Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 5, 443–452
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

Can the inner gap sparking take place in millisecond pulsars? *

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Received 2003 March 24; accepted 2003 May 20

Abstract The inner vacuum gap model has become the foundation stone of most theories on pulsar radio emission. The fundamental picture of this model is the sparking, which was conjectured to be induced by magnetic absorption of background gamma photons. However, a question is, can the sparking be triggered in the millisecond pulsars (MSPs) with magnetic fields (B) only about 10^8 G? We investigate this problem by including the pair production above the inner gap. Under the assumption that the magnetic field is dipolar, our results show the background gamma-ray emission can not be the key factor that triggers the sparking, at least not in MSPs with $B \sim 10^8$ G, if the temperature in the polar cap region is only so high as is observed ($< 4 \times 10^6$ K). Some other mechanisms are required.

Key words: pulsar: general—gamma rays—magnetic fields

1 INTRODUCTION

The inner vacuum gap model was proposed by (Ruderman & Sutherland 1975, hereafter RS) to explain pulsar radio emission. In this model, RS suggested that the positive ions can not be pulled out from the stellar surface by the electric field because of high binding energy. As a consequence, a vacuum gap, with a typical height of 10^4 cm, is left on the polar cap surface when plasma flows away across the light cylinder. However, the gap is unstable, pair cascade (sparking) will develop until a large number of particles are generated and ultimately screen the huge potential drop between two ends of the gap. Then the gap is formed again, waiting for the next sparking. The particles generated in the gap flow out along the open field lines and produce radio waves through some coherent mechanisms which are unclear yet.

By now most theoretical models that explain pulsar radio emission are based on the picture of inner gap sparking, e.g. the inverse Compton scattering model (Qiao & Lin 1998; Xu et al. 2000; Qiao et al. 2002), the spark model (Gil & Sendyk 2000; Melikidze et al. 2000) and plasma emission model (Melrose & Gedalin 1999; Usov 2002). The bases of the inner gap model are still questionable, however, can the inner gap be formed? Can the sparking take place?

* Supported by the National Natural Science Foundation of China.

As to the first problem, although theoretical studies suggest that the gap can not be formed if the temperature of the neutron star surface is high enough, (e.g. $\geq 10^7$K, Gil & Melikidze 2002), the phenomenon of periodic subpulse drifting observed in some pulsars provides a solid observational support for the inner gap model (Deshpande & Rankin 1999). Furthermore, if pulsars are strange quark stars with bare polar cap surfaces (e.g. Xu et al. 1999), then the vacuum gap must form.

For the second problem, RS suggested that the Galactic background gamma-ray photons may be absorbed by the magnetic field in the gap and provide primary $e^{\pm}$, thus triggering the sparks. This hypothesis was further investigated by Shukre & Radhakrishnan (1982, hereafter SR). Assuming that the surface magnetic field is dipolar, and considering only the $\gamma - \boldsymbol{B}$ absorption in the gap, they found that these photons can be effective in triggering the sparks within a narrow window of magnetic field from $\sim 10^{11}$ G to $\sim 10^{13}$ G. However, they did not discuss the triggering difficulty in pulsars with lower magnetic field, especially in MSPs. In this paper, we reinvestigate this problem by taking account of the diffuse gamma photons absorbed above the polar cap.

In Sect. 2 we summarize the observational properties of the diffuse gamma-ray emission. In Sect. 3 the absorption of background photons in the open field line region is studied. Our conclusions and a discussion are presented in Sect. 4.

2 THE DIFFUSE GAMMA-RAY BACKGROUND EMISSION

The *EGRET* all-sky survey provides detailed information about the diffuse gamma-ray background from 1 MeV to above 100 GeV (Strong et al. 1994; Hunter et al. 1997; Sreekumar et al. 1998). The observed diffuse emission consists of a Galactic component emitted from the Galactic plane and an isotropic extragalactic component. Neither of them show any significant variations with direction in the spectral index, which averages about 2.1. The gamma-ray intensity of the inner Galactic plane ($|l| < 40°$ and $|b| < 2°$) is not more than one order of magnitude higher than that of the extragalactic component, and the intensity of the outer Galactic plane is intermediate between the two (Strong et al. 1994; Hunter et al. 1997).

In this paper we adopt the spectrum

$$n_{\rm ext} = n_{\rm ext,0}\left(\frac{E_\gamma}{1{\rm MeV}}\right)^{-2.1}\ {\rm cm^{-2}s^{-1}sr^{-1}MeV^{-1}} \tag{1}$$

for the extragalactic component (given by Sreekumar et al. 1998) and

$$n_{\rm Gal} = n_{\rm Gal,0}\left(\frac{E_\gamma}{1{\rm MeV}}\right)^{-2.1}\ {\rm cm^{-2}s^{-1}sr^{-1}MeV^{-1}} \tag{2}$$

for the inner Galactic component, where $n_{\rm ext,0} \simeq 3.0\times10^{-3}$ and $n_{\rm Gal,0} \simeq 3.0\times10^{-2}$, and E_γ is gamma photon energy. SR used an earlier result $n = 1.1\times10^{-2}\ (E_\gamma/1{\rm MeV})^{-2.3}{\rm cm^{-2}s^{-1}sr^{-1}}$ ${\rm MeV^{-1}}$, which is a little steeper than the above spectra, and does not reflect the intensity difference between the two components.

3 BACKGROUND GAMMA PHOTON ABSORPTION IN PULSAR MAGNETOSPHERE

SR did not consider the electron-positron pairs that are created in the open field line region above the inner gap. However, electrons can flow into the gap, the reason is as follows. When non-neutral plasma flows out of the gap within a magnetic flux tube, its net charge density ($\rho \propto B$) will deviate from the local GJ density ($\rho_{\rm GJ} \propto B\cos\alpha$, the static charge density at which no electric field parallel to the magnetic field $\boldsymbol{B}$ exists, where α is the angle between $\boldsymbol{B}$ and pulsar angular velocity $\boldsymbol{\Omega}$, see Goldreich & Julian 1969) due to the magnetic field curvature. According to Maxwell Equations, a parallel electric field $\boldsymbol{E}_\parallel$ must be created. This effect may generate a potential drop of about $10^8 - 10^9$ Volts outside the gap (Cheng & Ruderman 1977), which is enough to accelerate an electron to a relativistic energy with Lorentz factor $\gamma \sim 10^2 - 10^3$).

In principle, electrons may be accelerated into the gap, but the detailed picture depends on the spatial configuration of the magnetic field and the vectors of ($\boldsymbol{\Omega}$) and the magnetic moment ($\boldsymbol{\mu}$). For instance, when $\boldsymbol{\Omega} \cdot \boldsymbol{\mu} < 0$, the plasma above the polar cap is positively charged. On the field lines below the magnetic axis (type I region, see Fig. 1a), $\boldsymbol{E}_\parallel$ points towards the light cylinder, while on the field lines between the rotational and magnetic axes (type II region), $\boldsymbol{E}_\parallel$ points to the star. Therefore, if a background gamma photon shooting towards the pulsar is absorbed in type I region, the electron created may be accelerated into the gap, thus contributing to the triggering of sparks. However, the positron never contributes even in type II region, because it will immediately be counter-accelerated outward once it enters the gap. In the case of $\boldsymbol{\Omega} \cdot \boldsymbol{\mu} > 0$ (Fig. 1b), electrons in type II region are able to flow into the gap. Next we present the formulae and numerical results for the $\gamma - \boldsymbol{B}$ absorption in a magnetic flux tube extending far way from the polar cap (Fig. 2).

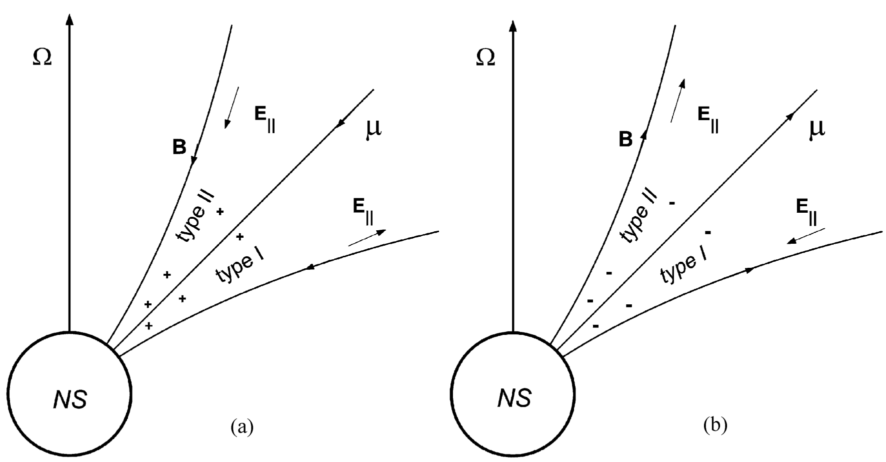

Fig. 1 Schematic diagrams for rotators with (a) $\boldsymbol{\Omega} \cdot \boldsymbol{\mu} < 0$ and (b) $\boldsymbol{\Omega} \cdot \boldsymbol{\mu} > 0$, respectively.

3.1 Basic Formulae

The asymptotic form of the attenuation coefficient of γ-B process was first given by Erber (1966), which reads

$$k = 0.23\frac{\alpha}{\lambda}\frac{B}{B_{\rm q}}\sin\theta\exp(-\frac{4}{3\chi})\text{cm}^{-1}. \qquad (\chi \ll 1) \tag{3}$$

After considering the quantum effect in near threshold regime ($E_\gamma \sin\theta \geq 2mc^2$ but $E_\gamma \sin\theta \sim 2mc^2$), Daugherty & Harding (1983) gave a modified form

$$\begin{aligned} k &= 0.23\frac{\alpha}{\lambda}\frac{B}{B_\mathrm{q}}\sin\theta\exp(-\frac{4}{3\chi}f)\mathrm{cm}^{-1} \qquad (\chi \ll 1, \epsilon\sin\theta \geq 1) \\ &= 0, \qquad (\epsilon\sin\theta < 1) \end{aligned} \tag{4}$$

where

$$\chi = \epsilon(B/B_\mathrm{q})\sin\theta,$$

$$\epsilon = E_\gamma/2mc^2\,,$$

$$f = 1 + 0.42(\epsilon\sin\theta)^{-2.7}(B/B_\mathrm{q})^{-0.0038},$$

where $\alpha = 7.297 \times 10^{-3}$ is the fine structure constant, $\lambda = 2.43 \times 10^{-10}$cm the Compton wavelength of the electron, mc^2 the electron rest energy, $B_\mathrm{q} = 4.414 \times 10^{13}$ G, and θ the angle between the directions of photon and $\boldsymbol{B}$.

The mean free path of a gamma photon in a uniform magnetic field is $l = 1/k$. Then, the energy of the photon which is absorbed by the magnetic field after moving through a distance l reads

$$\epsilon \simeq 58.9\frac{f}{21.2 + \ln(B_{12}\sin\theta l_4)}\frac{1}{B_{12}\sin\theta}, \tag{5}$$

where $B_{12} = B/(10^{12}\mathrm{G})$ and $l_4 = l/(10^4\mathrm{cm})$. Considering that commonly the curvature radius of pulsar magnetic field is greater than 10^5 cm, we assume $l_4 = 1$. On this scale, the magnetic field can be regarded as approximately uniform at any altitude, which ensures that Eq. (5) is valid.

Since the term $21.2+\ln(B_{12}\sin\theta l_4)$ is not sensitive to B_{12}, l_4 and $\sin\theta$, we accept a mediate value 15 (between $B_{12} = 1$ and $B_{12} = 10^{-4}$) for simplicity. Assuming that the magnetic field is dipolar, i.e. $B = B_\mathrm{s}(R/r)^3$, and let $f \simeq 1$ (which is correct in most cases, even when $\epsilon\sin\theta \sim 1$ f is not more than 1.42), for a given θ we have

$$\mathrm{d}\epsilon = \frac{12.0}{\sin\theta B_{\mathrm{s},12}}\frac{r^2}{R^3}\mathrm{d}r, \tag{6}$$

where R is the stellar radius, B_s is the surface magnetic field.

The above equations reveal two main properties of $\gamma - \boldsymbol{B}$ absorption in pulsar magnetosphere. First, along a given trajectory (fixed θ), the photons that are absorbed within a thin layer from r to $r + dr$ are nearly mono-energetic (here the radius r is counted from the stellar center), the photon energy increases with radius. Secondly, when B_{12} is greater than $B_{\mathrm{cr},12} \simeq 4$, the condition $\epsilon\sin\theta \geq 1$ is no longer satisfied. It means that for pulsars with surface magnetic field higher than B_cr, almost all the background gamma photons satisfying the above condition will be absorbed above the gap.

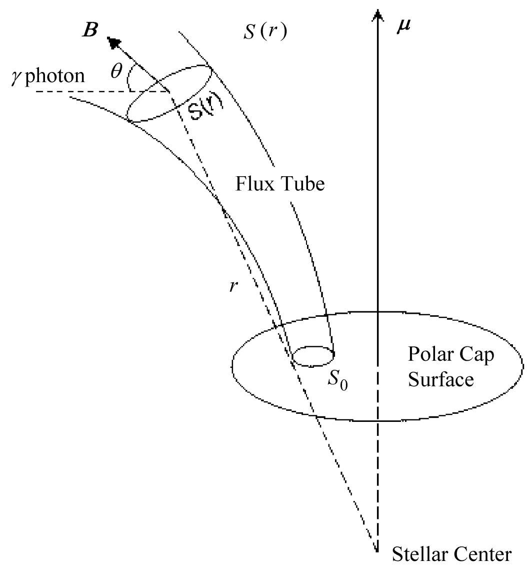

Fig. 2 Schematic diagram for the geometry of $\gamma - \boldsymbol{B}$ absorption.

Now we derive the number flux of the photons that are absorbed in a flux tube, of which the cross section area is S_0 on the polar cap surface (see Fig. 2). Due to magnetic flux conservation, the area of the tube surface at radius r is $S(r) = S_0 B_\mathrm{s}/B = S_0(r/R)^3$. Through each unit area $d\sigma$ on the surface, the number flux of the absorbed photons reads

$$\begin{aligned}\frac{\mathrm{d}N}{\mathrm{d}t\mathrm{d}r\mathrm{d}\sigma} &= \int n\left[\epsilon(\theta,r)\right]\frac{\mathrm{d}\epsilon}{\mathrm{d}r}\mathrm{d}\Omega \\ &= \int_0^{2\pi}\mathrm{d}\varphi\int_{\theta_\mathrm{b}}^{\theta_\mathrm{u}} n\left[\epsilon(\theta,r)\right]\frac{\mathrm{d}\epsilon}{\mathrm{d}r}\mathrm{d}\theta, \end{aligned}\tag{7}$$

where $n(\epsilon) = \mathrm{n}_0\epsilon^{-2.1}$ is the gamma photon spectrum. In the above equation the local spherical coordinate system is used, with the outward polar axis parallel to the tangent of the local magnetic field, and azimuthal angle φ. According to the $\gamma - \boldsymbol{B}$ threshold, the lower bound of the polar angle θ is $\theta_\mathrm{b} = 1/\epsilon_\mathrm{max}$, where ϵ_max is the maximum energy of the background gamma photons. Noting that $\epsilon_\mathrm{max} \sim 100\,\mathrm{GeV}$ is observed by *EGRET*, we have $\theta_\mathrm{b} \simeq 0$. The upper bound θ_u is not so certain, because the gamma photons with θ near $\pi/2$ have a large probability of being absorbed in the nearby flux tubes. First, to figure out the upper limit of the photon flux, we can assume $\theta_\mathrm{b} = 0$ and $\theta_\mathrm{u} = \pi/2$. Because $\mathrm{d}N/(\mathrm{d}t\mathrm{d}r\mathrm{d}\sigma)$ given by Eq. (7) has the same value everywhere on the tube surface, the number flux of the absorbed photons passing through the whole tube surface is

$$\frac{\mathrm{d}N}{\mathrm{d}t\mathrm{d}r} = S(r)\int_0^{2\pi}\mathrm{d}\varphi\int_0^{\pi/2} n\left[\epsilon(\theta,r)\right]\frac{\mathrm{d}\epsilon}{\mathrm{d}r}\mathrm{d}\theta. \tag{8}$$

Substituting Eqs. (5) and (6) in it and integrating over r, we obtain the total number flux

$$\frac{\mathrm{d}N}{\mathrm{d}t} = 24.0\pi n_0 B_{\mathrm{s},12} S_0\int_{r_\mathrm{b}}^{r_\mathrm{u}} B_{12}^{0.1}\frac{1}{r}$$

$$\times \int_0^{\pi/2} \left[\frac{21.2+\ln(B_{12}\sin\theta l_4)}{58.9}\right]^{2.1} \sin^{2.1}\theta \mathrm{d}\theta \mathrm{d}r$$
$$= 11.4 n_0 B_{\mathrm{s},12}^{1.1} S_0 \left(\frac{R}{r}\right)^{0.3} |_{r_\mathrm{u}}^{r_\mathrm{b}}, \tag{9}$$

where the average value $[21.2 + \ln(B_{12}\sin\theta l_4)] \simeq 15$ has been used. The integral is performed within the *EGRET* spectrum, namely, the photon energy is less than 100 GeV, which sets the lowest magnetic field $B_{\mathrm{low},12}$ to $\sim 10^{-5}$ for the gamma photons to be able to convert into pairs. Then the upper bound of r is determined as

$$r_\mathrm{u} = R\Big(\frac{B_{\mathrm{s},12}}{B_{\mathrm{low},12}}\Big)^{1/3}. \tag{10}$$

The lower bound depends on comparing B_s and B_cr:

$$r_\mathrm{b} = R\Big(\frac{B_{\mathrm{s},12}}{B_{\mathrm{cr},12}}\Big)^{1/3} \quad (B_{\mathrm{s},12} \geq B_{\mathrm{cr},12})$$
$$= R. \quad (B_{\mathrm{s},12} < B_{\mathrm{cr},12}) \tag{11}$$

At this point, we have reached our final result

$$\frac{\mathrm{d}N}{\mathrm{d}t} \simeq 11.4 n_0 S_0 B_{\mathrm{s},12}^{1.1} A, \tag{12}$$

where $A \simeq 0.75/B_{\mathrm{s},12}^{0.1}$ when $B_{\mathrm{s},12} \geq B_{\mathrm{cr},12}$ and $A \simeq 1 - 0.32/B_{\mathrm{s},12}^{0.1}$ when $B_{\mathrm{s},12} < B_{\mathrm{cr},12}$.

It is worth noting that more gamma photons are absorbed by the magnetic field above the gap than in the gap. For the latter component, the factor A is $1 - [R/(R+h)]^{0.3} \simeq 0.3h/R \sim 10^{-2}$, while for the former component, A is about 1, thus the photons absorbed in the gap only account for about 1% of the total. Therefore, the $\gamma - \boldsymbol{B}$ pair production above the gap should not be neglected.

Zhang & Qiao (1998) proposed that when the polar cap temperature is higher than 4×10^6 K, two photon annihilation (gamma-ray photons colliding with thermal X-ray photons from the polar cap surface) will play a non-negligible role in pair production in the polar cap region. However, so high a temperature has not been observed in radio pulsars (see Zhang & Qiao 1996). Here we neglect this effect.

3.2 Implication on the Inner Vacuum Gap Sparking

How do we judge whether or not the $\gamma - \boldsymbol{B}$ absorption of background gamma photons plays the key role in triggering the sparks? A pertinent way is to compare the triggering timescale τ, defined as the time in which one pair or electron is accumulated in the spark region, with a certain observational timescale. As we know, microstructures observed in bright normal pulsars often show quasi periodicity on the order of 10^{-4}s (Lyne & Smith 1998; Popov et al. 2002). This periodicity, which reflects the separation between nearby micropulses, can naturally be explained as the time interval between two successive discharges (e.g. Lyne & Smith 1998). In MSPs, instead of the microstructure, spiky structures have been discovered, also with a time scale of $\sim 10^4$ s (e.g. PSR J0437–4715, Vivekanand 2000). Therefore, we propose $\tau \leq 10^{-4}$ s as the criterion that the background gamma-ray emission plays a decisive role in triggering the sparks.

It has been suggested that the scale of the sparks is roughly the gap height h (Gil & Sendyk 2000). For a RS-type vacuum gap, the gap height is $h \simeq 5 \times 10^3 \zeta^{-3/7} R_{\mathrm{c},6}^{2/7} P^{3/7} B_{\mathrm{s},12}^{-4/7}$cm, where ζ is a factor due to inertia-frame-dragging modification ($\zeta \sim 0.85$), $R_{\rm c,6} = R_{\rm c}/(10^6{\rm cm})$ is curvature radius of the surface magnetic field (Zhang et al. 2000). In this case, let $S_0 = \pi h^2$, the triggering timescale reads $\tau \equiv 1/({\rm d}N/{\rm d}t) = 1.2 \times 10^{-9} R_{\rm c,6}^{-4/7} P^{-6/7} B_{\rm s,12}^{3/70} (n_0 A)^{-1}{\rm s}$.

Using archived data of more than 1300 radio pulsars from ATNF Pulsar Catalogue (http: //www.atnf.csiro.au /research/pulsar/catalogue) and only considering the extragalactic diffuse gamma-ray emission, we calculated τ and plotted them versus P in Fig. 3a. It shows that when $R_{\rm c} = 10^6$ cm the criterion is satisfied for all the pulsars, but when $R_{\rm c} = 10^5$ cm, the criterion is not satisfied for several fastest MSPs.

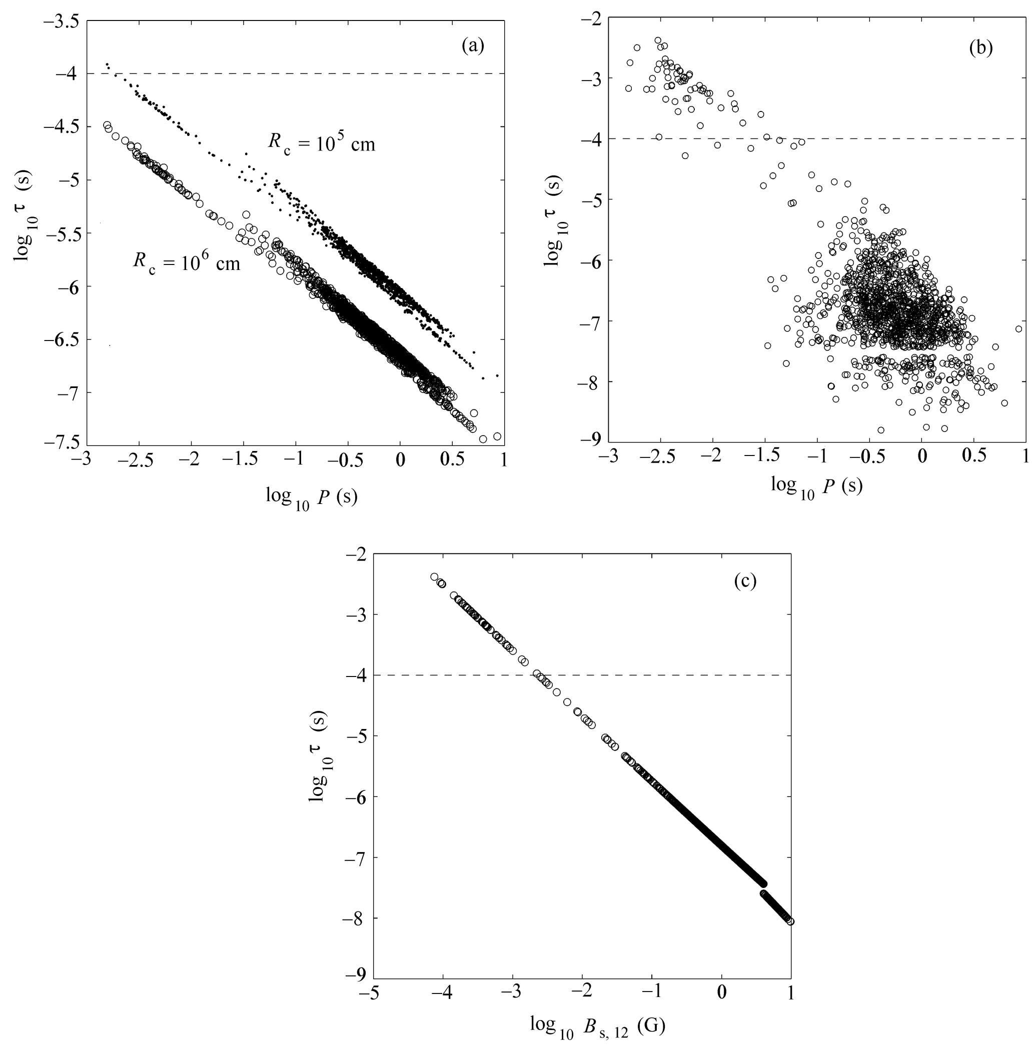

Fig. 3 Plots of $\tau - P$ in (a) case I and (b) case II, and $\tau - B_{\rm s,12}$ in case II (c) for $\sim$1300 radio pulsars. The criterion of $\tau < 10^{-4}$s is plotted as the dashed line. In panel (a) the dots and the open circles represent the results for $R_{\rm c} = 10^5$ cm and $R_{\rm c} = 10^6$ cm, respectively. Here, $\theta_{\rm u} = \pi/2$ is used.

The above pictures are based on the assumption that the spark radius D is equal to the RS-gap height h (case I), which gives a result that τ depends on pulsar period and surface magnetic field. In fact, the dynamics of sparking process has not been well studied, the possibility that $D \neq h$ can not be excluded. As an extreme case, we assume that D does not depend on period and magnetic field (case II), then $\tau = 0.1 B_{\rm s,12}^{-1.1} (n_0 S_0 A)^{-1}$. Typically we take $D = 10^4$ cm. In Fig. 3c, τ versus $B_{\rm s,12}$ is presented and τ versus P is plotted in Fig. 3b for comparison, although it does not depend on P. Combining these two figures, one can see that for those pulsars with $B <\sim 2 \times 10^9$ G (with period less than $\sim$30 ms) the criterion is not satisfied.

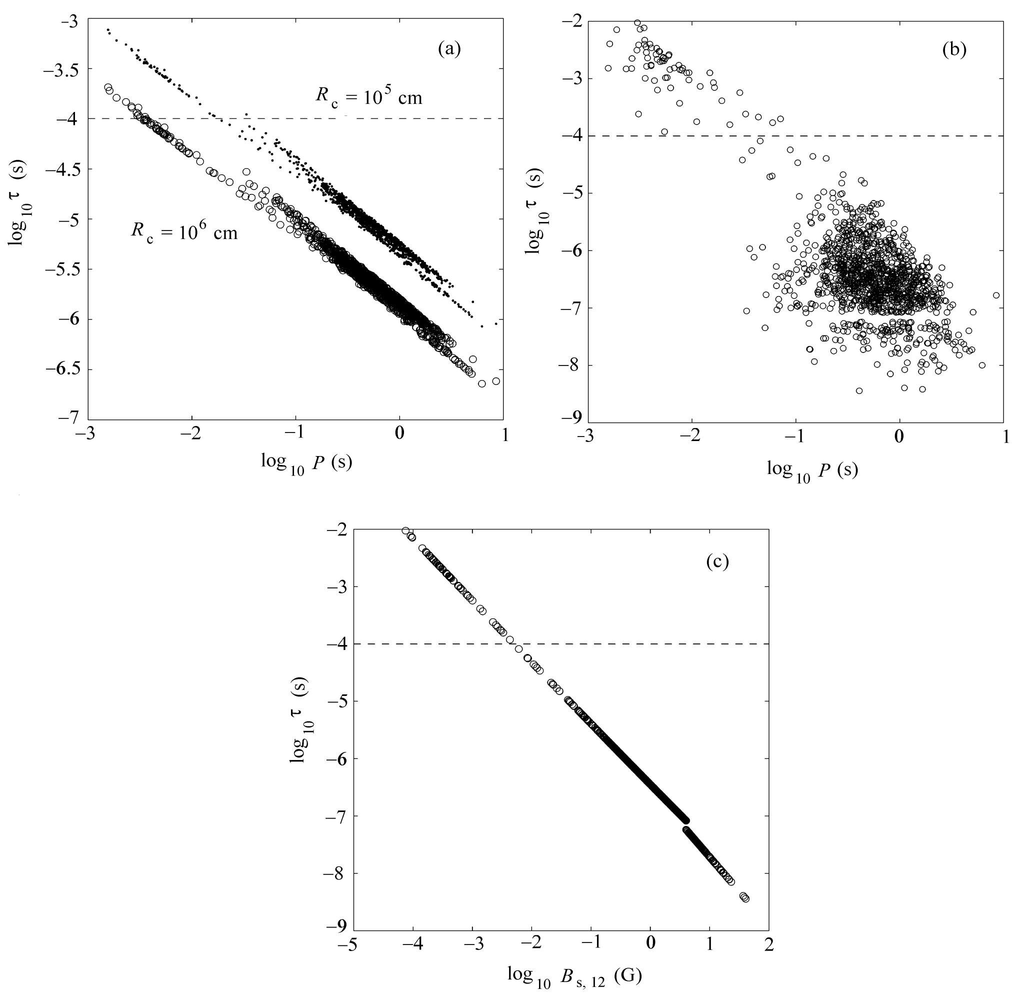

Fig. 4 Plots of $\tau - P$ in (a) case I and (b) case II, and $\tau - B_{\rm s,12}$ in case II (c) for $\sim$1300 radio pulsars. In panel (a) the dots and the open circles refer to $R_{\rm c} = 10^5$ cm and $R_{\rm c} = 10^6$ cm, respectively. Here, $\theta_{\rm u} = \pi/3$ is used.

As is pointed out in Section 3.1, the upper bound $\theta_u = \pi/2$ leads to an overestimation of the photon flux. In order to show how the upper bound affects the results we simply assume $\theta_u = \pi/3$ rather than determine its actual value by dealing with the complex geometry. The timescale becomes $\tau = 2.9 \times 10^{-9} R_{c,6}^{-4/7} P^{-6/7} B_{s,12}^{3/70} (n_0 A)^{-1}$s for case I and $\tau = 0.23 B_{s,12}^{-1.1} (n_0 S_0 A)^{-1}$ for case II. The $\tau - P$ and $\tau - B$ plots are presented in Fig. 4. It is shown that in case I the criterion is never satisfied for the handful of MSPs whether R_c is 10^6 cm or 10^5 cm, in case II, the criterion is not satisfied for the pulsars with $B <\sim 6 \times 10^9$ G and $P <\sim 60$ ms. Therefore, in general, for any situation between these two cases (I and II), the triggering problem exists at least in those MSPs with $B \sim 10^8$ G.

In the above calculation we used the flux of the isotropic extragalactic diffuse emission. What would the consequence be when we take into account the Galactic component? First, to be sure, the enhancement in photon flux from the galactic plane will increase $\mathrm{d}N/\mathrm{d}t$, but only by a factor of a few units at most because of the narrow solid angle of the inner Galaxy to pulsars. Secondly, although the relative position may result in some difference in $\mathrm{d}N/\mathrm{d}t$ when the two halves of the polar cap in turn point to the Earth, it is unlikely to cause any significant observational consequence in the pulsar emission because of the complexity in the whole cascade process and emission process. In fact, we fail to find any correlation between the observational properties and pulsar spatial distribution.

4 CONCLUSIONS AND DISCUSSION

In the inner gap model, the initiation of sparking is a challenging question. We reinvestigate the role of the background diffuse gamma-ray photons in triggering the sparks, which was originally proposed by RS. Assuming that the magnetic field is dipolar, we show that even including the contribution of the photons absorbed by the magnetic field above the gap, the background gamma-ray emission is not a crucial factor in triggering the sparks in millisecond pulsars with $B \sim 10^8$ G. Some other mechanisms are required.

A discussion now follows.

(1) In Section 3.1 the approximation $[21.2 + \ln(B_{12} \sin\theta l_4)] \simeq 15$ is used. In fact the average value is less than 15 for MSPs, e.g. may be $\sim$10. When taking into account this the triggering timescale will increase by a factor of $\sim$2, causing more MSPs to have the triggering problem. Additionally, there seem no reasonable grounds for relaxing the criterion $\tau < 10^{-4}$ s significantly. These factors make our results and conclusion solid.

(2) In case I, $R_c \sim 10^6$ cm is assumed, as RS proposed, to obtain the gap height. This curvature radius requires a scenario of strong multipolar magnetic field near the polar cap, which has been proposed by some authors (e.g. Gil 1985; Asseo & Khechinashvili 2002). In this case, on one hand, the configuration of field lines will differ from the dipole when very close to the polar cap surface, on the other hand, strong surface magnetic field (e.g. 10 to 100 times the observed value derived from P and $\dot{P}$, viz. $B_s \simeq 3.2 \times 10^{19} (P\dot{P})^{1/2}$G, where $\dot{P}$ is the period derivative) is helpful to reduce τ. The latter factor may be much more effective in reducing τ than the former. Unfortunately, until now we still have no clear picture of the multipolar component on any pulsar to evaluate its effect. Direct observational evidence is expected to probe the multipolar magnetic field.

(3) A possible alternative mechanism is that one sparking may trigger a nearby sparking due to the $\boldsymbol{E} \times \boldsymbol{B}$ drifting effect (RS), which may result in the subpulse drifting phenomenon. However, two observational facts seem to show that different sparks have no or a weak relation:

the first is that a number of substructures separated on timescale of 10^{-4} s are observed in an individual pulse, indicating that some sparks may occur simultaneously, the second is that no subpulse drifting is observed in MSPs. Anyway, the dynamics needs to be studied further by considering the interaction between the two triggering mechanisms; perhaps it is just the copious pairs created by the background gamma photons that help the sparks drift.

Acknowledgements We are grateful to Dr. B. Zhang and Dr. J.L. Han for their helpful comments and discussions. This work is supported by National Nature Science Foundation of China (10073001, 10173002, 10273001), and by the Special Funds for Major State Basic Research Projects of China.

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