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

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ABSTRACT

We consider the problem of the thermal X-ray radiation from the hot polar cap of radio pulsars showing evidence of $E \times B$ 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 $E \times B$ plasma drift, and the thermal X-ray luminosity $L_x$ 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 the present paper we consider two more pulsars: PSRs B0656+14 and B0628-28, whose data 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 $L_x$ 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 $L_x$ and too low $P_4$, while the space charge limited model predicts too low $L_x$ and the origin of the subpulse drift has no natural explanation.

Key words: pulsars: pulsars: individual: B0628-28; B0656+14; 0943+10; 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% 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 a Vacuum Gap (VG) around the magnetic axis due to the $E \times B$ 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 $P_4$ ($P_3$ 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 & Sharlemann 1979), predicts too low a heating rate and has no natural explanation for the phenomenon of drifting subpulses (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) developed further 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). Since 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 to understand a mechanism of drifting subpulses, which appears to be a common phenomenon in radio pulsars.

ZSP05 were the first who attempted 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 (2006 a,b; hereafter Paper 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 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 hot spot, much smaller than the canonical polar cap. PSR B1133+16 is almost a twin of PSR B0943+10 in terms of $P$ and $P_4$ 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 Eqs. 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 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 paper 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 the PSG model, increasing the number of pulsars that pass the model test expressed by Eqs. (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.

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 $\rho$ from the co-rotational charge density (Goldreich & Julian 1969) $\rho_{cG} = -\Omega \cdot B_c/2\pi c \approx B_c/\epsilon P$. 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 binding of the positive $^{56}$Fe ions (at least partially) in the neutron star surface. If this is really possible (see Mendin & 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 $\Delta V$ corresponding to a shielding factor $\eta = 1 - \rho_i/\rho_{cG}$ (see GMG03 for details), where $\rho_i$ is the charge density of the ejected ions, $\Delta V = \eta (2\pi/\epsilon P) B_c h^2$ 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 $\rho = \rho_i + \rho_+ \eta$ reaches the co-rotational value $\rho_{cG}$.1
GMG03 argued that the actual potential drop $\Delta V$ should be thermostatically regulated and there should be established a quasi-equilibrium state, in which heating due to electron bombardment is balanced by cooling due to thermal radiation. The quasi-equilibrium condition is $Q_{\text{cool}} = Q_{\text{heat}}$, where $Q_{\text{cool}} = \gamma T^3$ is the cooling power surface density due to thermal radiation from the polar cap surface and $Q_{\text{heat}} = \gamma m_e c^2 n$ is the heating power surface density due to back-flow bombardment, $\gamma = e \Delta V/m_e c^2$ is the Lorentz factor, $n = n_{\text{GJ}} - n_i = \eta n_{\text{GJ}}$ 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 thermionic ions and $n_{\text{GJ}} = \rho_{\text{GJ}}/e = 1.4 \times 10^{13} b P_{-15}^{0.5} P^{-0.5} \text{cm}^{-3}$ is the corontational charge number density. It is straightforward to obtain an expression for the quasi-equilibrium surface temperature in the form $T_s = (6.2 \times 10^3 K) (P_{-15}/P_s)^{1/4} n^{1/2} b^{1/2} h^{1/2}$, where the parameter $b = B_s/B_d = A_{\text{pc}}/A_{\text{bol}}$ describes the domination of the local actual surface magnetic field over the canonical dipolar component at the polar cap, and $P_{-15}$ is the normalized period derivative. Here $A_{\text{pc}} = \pi r_p^2$ and $A_{\text{bol}} = A_p = \pi r_p^2$ is the actual (bolometric) emitting surface area, with $r_{\text{pc}}$ and $r_p$ being the canonical (RS75) and the actual polar cap radius, respectively. Since the typical polar cap temperature is $T_s \sim 10^6$ 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 $\Delta V$ and the perpendicular (with respect of the magnetic field lines) electric field $\Delta E$, which causes $\mathbf{E} \times \mathbf{B}$ 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 $\Delta E = 0.5 \Delta V/h = \eta (\pi/c) B_s h$ (see Appendix A in GMG03 for details). Due to the $\mathbf{E} \times \mathbf{B}$ drift the discharge plasma performs a slow circumferential motion with velocity $v_d = c \Delta E/B_s = \eta 
abla / P$. The time interval to make one full revolution around the polar cap boundary is $P_k \approx 2 \pi r_p / v_d$. One then has

$$\frac{P_k}{P} = \frac{r_p}{2 \pi h}.$$  (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 circuital periodicity $P_k$ can be measured/estimated from the pattern of the observed drifting subpulses (Deshpande & Rankin 1999, Gil & Sendyk 2003). According to RS75, $P_k = N P_3$, 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 (distance between the observed subpulse drift bands). On the other hand $N \approx 2 \pi r_p / 2 h = \pi a$, where the complexity parameter can be estimated from the approximate formula $a = 5 P_0^{0.22} P^{-0.64}$ (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 $P_k / P = a/(2 \pi)$. 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 $T_s$ is $L_s = \sigma T^4_n \pi r_p^2 = 1.2 \times 10^{31} (P_{-15}/P_s^3) (\eta \nabla / r_p)^2 \text{ erg/s}$, which can be compared with the spin-down power $\dot{E} = I \Omega \dot{\Omega} = 3.95 I_{45} \times 10^{34} P_{-15}/P_s^3 \text{ erg/s}$, where $I = I_{45} 10^{45} \text{g cm}^2$ is the neutron star moment of inertia and $I_{45} = 1.1^{+0.25}_{-0.22}$. Using equation (1) we can derive the formula for thermal X-ray luminosity as

$$L_x = 2.5 \times 10^{31} (P_{-15}/P_s^3) (P_3/P)^{-2},$$  (2)

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

$$L_x / E = \left( \frac{0.63}{4 \pi} \right) \left( \frac{P_3}{P} \right)^{-2}.$$  (3)

This equation is very useful for a direct comparison with the observations, since it contains only the observed quantities (although it is subject to a small uncertainty factor related to the unknown moment of inertia$^2$), 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 E x 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 microscropic properties of PSG model require a more sophisticated analysis, like the one presented in our Paper II. Here we can give simplified but more intuitive estimate of the screening factor $\eta = (a/2) (P/P_3) = (1/2 \pi) (P/P_3)$ and the number of sparks $N = (P_4/P_3) = \pi a$, 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 they have known values of the circumstantial subpulse drifting periodicity. The predicted values of $P_k$ 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

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$^2$ Considering general relativity, the moment of inertia of a neutron star can be written as $I = 0.21 M R^2 / (1 - 2 GM/c^2 R^2)$, where $M$ and $R$ is the neutron star mass and radius, respectively (Ravenhall & Pethick, 1994). Taking $M = 1.4$ solar masses and $R$ ranging from $8 \times 10^5$ to $1.7 \times 10^6$ cm, for the softest and stiffest equations of state, respectively, one obtains the moment of inertia ranging from $7.82 \times 10^{44}$ to $2.25 \times 10^{45}$ g cm$^2$, respectively.
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 ($P, P_{15}, \dot{E} \times 10^{-32}, D$) 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, $D = 0.631^{+0.133}_{-0.104}$ 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 $P_t$ 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, $D = 0.35^{+0.02}_{-0.02}$ kps) is almost a twin of PSR B0943+10, in both radio and X-ray bands as it was demonstrated in Papers I and II (see Table 1 and Fig. 1). Error bars for $P_t$ 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, $D = 0.288^{+0.033}_{-0.027}$ 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 photometric 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 $L_x \sim 5.7 \times 10^{31}$ ergs/s. This value, when inserted into equation (2), returns the predicted value of $P_t = 20.6P$. 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 $P_t$. Since 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). Asgkar & 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 $E \times B$ 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.

![Figure 1](image-url)
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 $P_c$ of the spark-associated drift detected in radio band, not necessarily in the form of regularly drifting subpulses. This relationship expresses the fact that both $E \times B$ 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 $P_c$ 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 acceleration region in pulsars developed by GMG03, we clean prediction from this model (equation 3) will be unambiguously further tested with more pulsars in the future. PSR B0826-34 with $P_c$ about 14 or 7.5 $P$ (Gupta, Gil, Kijak et al. 2004) and PSR B0834+06 with $P_c$ about 15 $P$, will be examined in the near future.

For the carousel circulation time $P_c$ to be measurable at all, it requires a strong unevenness in the circulatory 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 favorable conditions do not occur frequently in pulsars and therefore direct measurements of $P_c$ are very rare. In principle, in a clean case, using the fluctuation spectra analysis, one should be able to detect the primary feature $P_c$, 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 features 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 strong long period feature associated with the amplitude modulation due to the circulation of one or few sparks (see their Fig. 3). Most interestingly, however, Rankin & Suleymanova (2006) were able to detect a long period circulational feature $P_a$ 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 $E \times B$ drift motion is always performed at the same rate in a given pulsar. The problems is how to reveal this motion.

Different methods of analysis of pulsar intensity fluctuations are sensitive to different effects. The method used WES06 has an obvious advantage of finding periodicities even in a 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 at least in three cases their reported values correspond to carousel circulation times $P_a$. We base our argument mainly on the fact that they satisfy nicely our empirical relationship (Eq. 3 and Fig. 1), without any obvious selection effect involved. Moreover, in B1133+16 the value of $P_a = (33\pm3)P$ is close to $(37.4\pm1.4)P$ detected in the twin pulsar B0943+10 (see Paper I for 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 $\eta$ for the pulsars discussed in this paper. In the two twin pulsars both $N$ and $\eta$ 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 $P_3$ and $P_a$, 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 4 times greater, and the screening parameter is quite high (corresponding to about 75 % 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, Harding & Muslimov 2000 and Gil & Melikidze 2002 for some details).

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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 $P_3$ periods. Thus, at least in this sequence the subpulse drift in PSR B0834+06 seems aliased.
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