0 \times 10^{28}$ | $9 \times 10^{-1}$ | $3.1 \pm 0.9$ |
| B1133+16  | 1.19   | 3.73     | $8.8 \times 10^{31}$ | $33 \pm 3$ | $32 \pm 4$ | $3 \times 10^{-1}$ | $3.2 \pm 0.9$ |
| B0834+06  | 1.27   | 6.8      | $1.3 \times 10^{32}$ | $30.2 \pm 0.2$ | $6.8 \times 10^{28}$ | $1 \times 10^{-1}$ | $2.0 \pm 0.7$ |
| B1929+10  | 0.23   | 1.16     | $3.9 \times 10^{33}$ | $50 \pm 5$ | $1.7 \times 10^{30}$ | $1 \times 10^{-1}$ | $3.5 \pm 0.5$ |
| B0656+14  | 0.38   | 55.0     | $3.8 \times 10^{34}$ | $20 \pm 1$ | $5.7 \times 10^{31}$ | $1 \times 10^{-1}$ | $1.25 \pm 0.03$ |
| B1055-52  | 0.19   | 5.8      | $3.0 \times 10^{34}$ | $22 \pm 5$ | $1.6 \times 10^{32}$ | $1 \times 10^{-1}$ | $1.8 \pm 0.09$ |
| B0628-28  | 1.24   | 7.12     | $1.5 \times 10^{32}$ | $7 \pm 1$ | $2.5 \times 10^{30}$ | $1 \times 10^{-1}$ | $3.3 \pm 0.6$ |
| B0826-28  | 1.65   | 0.99     | $6.2 \times 10^{30}$ | $14 \pm 1$ | $1.45 \times 10^{29}$ | $1 \times 10^{-2}$ | $2 \times 10^{-2}$ |

Note.—Errors in $L_b$ and $T_s$ correspond to a 2 $\sigma$ (90% confidence) level.

References.—(1) Deshpande & Rankin 1999; (2) Paper I; (3) HR07; (4) RW07; (5) this paper; (6) Paper II; (7) Biggs (1990); (8) Gupta et al. 2004; (9) Zhang et al. 2005; (10) Kargaltsev et al. 2006; (11) M07; (12) DL05; (13) Tepedelenlioglu & Ogelman 2005.
polar cap (again much smaller—by about 100 times—than the canonical one). As one can see in Figure 1, with the inferred values of $P_4$ and $L_b$, the pulsar B1133+16 nicely clusters with its twin along the critical curve expressed by equation (1). Note that the filled circle for B1133+16 represents our prediction and the green star represents the estimate of $P_4$ by HR07.

Encouraged by the observational confirmation of our prediction of $P_4$ in B1133+16, we applied the same method to two other pulsars for which the measurements or estimates of thermal bolometric luminosity were available (Gil et al. 2007, hereafter Paper II). One of the famous Three Musketeers, PSR B0656+14, in which thermal X-rays from a small hot polar cap were clearly detected by De Luca et al. (2005, hereafter DL05), was an obvious choice. The BB thermal luminosity $L_b \approx 5.7 \times 10^{31}$ ergs s$^{-1}$ (Table 1), when inserted into equation (1), returned the predicted value of $P_4 = 20.6P$. Amazingly, Weltevrede et al. (2006b) reported a long-period fluctuation spectral feature $(20 \pm 1)P$ associated with the quasi-periodic amplitude modulation of erratic and strong radio emission detected from this pulsar. Thus, it was tempting to interpret this period as the circulation time and strong radio emission detected from this pulsar. Thus, it was associated with the quasi-periodic amplitude modulation of erratic data, are given in Table 1.

The values of $P_4$ and $L_b$, along with their error bars (2 $\sigma$) and references for the data, are given in Table 1.

The efficiency of thermal X-ray emission from a hot polar cap $L_b/E$ vs. circulation period $P_4$ of drifting subpulses in the radio band. The solid curve represents the prediction of the PSG model (eq. [1]), while the dotted curves correspond to uncertainties in determining the moment of inertia (see the Appendix). The values of $P_4$ and $L_b$, along with their error bars (2 $\sigma$) and references for the data, are given in Table 1.

For the second of the Three Musketeers, PSR B1055–52, we have just found evidence of a low-frequency feature $f \sim 0.042$ cycles $P^{-1}$ (Biggs 1990), which can be interpreted as the carousel periodicity $P_4/P \sim 22$. Using this interpretation, which was very fruitful in several other cases discussed above and below, we examine thermal X-ray radiation from the small hot spot detected in this pulsar and attempt to test our PSG model in §4.4. The third Musketeer (Gemina) is radio quiet, so although it shows thermal BB X-ray emission from the small hot spot, it is not useful for our analysis.

Another pulsar that we were able to examine using our method of inferring values of $P_4$ from intensity modulation spectra was PSR B0628–28. As indicated in Table 1, it was detected in X-rays by Tepeledenlioglu & Ogelman (2005) using Chandra and XMM-Newton. This was an exceptional pulsar (called “overluminous” by Becker et al. 2005) with an efficiency much larger than that of typical pulsars (Becker & Trümper 1997). For the thermal BB component alone, $L_b/E \sim 1.9 \times 10^{-2}$ (Table 1). This value inserted to equation (1) gives the predicted value of $P_4 \sim (6 \pm 1)P$. Interestingly, Weltevrede et al. (2006b) reported for this pulsar a relatively short periodicity of $(7 \pm 1)P$ (Table 1). If this periodicity is interpreted as the circulation time $P_4$, then this pulsar is not exceptional at all. It lies on the theoretical curve (eq. [1]) in Figure 1 at exactly the right place. PSR B0628–28 is just another (fourth) pulsar that satisfies the predictions of equation (1), which relates the efficiency of thermal X-ray radiation from a hot polar cap to the circulational periodicity associated with drifting subpulses observed in radio emission.

In order to expand the sample of pulsars with measured/estimated values for both $L_b$ and $P_4$, we recently launched an observational campaign using the XMM-Newton observatory. We targeted two old pulsars with $P_4$ measurements but no previous X-ray observations. The two pulsars, PSR B0826–34 and PSR B0834+06, were observed during the XMM-Newton Cycles AO5 and AO6, respectively. Simultaneous radio monitoring was also performed, and we will report on these observations in a separate paper. PSR B0826–34 was not detected, although we have derived an upper limit for its thermal luminosity. We clearly detected PSR B0834+06, whose spectrum is best modeled by BB radiation from a small hot spot. We interpret this as being due to PC heating by back-flow bombardment, and have found that the bolometric $L_b$ agrees well with the value predicted by equation (1) in the PSG model. For completeness, in this paper we include yet another pulsar, PSR B1929+10, whose bolometric thermal luminosity was recently determined by Misanovic et al. (2007, hereafter M07). We show that this pulsar also satisfies equation (1) by finding a suitable feature in the modulation spectra database of W06a and W06b (see § 4.3 for some details). The number of pulsars satisfying and/or consistent with equation (1) has thus increased to seven. To the best of our knowledge, no single counterexample exists. It is worth emphasizing that the only pulsars that can be used for this analysis are those for which both the bolometric luminosity $L_b$ of thermal X-rays from a hot polar cap and the circulational periodicity $P_4$ of drifting subpulses observed in the radio band are known. In our sample of 8 available cases, in 4 pulsars (B0656+14, B1055–52, B0834+06, and B1929+10$^7$) small hot spots were clearly detected, while in 3 others, it is either possible to show evidence of hot-spot thermal emission (B1133+16 and B0628–28), or at least impossible to exclude such a component.

$^7$ Recently, Hui & Becker (2008) analyzed the same XMM-Newton data of B1929+10 (using a different method for data binning, resulting in better photon statistics per spectral bin) and argued that the hot BB component is statistically unjustified. However, if they allowed the BB radius and the temperature of the hot spot to be free parameters, then the best fit resulted in a very small hot-spot area, with a radius $r_b = 25.81^{+14.51}_{-6.66}$ m, perhaps even smaller than the one obtained by M07. In the opinion of Hui & Becker (2008), this is unacceptably small when compared to the canonical PC radius. However, within our model, this is the result of a relatively low dipolar surface magnetic field $B_d = 5 \times 10^{11}$ G. The actual non-dipolar magnetic field must be much higher (by about 400 times) to provide enough binding energy (ML07) for the creation of the PSG in this pulsar, which results in a hot-spot radius of $r_b = 300/20 = 15$ m (see § 5 for more details).
(B0943+10). The last case (B0826–34) is uncertain, as we only have an upper limit for X-ray detection (consistent with the PSG model).

3. NEW X-RAY DATA

We have observed two radio pulsars with the *XMM-Newton* observatory (Jansen et al. 2001), B0834+06 and B0826–34, known for their prominent subpulse drift. They are shown in red in Figure 1 to distinguish them from the four pulsars previously analyzed in Papers I and II (shown in black). Yet another pulsar, B1929+10, (shown in blue in Fig. 1) is discussed in § 4.3, as its values of $L_b$ and $P_a$ have recently become available.

### 3.1. *PSR B0834+06*

The pulsar PSR B0834+06 was observed with *XMM-Newton* on 2007 November 17 and 18 for a total of ~71.7 ks. The EPIC MOS (Turner et al. 2001) and EPIC pn (Strüder et al. 2001) cameras were operated in imaging mode (see Table 2). The observation was scheduled at the end of the satellite revolution, and the detector background strongly increased when the satellite entered the radiation belts. To maximize the signal-to-noise ratio, we rejected the period of high background, which resulted in net exposure times of around 50 ks (Table 2).

For the X-ray analysis we used the *XMM-Newton* Science Analysis System (SAS), version 7.1.0, together with XSPEC, version 11.3.2p, for spectral modeling. Standard SAS source detection based on a maximum likelihood technique was simultaneously applied to the X-ray images obtained from the three EPIC instruments and five different energy bands (B1, 0.2–0.5 keV; B2, 0.5–1.0 keV; B3, 1.0–2.0 keV; B4, 2.0–4.5 keV; and B5, 4.5–12.0 keV). A weak source was found at the position of the pul-

### Table 2

*XMM-Newton* EPIC Observations of PSR B0826–34 and PSR B0834+06

| PSR B0826–34 (Obs. ID 0400020101) |  |
|-----------------------------------|--|
| **R.A. (J2000.0)** | 1269 |
| **Decl. (J2000.0)** | 08 37 05.6 |
| **Satellite Revolution** | 06 10 15 |
| **Instrument** | 0454 |
| **Start Time (UT)** | 13:44:24 |
| **End Time (UT)** | 09:19:30 |
| **Exposure** (ks) | 38.83 |


### Table 2

*XMM-Newton* EPIC Observations of PSR B0826–34 and PSR B0834+06

| PSR B0834+06 (Obs. ID 0501040101) |  |
|-----------------------------------|--|
| **R.A. (J2000.0)** | 1454 |
| **Decl. (J2000.0)** | 06 10 15 |
| **Satellite Revolution** | 0454 |
| **Instrument** | 06 10 15 |
| **Start Time (UT)** | 13:44:24 |
| **End Time (UT)** | 09:19:30 |
| **Exposure** (ks) | 48.95 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

a The three EPIC instruments were operated in full-frame CCD readout mode, with 73 ms frame time for pn and 2.6 s for MOS with thin optical blocking filters.

b Net exposure times after background screening.

(1.4 ± 0.3) × 10^{-2} counts s^{-1}, which is insufficient for a detailed spectral analysis. To obtain constraints on the shape of the X-ray spectrum, we therefore use hardness ratios (X-ray colors) derived from the count rates in the standard energy bands and compare them with those expected from various model spectra. Because the EPIC pn detector is more sensitive, in particular at low energies, where most of the counts are detected, we only use count rates obtained from EPIC pn. Hardness ratios are defined as

$$HR_1 = \frac{R_1}{R_2} = \frac{R_1 - R_1}{R_1 + R_2},$$

where $R_1$ and $R_2$ are the count rates in the energy bands $B_i$ and $B_j$, respectively.

The distance to PSR B0834+06, estimated as 643 pc, was derived from its dispersion measure of $DM = 12.86$ pc cm^{-3} (from the online ATNF pulsar catalog). Assuming a 10% ionization degree of the interstellar matter along the line of sight to PSR B0834+06, this converts to a hydrogen column density of $N_H = 4.0 \times 10^{20}$ cm^{-2}. Because of the low statistical quality of the X-ray data, we are not able to derive tight constraints on the absorbing column density. Therefore, we limit our investigated model parameter space to $N_H$ values between $1.0 \times 10^{20}$ cm^{-2} (a lower limit reached within a distance of 200 pc; Posselt et al. 2008) and $8.0 \times 10^{20}$ cm^{-2} (allowing an uncertainty of a factor of 2 in the assumed ionization degree for the conversion from DM to $N_H$).

As model spectra, we tested power-law (PL) and blackbody (BB) emission, and a combination of the two. In all model spectra, absorption was included, assuming elemental abundances from Wilms et al. (2000). For the absorbed power-law model, we explored the parameter space for $N_H$ between $1.0 \times 10^{20}$ and $8.0 \times 10^{20}$ cm^{-2}, with a step size of $1.0 \times 10^{20}$ cm^{-2}, and with a photon index $\gamma$ between 1 and 5 in steps of 0.2. Figure 2a shows the hardness ratios $HR_1$ versus $HR_2$ derived at the parameter grid points. The measured hardness ratios $HR_1$ and $HR_2$ are drawn with 1 σ (solid lines) and 2 σ (dotted lines) error bars. The rectangular boxes around the error bars indicate the corresponding confidence areas, although in reality these are limited by error ellipses that fit inside the boxes. As can be seen, the power-law model spectra cannot reproduce the measured hardness ratios within the

8 See http://www.atnf.csiro.au/research/pulsar/psrcat/.
The above results are summarized in Figure 3, which presents $L_b$ versus $kT$ as obtained from the modeled hardness ratios in Figures 2b–2d, where symbols (circles and squares for the 1σ and 2σ levels, respectively), their colors (red, blue, and green for BB, BB+PL, and the BB+PL model, respectively), and related numbers correspond to those used in Figures 2b–2d. We can summarize by saying that thermal radiation from the hot polar cap of PSR B0834+06 is described by $kT = 140^{+85}_{-35} \pm 190$ eV and $L_b = 9.9^{+4.3}_{-4.4} \times 10^{28}$ erg s$^{-1}$. It should be noted that the luminosity of the BB component increases even though a power-law component is added to the model spectrum. This is because the power law rises toward the low energies, and a higher $N_H$ value is required to compensate for that. A higher $N_H$ in turn increases the bolometric luminosity of the BB component in order to match the observed spectrum (hardness ratios and count rates) again. These effects are also evident in the second case, where we used a flux ratio of $F_{bb} : F_{pl} = 1 : 1$ (Fig. 2d). Here, HR2 increases further, and the upper limits for $L_b$ also rise somewhat ($kT = 140^{+80}_{-40} \pm 210$ eV; $L_b = 9.9^{+5.4}_{-4.4} \times 10^{28}$ erg s$^{-1}$).

The pulsar PSR B0826–34 was observed with XMM–Newton on 2006 November 13 and 14 with the EPIC MOS and EPIC pn
cameras operated in imaging mode (Table 2). Strong background flaring activity also occurred near the end of this observation. After background screening, a total exposure time of ~38.8 ks was obtained.

We selected this source because it was one of the few pulsars with a known $P_d$ value (Gupta et al. 2004). When applying for the XMM-Newton observing time, we realized that PSR B0826–34 would be at best a very weak source like PSR B0943+10 (detected by Zhang et al. 2005), or even weaker. Indeed, the spin-down value would be at best a very weak source like PSR B0943+10 (detected in a 50 ks XMM-Newton exposure, or an exposure time at least 6 times longer would be required. We used $P_d/P = 15$ in the scientific justification for the XMM-Newton proposal, using equation (1) to predict a quite luminous hot PC in PSR B0834+06, emitting with $L_b = 3.6 \times 10^{29}$ erg s$^{-1}$. The model simulations indicated a count rate of about 0.018 counts s$^{-1}$, which implied a very promising case. Slightly before the scheduled XMM-Newton observing session, a new estimate was obtained by Rankin & Wright (2007, hereafter RW07), who argued, using their new Arecibo data and a new technique involving a distribution of null pulses, that $P_d/P \sim 30.25$. They argued that the number of sparks and/or subbeams involved in the nonalised subpulse drift with a true primary period $P_3/P_2 = 2.16 \pm 0.01$ was 14, and thus $P_d/P = 30.24 \pm 0.15$ (Table 1). According to equation (1), this would imply a luminosity $4.16$ times lower than the value of $L_b = 3.6 \times 10^{29}$ erg s$^{-1}$ given in our proposal, i.e., $L_b = 8.85 \times 10^{28}$ erg s$^{-1}$, or $L_b/E = 0.67 \times 10^{-3}$. Amazingly, this is almost exactly the central value of our best fit for a hot BB component in PSR B0834+06 (see Table 1 and Figs. 1 and 3). Thus, our measurements as interpreted within the PSG model (eq. [1]) strongly support the value of $P_d/P = 30.25 \pm 0.25$ obtained by RW07, while the value of $P_d/P = 15 \pm 0.8$ obtained by AD05 is highly unlikely.

4.2. PSR B0826–34

The carousel rotation time in this pulsar was obtained by means of computer simulations compared with real single-pulse data from Gupta et al. (2004). According to equation (1), its value $P_d = (14 \pm 1)$P implies an efficiency $L_b/E = 3.2 \times 10^{-3}$. These values are indicated by the red horizontal error bar labeled “B0826–34” in Figure 1. The upper limit of $2.2 \times 10^{-2}$ is marked by the short arrow above. This pulsar would either have to be much more efficient in converting the spin-down power into X-rays to be detected in a 50 ks XMM-Newton exposure, or an exposure time at least 6 times longer would be required.

4.3. PSR B1929+10

Recently, M07 argued that X-rays from PSR B1929+10 include both magnetospheric and thermal components. The BB fit to the latter gives a temperature $kT = 0.3$ keV and a projected surface area $A_p \sim 3.4 \times 10^{27}$ m$^2$, or a radius $r_p$ of about 33 m (much smaller than the canonical $A_p = 2 \times 10^{27}$ m$^2$, or $r_p \sim 300$ m). This corresponds to a bolometric luminosity $L_b \sim (1-2) \times 10^{30}$ ergs s$^{-1}$.
emitted from a hot \((T = 3.5 \times 10^6 \text{ K})\) polar cap with a radius of about 33 m. We used the central value of B1929+10, \(L_b = 1.17^{+0.13}_{-0.15}\) ergs s\(^{-1}\), with 2 \(\sigma\) errors from M07 (see the top panel in their Fig. 11).

For each new pulsar with a known thermal bolometric luminosity \(L_b\), we searched the available databases for a possible value of \(P_4\). In the case of PSR B1929+10, we found in W06a (their Fig. A13) a clear but weak low-frequency spectral feature at about 0.02 cycles \(P^{-1}\). This translates into a long periodicity \(P_4/P = 50^{+35}_{-25}\), with errors estimated from the half-width of the low-frequency feature. Going back to Figure 1, we see that the data point (blue dot) for B1929+10 (Table 1) fits the theoretical curve very well. This is an important point, as it extends the parameter space to the low-efficiency/long-period region in our Figure 1. The range of parameters for our 7 cases under examination increased the efficiency \(L_b/E\) and the tertiary period \(P_3/P\) by factors of 67 and 7, respectively.

4.4. PSR B1055−52

This is a bright radio pulsar showing complex patterns of single-pulse intensity modulations. The drifting subpulses are not apparent, but this could be the result of a central cut of the line of sight throughout the emission beam. Indeed, this pulsar has a strong interpulse separated from the main pulse by about 145\(\sigma\) s. This pulsar has a strong parent, but this could be the result of a central cut of the line of sight throughout the emission beam. Indeed, this pulsar has a strong parent. We used the central value of B1929+10, \(L_b = 1.17^{+0.13}_{-0.15}\) ergs s\(^{-1}\), with 2 \(\sigma\) errors from M07 (see their Fig. A13) a clear but weak low-frequency spectral feature at about 0.02 cycles \(P^{-1}\). This translates into a long periodicity \(P_4/P = 50^{+35}_{-25}\), with errors estimated from the half-width of the low-frequency feature. Going back to Figure 1, we see that the data point (blue dot) for B1929+10 (Table 1) fits the theoretical curve very well. This is an important point, as it extends the parameter space to the low-efficiency/long-period region in our Figure 1. The range of parameters for our 7 cases under examination increased the efficiency \(L_b/E\) and the tertiary period \(P_3/P\) by factors of 67 and 7, respectively.

Within the partially screened gap (PSG) model of the inner acceleration region in pulsars developed by G03, we derived in Paper I a simple and clean relationship (eq. [1]) between the thermal X-ray bolometric luminosity \(L_b\) from a hot PC heated by sparks and the circulation time \(P_3\) of the spark-associated drift detected as the subpulse drift in pulsar radio emission. This relationship expresses the well-justified assumption (see the Appendix) that both the drifting rate and the polar cap heating rate are determined by the same value of electric field within the inner acceleration region. Indeed, the drifting rate described by measurable \(P_4\) is determined by the tangential (with respect to surface magnetic field) component of the electric field, while the heating rate described by measurable \(L_b\) is determined by its component parallel to the surface magnetic field in the (partially screened) gap. In Paper II, we showed that PSRs B0943+10, B1133+16, B0628−20, and B0656+14, which were the only pulsars for which both \(L_b\) and \(P_4\) were known at the time, satisfied equation (1) quite well (see also Fig. 1 and Table 1). This suggested that the PSG model may indeed be a reasonable description of the inner accelerator region near the polar cap. In this paper, we support this view by demonstrating that another three pulsars (B0834+06, B1929+10, and B1055−52) also satisfy equation (1). Yet another pulsar, B0826−34, in which only the upper limit for \(L_b\) was obtained, demonstrated a consistency with equation (1) as well.

Only for a handful of pulsars has the circulation (carousel) time been measured or constrained so far. Measurement of \(P_4\) by means of modulation spectral analysis requires a strong unevenness in the circulating system, such as perhaps a distinguished group of adjacent sparks or even just a single spark (see also the scenario discussed by Gil & Sendyk 2003). Moreover, this feature should persist considerably longer than the circulation time. Such favorable conditions do not occur frequently in pulsars, and therefore direct or indirect measurements of \(P_4\) are very rare. In principle, in a clean case 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, as well as the direct low-frequency feature 1/\(P_4\) (as in the case of PSR B0943+10; Deshpande & Rankin 2001; Asgekar & Deshpande 2001; Gil et al. 2003). However, the results of Paper II clearly showed that \(P_4\) can also be found in pulsars without regularly drifting subpulses (and/or in erratic drifting modes). This strongly suggested that regardless of the degree of organization of spark plasma filaments at the polar cap, the slow circumferential plasma drift always performed at about the same rate in a given pulsar. The problem was how to reveal this motion. Two new methods were discussed, or at least mentioned, in Paper I. The first is the 2D phase-resolved modulation spectral analysis developed by Edwards & Stappers (2002, 2003) and implemented by Weltevrede et al. (W06a; W06b). The second method, based on examination of the distribution of nulls in the long sequence of single pulses, was recently developed by HR07 and RW07. In view of the main results obtained in this paper, the latter method deserves some more detailed discussion here.

As discussed in § 3.1, there is a controversy about the actual value of \(P_4\) in PSR 0834+06. AD05 reported that the alias-corrected \(P_4/P = 1.88 \pm 0.01\) and \(P_4/P = 15 \pm 0.8\), implying a number of sparks \(N = P_4/P = 8\). These authors found just one sequence of 64 pulses in which the fluctuation spectrum analysis revealed the low-frequency feature at about 1/15 = 0.067. On the other hand, RW07 found a nonalised primary drift periodicity \(P_4/P = 2.16 \pm 0.011\) and a number of sparks \(N = 15\), implying a long tertiary periodicity \(P_4/P = 30.24 \pm 0.15\). This longer cycle with \(P_4 \sim 30P\) was supported by our measurements of \(L_b\) and the PSG model expressed by equation (1). RW07 examined an interaction between nulls and emission in PSR B0834+06. They found that null pulses are not randomly distributed and that the most likely periodicity in their appearance is about 30P. Following the previous discovery of HR07 that null pulses and drifting subpulses in PSR B1133+16 are associated with the same long periodicity (about 33P), RW07 convincingly argued that short pseudo-nulls (1 pulsar period or less) are just a result of an irregular distribution of subpulse subbeams/sparks that persist on timescales of at least hundreds of pulsar periods. The short-time pseudo-nulls appear when the line of sight cuts through the
low-level emission region in the radio beam. Our results on both B1133+16 and B0834+16 strongly support this picture. The interesting question, then, is why AD05 obtained such a strong feature at 15P for a sequence of 64 single pulses from B0834+06. RW07 admitted that they also found in their data some sequences showing a periodicity of 15P, which seemed to be a subharmonic of a 30P cycle. We noticed yet another problem with the result of AD05. In our opinion, these authors have used their equations (2) and (3) incorrectly. In fact, they used the longitudinal distance between the profile components for \( \Delta \phi \), and as a consequence the azimuthal magnetic angle between the neighboring subbeams was \( \Delta \theta = 50^\circ \), which ignored the subpulses appearing in the saddle of the profile. We believe that they should have used \( \Delta \theta \sim 25^\circ \), and as a result, the number of sparks would have been \( N = 360/25 = 14 \) instead of 8. This is consistent with our estimate, in which we found that the spectrum can be described equally well by a PL and a clean prediction (eq. [1]), which allows a hot spot radius as small as 4 m. This is the smallest hot spot cap ever observed, with a ratio \( b = A_{\text{rc}}/A_p = 1.77 \times 10^4/d_{130}^2 \), which is equal to 1770 and 923 (the highest values ever obtained) for distances of 0.13 and 0.18 kpc, respectively. Accordingly, the actual surface magnetic field \( B_d = bB_d \) (Gil & Sendyk 2000; ML07) is equal to 4.5 and 2.3 \( \times 10^{14} \) G for distances of 0.13 and 0.18 kpc, respectively. Interestingly, the latter value agrees almost exactly with ML07 (their Fig. 7, solid red line), while the former implies too high a surface temperature, exceeding 5 MK. Thus, the extremely small hot polar cap with \( T_s = 3.2 \) MK results from the fact that the actual surface magnetic field must be about 1000 times stronger than the dipolar component in order to provide enough cohesive energy to develop PSG in this pulsar. We can therefore say that the case of PSR J0108-1431 strongly supports the PSG pulsar model, the ML07 cohesive energy calculations for the condensed Fe polar cap surface, and the NE2001 distance to this pulsar (about 0.184 kpc). If one adopts 0.184 kpc as the proper distance to PSR J0108-1431, then the bolometric BB luminosity is \( L_b \sim 2.5 \times 10^{36} \) erg s\(^{-1}\), and the efficiency \( L_b/E \sim 4.3 \times 10^{-3} \). With this value, equation (1) predicts a tertiary periodicity \( P_d/P \sim 12 \). However, the confirmation of this by means of single-pulse radio observations of PSR J0108-1431 seems hopeless with present day technology, as the pulsar is also extremely weak in the radio band (Tauris et al. 1994).

Thus, our PSG model seems to account for the physical phenomena at and above the actual pulsar polar cap quite well. Other available inner acceleration models do not match the observations well. The pure vacuum gap model (RS75) has \( \eta = 1 \). Although it also satisfies equation (1), it predicts a very high polar cap heating rate, typically \( L_b \sim (10^{-1} - 10^{-2})E \) (Zhang et al. 2000), and therefore a very small \( P_d \). The predicted high \( L_b \) has been ruled out by the X-ray observations of many old pulsars (Zhang et al. 2005; Tepedelenlioğlu & Ögelman 2005; Kargaltsev et al. 2006; this paper), and the predicted low \( P_d \) is also inconsistent with radio observations. On the other hand, as discussed in § 1, the steady state SCLF model does not predict the existence of the “sparks,” whose drifts around the polar cap region provide the most natural interpretation of the observed drifting-subpulse patterns. A modified unsteady SCLF model (which has not been discussed in the literature) may be able to introduce a sparking-like behavior. Based on similar logic (i.e., that the potential drop along the magnetic field line in the gap is equal to the horizontal potential drop across the spark; see the Appendix), an equation similar to equation (1) can be derived for the SCLF model. However, since this model introduces a very small effective \( \eta \) value \( \eta \sim (2\pi R_c/cP)^{1/2} \ll 1; \) Harding &Muslimov 2001), the predicted polar cap heating rate is too low to interpret the observations, typically \( L_b \sim (10^{-4} - 10^{-3})E \) (Harding & Muslimov 2002). Also, the corresponding drifting velocity is too small, such that the predicted \( P_d \) is too long compared with the radio data. The PSG model predicts an intermediate particle inflow rate and gives a clean prediction (eq. [1]), which allows \( L_b \) to be a moderate value. This is strongly supported by the data.

In order to solve the binding energy problem in the canonical dipolar magnetic field at the neutron star surface, it has been conjectured that drifting-subpulse pulsars are bare strange stars (Xu et al. 1999). The simplest model does not allow a hot polar cap because of the high thermal conductivity of the bare strange star surface layer, which is ruled out by the data. Yue et al. (2006) argued that PSR B0943+10 may be a low-mass quark star (\( \sim 0.02 \, M_{\odot} \)). However, subpulse drifting seems to be the most common behavior of radio pulsars (W06a, W06b), some of which have well-measured masses around \( 1.4 \, M_{\odot} \) (Thorsett & Chakraborty 1999).
The cohesive energy calculations of Fe ion chains in an ultrastrong magnetic field by ML07 seem to be strongly supported by the X-ray observations discussed in this paper. Finally, we would like to address a hypothesis put forward by Becker et al. (2006) that in old pulsars (>10⁶ yr), the magnetospheric emission dominates over thermal emission, including both cooling radiation and hot polar cap emission components. These authors suggested that the latter radiation component decreases along with the former one, and therefore that the hot polar caps in cooling neutron stars could be formed by anisotropic heat flow due to the presence of the magnetic field rather than by particle bombardment. While in young neutron stars with core temperatures ~10⁸ K, the strong crustal magnetic fields may channel the heat toward the polar cap, resulting in a Tₚ of a few MK (Perez-Azorin et al. 2006; Geppert et al. 2006), in pulsars older than 10⁶ yr this mechanism is much less efficient, and the only viable process that can produce such hot and small polar caps is back-flow particle bombardment. Almost all pulsars presented and examined in this paper are older than 1 Myr (an exception is the 110 kyr PSR B0656+14). For instance, PSR B0834+06 is 3 Myr old, and its X-ray emission is dominated by the hot BB component (a counterexample to Becker et al. 2006). In PSR B1929+10 (3.1 Myr old), the luminosity of the hot BB component is at least comparable to the magnetospheric X-ray radiation (M07). The very old (170 Myr) rotation-powered non-recycled pulsar J0108-1431 clearly shows BB radiation from the hot polar cap (Pavlov et al. 2008), which is probably accompanied by magnetospheric emission, although there is no evidence of cooling radiation from the whole surface, as expected for such an old pulsar.

In summary, both the polar cap full cascade (Zhang & Harding 2000) and the downward outer gap cascade (Cheng et al. 1998), which have been proposed to interpret nonthermal X-ray emission from spin-down-powered pulsars, are expected to be less significant in pulsars from our sample than in young pulsars. The predicted values of X-ray luminosity in these models are typically lower than that of the polar cap heating in the PSG model (eq. [1]). As other available models of the pulsar inner accelerator (the pure vacuum gap model and the space-charge limited flow model) either overpredict or underpredict the polar cap heating level, we conclude that the pulsar inner accelerator is likely partially screened due to a self-regulated sub-Goldreich Julian flow. Also, the pure vacuum gap model predicts too fast a drifting, and the space-charge limited flow model has no natural explanation for the subpulse drift phenomenon. We thus strongly believe that thermal radiation associated with polar cap heating due to a partially screened inner accelerator is a common component of pulsar X-ray emission regardless of the pulsar’s age, and that this component plays an especially significant role in the spectra of old pulsars.

Our results are partly based on observations made with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA member states and the USA (NASA). We acknowledge the support of NASA grants NNX07AF07G and NNX08AC67G. J. G. was partially supported by the Polish State Committee for Scientific Research grant NN203 2738 33, and G. M. was partially supported by the Polish State Committee for Scientific Research grant NN203 1262 33, as well as by the Georgian grants NSF ST06/4 096 and INTAS 06 1000017 9258. The XMM-Newton project is supported by the Bundesministerium für Wirtschaft und Technologie/Deutsches Zentrum für Luft und Raumfahrt (BMW/DLR, FKZ 50 OX 0001) and the Max Planck Society. We thank Dipanjan Mitra for stimulating discussions, critical reading of the manuscript, and helpful comments.

APPENDIX

INNER ACCELERATION REGION IN PULSARS

The charge-depleted inner acceleration region above the polar cap results from the deviation of a local charge density ρ from the coronal thermal charge density (Goldreich & Julian 1969) ρ₀ = −Ω × Bₛ/zπc ≈ Bₛ/cP. For isolated neutron stars, one might expect the surface to consist mainly of the iron formed at the neutron star’s birth (e.g., Lai 2001). Therefore, the charge depletion above the polar cap could result from binding of the positive ⁵⁶Fe ions (at least partially) in the neutron star surface. If this is really possible (see Medin & Lai 2006, 2007 and Paper II for details), then the positive charges cannot be supplied at a rate that would compensate for 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 positrons to relativistic energies and power the pulsar radiation mechanism, while the electrons bombard the polar cap surface, causing a thermal ejection of ions, which would otherwise be more likely bound in the surface in the absence of additional heating. This thermal ejection would cause partial screening of the acceleration potential drop ΔV, corresponding to a shielding factor η = 1 − ρ₁/ρ₀ (see G03 for details), where ρ₁ is the charge density of the ejected ions, ΔV = η(2πc/P)Bₛh² 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 ρ = ρ₁ + ρ₂ reaches the coronal value ρ₀. In terms of the binding of ⁵⁶Fe ions, the screening factor η = 1 − exp(Cᵣ − εₑ/kTₛ), where εₑ is the cohesive energy of the condensed iron surface, Tₛ is the actual surface temperature, Tᵣ = εₑ/kCᵣ is the critical temperature above which the iron ions are ejected with the maximum corotation-limited rate, and Cᵣ = 30 ± 3 (ML07).

Because of the exponential sensitivity of the accelerating potential drop to the surface temperature, the actual potential drop should be thermostatically regulated. In fact, when the potential drop is large enough to ignite cascading pair production, the back-flowing relativistic charges will bombard the polar cap surface and heat it at a predictable rate. This heating will induce thermionic emission from the surface, which will, in turn, decrease the potential drop that caused the thermionic emission in the first place. As a result of these two oppositely directed tendencies, a quasi-equilibrium state should be established, in which heating due to electron bombardment is balanced by cooling due to thermal radiation. This should occur at a temperature slightly lower than the critical temperature above which the polar cap surface delivers thermionic flow at the coronal thermal charge density level. This is the essence of the PSG model. For practical reasons, it is assumed that Tᵣ = Tₛ, although in reality Tᵣ is a few thousand K lower than Tₛ, the latter being strongly dependent on the surface magnetic field Bₛ. This is illustrated by Figure 7 in ML07, which was prepared for the pure VG model. The PSG model is realized along the red (for Fe) line in this figure, which shows that for a few MK surface temperatures, as suggested by X-ray observations of pulsar hot spots (see Paper II and references therein), the surface magnetic field must be close to 10¹⁴ G in all pulsars. For most pulsars, this is a much stronger field than that inferred from pulsar spin-down due to magnetic dipole radiation. Therefore, the surface magnetic
field in neutron stars must be dominated by crust-anchored non-dipolar magnetic anomalies. Such a strong and curved surface magnetic field is also necessary for development of the cascading pair production via curvature radiation (e.g., RS75; Gil & Melikidze 2002).

Several models proposed for generating pulsar radio emission based on the concept of vacuum gaps need radii of curvature of the surface magnetic field much smaller than the stellar radius (see, e.g., Gil et al. 2002). A possible way to generate such fields would be via currents in the neutron star crust (e.g., Urpin et al. 1986; Geppert et al. 2003). Mitra et al. (1999) examined the evolution of multipole components generated by currents in the outer crust. They found that mostly low-order multipoles contribute to the required small radii of curvature and that the structure of the surface magnetic field is not expected to change significantly during the radio pulsar lifetime.

The spark plasma inside the PSG must slowly drift with respect to the polar cap surface due to non-corotational charge density. This drift will manifest itself by observed subpulse drifting, provided that the spark arrangement is quasi-stable over timescales of hundreds of pulses or so. The deviation of the charge density from the corotational value generates an electric field \( \mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 \) just above the polar cap surface. The parallel component causes acceleration of charged particles, while the perpendicular component participates in the subpulse drift. The tangential electric field at the polar cap boundary \( \mathbf{E}_1 = 0.5 \Delta V / h = \eta \pi / c \mathbf{B}_s h \) (see Appendix A in G03 for details). Due to the \( \mathbf{E} \times \mathbf{B}_s \) drift, the discharged plasma performs a slow circumferential motion around the magnetic axis (see the next paragraph) with velocity \( v_d = c \Delta \mathbf{E}_1 / \mathbf{B}_s = \eta \pi \mathbf{h} / P \). The time interval to make one full revolution around the polar cap boundary is \( P_4 \approx 2 \pi r_p / v_d \). One then has

\[
P_4 \approx \frac{P_4}{P} = 2 \left( \frac{r_p}{\eta \pi \alpha} \right), \tag{A1}\]

where the coefficient \( \alpha = \Delta \mathbf{E}_1 / \Delta \mathbf{E}_1 \) should be close to unity. 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). In practice, \( P_4 \) is measured from the low-frequency features in the modulation spectra obtained from good-quality single-pulse data of pulsars with drifting subpulses. According to RS75, \( P_4 = N P_3 \), 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 (the distance between the observed nonaliased subpulse drift bands).

The circumferential motion around the magnetic axis, as in RS75, holds only when the magnetic and the spin axes are almost parallel (an almost-aligned rotator, in which the line-of-sight trajectory is almost that of the circumferential tracks of sparks moving around the magnetic axis). Many pulsars with drifting subpulses indeed have a very broad profile characteristic of almost-aligned rotators (e.g., B0826−34 and B0818−41). Others, which are not broad-profile pulsars and show regular drifting, must have a very high impact angle, i.e., one grazing the emission beam. In such cases, one cannot exclude the almost-aligned geometry. In the more general (inclined) case, the spark trajectory does not have to be closed on the polar cap, as sparks should rather follow the trajectory of the line of sight projected onto the polar cap, being slightly late behind the star’s rotation. However, observations of drifting subpulses in some pulsars do not support such a scenario, being consistent with the circumferential motion of the spark-associated subbeams of subpulse radiation, even if the pulsar is not an aligned rotator. Indeed, orderly drifting subpulses always demonstrate a systematic intensity modulation that either increases or decreases toward the pulse profile midpoint. Also, in pulsars with a more central cut of the line-of-sight trajectory, the subpulse drift is less apparent (or nonexistent), but a characteristic phase-stationary modulation of subpulse intensity modulation persists. These properties strongly suggest that sparks move on closed trajectories on the polar cap, although they do not have to be circular, as in the axially symmetric RS75 model, to the extent that in some of the detections of circumferential motion with a specified value of pulse drift is less apparent (or nonexistent), but a characteristic phase-stationary modulation of subpulse intensity modulation persists. Several models proposed for generating pulsar radio emission based on the concept of vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of the vacuum gaps need radii of curvature of

The quasi-equilibrium condition is \( Q_{\text{cool}} = Q_{\text{heat}} \), where \( Q_{\text{cool}} = \sigma T_4^4 \) is the cooling power surface density by thermal radiation from the polar cap surface, \( Q_{\text{heat}} = \gamma m_e c^3 n \) is the heating power surface density due to back-flow bombardment, \( \gamma = e \Delta V / m_e c^2 \) is the Lorentz factor, \( n = n_{\text{g3}} - n_i = \eta n_{\text{g3}} \) is the number density of the back-flowing particles that deposit their kinetic energy at the polar cap surface, \( \eta \) is the shielding factor, \( n_i \) is the charge number density of the thermonic ions, \( n_{\text{g3}} = \rho_{\text{g3}} / e = 1.4 \times 10^{11} h \rho_{\text{g3}}^{0.5} P^{-0.5} \) cm\(^{-3} \) is the corotational charge number density, and \( \bar{P} \) is the time derivative of the period in \( 10^{-15} \). It is straightforward to obtain an expression for the quasi-equilibrium surface temperature in the form \( T_4 = (2 \times 10^6 K) (\bar{P}^{-15} / P)^{14/3} b^{1/2} h^{1/2} \) (Paper II), where \( h = h / 10^5 \) cm, the parameter \( b = B_1 / B_1 = A_{pc} / A_p \) (Gil & Sendyk 2000; ML07) describes the domination of the local actual surface magnetic field over the canonical dipolar component at the polar cap, and \( \bar{P} \) is the normalized period derivative. Here, \( A_{pc} = \pi r_p^2 \) and \( A_p = \pi r_p^2 \) are the canonical (RS75) and actual emitting surface areas, respectively, where \( r_p \) and \( r_p \) are the canonical (RS75) and actual polar cap radii, respectively. Since the typical polar cap temperature is \( T_4 \sim 10^6 \) K (Paper II), the actual value of \( b \) must be much larger than unity, as expected for highly non-dipolar surface magnetic fields.

Using equation (A1), one can derive the formula for thermal X-ray luminosity as

\[
L_b = 2.5 \times 10^{31} \alpha^{-2} \left( \frac{P_{-15}}{P} \right)^{-2}, \tag{A2}\]

or in a simpler form representing the radiation efficiency with respect to the spin-down power, \( E = I \Omega^2 / I_{45} \times 10^{11} P_{-15} / P^3 \) erg s\(^{-1} \), where \( I = I_{45} \times 10^{45} \) g cm\(^2\) is the neutron star moment of inertia, and \( I_{45} = 1.12 \times 10^{45} \) (see Papers I and II for details). The equation

\[
\frac{L_b}{E} = 0.63 \left( \frac{\alpha^{-2}}{T_{45}} \right) \left( \frac{P_4}{P} \right)^{-2}, \tag{A3}\]
is very useful for direct comparison with observations, since it contains only the observed quantities (although it is subject to small uncertainty factors related to the unknown moment of inertia $I_45$ and the coefficient $\alpha_1$). It does not depend on any details of the sparking-gap model such as the non-dipolar surface magnetic field $b = B_s/B_d$, the height $h$ of the acceleration region, or the shielding factor $\eta$, since they cancel out in the derivation procedure as expected. Indeed, this equation reflects the fact that both the subpulse drifting rate (due to the $E < B_s$ 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. No other agency should be involved. In a practical application of equation (A3), we will set $I_45 = 1$ and $\alpha_1 = 1$. The former is commonly used, and the latter means that the values of the accelerating $E_k$ and perpendicular $E_\perp$ components of electric field in the PSG are almost the same. It is quite a reasonable assumption, all the more so since it seems to be supported observationally (Fig. 1).

REFERENCES

Arons, J., & Scharlemann, E. T. 1979, ApJ, 231, 854
Asgekar, A., & Deshpande, A. A. 2001, MNRAS, 326, 1249
———. 2005, MNRAS, 357, 1105 (AD05)
Becker, W., Jessner, A., Kramer, M., Testa, V., & Hovland, C. 2005, ApJ, 633, 367
Becker, W., & Trümper, J. 1997, A&A, 326, 682
Becker, W., et al. 2006, ApJ, 645, 1421
Biggs, J. D. 1990, MNRAS, 246, 341
Cheng, K. S., Gil, J., & Zhang, L. 1998, ApJ, 493, L35
Cordes, J. M., & Lazio, T. J. W. 2002, preprint (astro-ph/0207156)
De Luca, A., et al. 2005, ApJ, 623, 1051 (DL05)
Deshpande, A. A., & Rankin, J. M. 1999, ApJ, 524, 1008
———. 2001, MNRAS, 322, 438
Edwards, R. T., & Stappers, B. W. 2002, A&A, 393, 733
———. 2003, A&A, 407, 273
Geppert, U., Kükker, M., & Page, D. 2006, A&A, 457, 937
Gil, J., Lubarsky, Y., & Melikidze, G. I. 2004, ApJ, 600, 872
Gil, J., & Melikidze, G. I. 2002, ApJ, 577, 909
Gil, J., Melikidze, G. I., & Geppert, U. 2003, A&A, 407, 315 (G03)
Gil, J., Melikidze, G. I., & Mitra, D. 2002, A&A, 388, 235
Gil, J., Melikidze, G., & Zhang, B. 2006, A&A, 457, L5 (Paper I)
———. 2007, MNRAS, 376, L67 (Paper II)
Gil, J., & Sendyk, M. 2000, ApJ, 541, 351
———. 2003, ApJ, 585, 453
Goldreich, P., & Julian, H. 1969, ApJ, 157, 869
Gupta, Y., Gil, J., Kijak, J., & Sendyk, M. 2004, A&A, 426, 229
Harding, A. K., &Muslimov, A. G. 1998, ApJ, 508, 328
———. 2001, ApJ, 556, 987
———. 2002, ApJ, 568, 862
Herfindal, J. L., & Rankin, J. M. 2007, MNRAS, 380, 430 (HR07)
Hui, C. Y., & Becker, W. 2008, A&A, 486, 485
Jansen, F., et al. 2001, A&A, 365, L1
Kargaltsev, O., Pavlov, G. G., & Garmire, G. P. 2006, ApJ, 636, 406
Lai, D. 2001, Rev. Mod. Phys., 73, 629
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
Medina, Z., & Lai, D. 2006, Phys. Rev. A, 74, 062507
———. 2007, MNRAS, 382, 1833 (ML07)
Melikidze, G. I., Gil, J. A., & Pataraya, A. D. 2000, ApJ, 544, 1081
Misanovic, Z., Pavlov, G. G., & Garmire, G. P. 2007, ApJ, submitted (arXiv: 0711.4171) (M07)
Mitra, D., Konar, S., & Bhattacharya, D. 1999, MNRAS, 307, 459
Pavlov, G. G., Kargaltsev, O., Wong, J. A., & Garmire, G. P. 2008, ApJ, submitted (arXiv:0803.0761)
Perez-Azorin, J. F., Mirales, J. A., & Pons, J. A. 2006, A&A, 451, 1009
Posselt, B., Popov, S. B., Haberl, F., Trümper, J., Turolla, R., & Neuhauser, R. 2008, A&A, 482, 617
Rankin, J. M., & Suleymanova, S. A. 2006, A&A, 453, 679
Rankin, J. M., & Wright, G. A. E. 2007, MNRAS, 379, 507 (RW07)
Ruderman, M. A., & Sutherland, P. G. 1975, ApJ, 196, 51 (RS75)
Strüder, L., et al. 2001, A&A, 365, L18
Tauris, T. M., et al. 1994, ApJ, 428, L53
Tepedelenlioğlu, E., & Ögelman, H. 2005, ApJ, 630, L57
Thorsett, S. E., & Chakrabarty, D. 1999, ApJ, 512, 288
Turner, M. J. L., et al. 2001, A&A, 365, L27
Urpin, V. A., Levshakov, S. A., & Jakobov, D. G. 1986, MNRAS, 219, 703
Weltevrede, P., Edwards, R. I., & Stappers, B. W. 2006a, A&A, 445, 243 (W06a)
Weltevrede, P., Wright, G. A. E., Stappers, B. W., & Rankin, J. M. 2006b, A&A, 458, 269 (W06b)
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Xu, R. X., Qiao, G. J., & Zhang, B. 1999, ApJ, 522, L109
Yue, Y. L., Cui, X. H., & Xu, R. X. 2006, ApJ, 649, L95
Zhang, B., & Harding, A. K. 2000, ApJ, 532, 1150
Zhang, B., Harding, A., & Muslimov, A. 2000, ApJ, 531, L135
Zhang, B., Sanwal, D., & Pavlov, G. G. 2005, ApJ, 624, L109

XMM-NEWTON OBSERVATIONS OF RADIO PULSARS 507
No. 1, 2008