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in Spin-Powered Pulsars**

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T. Kamae and Y. Sekimoto

Dept. of Physics, Univ. of Tokyo, Bunkyo-ku, Tokyo 113, Japan

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department of physics
university of tokyo
bunkyo-ku
tokyo
japan

A UNIFIED PICTURE FOR HIGH ENERGY EMISSION IN SPIN-POWERED PULSARS

T. KAMAE¹ AND Y. SEKIMOTO²

Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan

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¹E-mail: kamae@phys.s.u-tokyo.ac.jp

²E-mail: sekimoto@phys.s.u-tokyo.ac.jp

ABSTRACT

Based on recent studies of soft γ -rays from PSR B1509–58, stability of the X-ray pulse from the Crab pulsar, and the interpulse emission from the Crab pulsar, a unified picture for high energy emission in spin-powered pulsars is proposed. The picture assumes that pulsed X-rays and γ -rays are emitted both from the polar cap and outer gap regions. We then note that the luminosity and characteristic energy of emitted X-rays and γ -rays are expected to scale differently to the pulsar parameters, because the relevant physics processes are different in the two regions. We assume two baseline emissions, the Crab broad interpulse emission for the polar cap region, the Vela double peak emission for the outer gap region, and, scale them to predict high energy emissions from other pulsars.

The luminosity and energy range of the predicted pulsed emissions agree reasonably well with observations for PSR B1509–58: the observed broad X-ray/soft γ -ray emission comes from the polar cap region, while the double peak emission expected from the outer gap region is probably too faint for EGRET to observe. A broad polar cap emission is predicted for the Vela pulsar in the MeV range at a luminosity between the Crab interpulse and the broad PSR B1509–58 pulse.

Subject headings: Pulsars: General — Acceleration of Particles — Gamma Rays: Theory — X-Rays: Stars

1. INTRODUCTION

Since the first discovery in 1967, more than 500 pulsars have been reported, mostly in the radio band (Taylor, Manchester, & Lyne 1993). Most of these pulsars are believed to be strongly magnetized, isolated neutron stars, spinning rapidly and converting their rotational energy to electromagnetic emission. These spin-powered pulsars are characterized by the period (P) and the period-derivative ($\dot{P}$) of the rotation: its age, surface magnetic field, and rotational energy loss rate are derived from these two parameters on the magnetic dipole radiation hypothesis (Pacini 1967; Pacini 1968; Gunn & Ostriker 1969).

High energy emission has been detected only from a very small fraction of isolated pulsars (eg. Friedlander, Gehrels, & Macomb 1993). The Crab and Vela pulsars have the two best studied in the X-ray, soft γ -ray, and high energy γ -ray bands (Knight 1982; Wilson & Fishman 1983; Harnden & Seward 1984; Mahoney et al. 1984; White et al. 1985; Agrinier et al. 1990; Nolan et al. 1993). PSR B1509–58 was discovered in the X-ray band (Seward & Harnden 1982) and has been studied recently in the soft γ -ray band (Ulmer et al. 1993; Gunji et al. 1994) as well as in the X-ray band (Kawai et al. 1991). Recent additions to the list include Geminga (Halpern & Holt 1992; Bertsch et al. 1992; Mayer-Hasselwander et al. 1994), PSR B1706–44 (Thompson et al. 1992), and PSR B1055–52 (Fierro et al. 1993).

Observed high energy photons from spin-powered pulsars are believed to be emitted by electrons and positrons moving at ultra-relativistic speeds in neutron stars' magnetosphere. Accelerating force is provided by the electric potential built up through magnetic induction in the fast spinning magnetosphere (Goldreich & Julian 1969). Models have been proposed to describe basic features of high energy emissions from pulsars (eg. Arons 1990; van Riper, Epstein, & Ho 1993). In them, pulsars are modeled

from 2 points of view: one view taken by global models aims at reconstructing global flows of charge, energy, and angular momentum (eg. Arons 1990; Michel 1991b), while the other view taken by phenomenological local models puts emphasis on reproducing observed high energy emission. No global model has yet attempted to fit observed spectra in real pulsars and hence we will confine our discussions to phenomenological local models.

Phenomenological local models are classified into 2 groups, according to the location where high energy emission takes place (eg. Arons 1990); polar cap models and outer gap models. In polar cap models, e^+e^- cascades develop above the magnetic poles and generate high energy photons (Sturrock 1971; Ruderman & Sutherland 1975). Outer gap models assume that electrons and positrons are accelerated, one inward and the other outward, in the “gaps” located between the null surface and the light cylinder. A wide spectrum of photons are then produced via synchrotron radiation and inverse Compton scattering, which in turn generate e^+e^- pairs via photon-photon collisions and complete a self-sustaining loop (Cheng, Ruderman, & Sutherland 1976).

Several phenomenological models have tried to reproduce X-ray/ γ -ray emissions for one or few selected spin-powered pulsars with some success (eg. Cheng, Ho, & Ruderman 1986a, 1986b; Harding 1981). The number of observed X-ray/ γ -ray pulsars has increased and it has become more difficult to explain observed variety of spectra and pulse profiles within either the polar cap emission or the outer gap emission.

The most successful prediction has been the one made by the outer gap model (Cheng et al. 1986a; Cheng et al. 1986b) and also by the polar cap model (Harding 1993) that the pulsed luminosity normalized by the rotational energy loss increases and the emission energy range moves upward as the pulsar period elongates. This “scaling approach” seems to point out a possible path to a deeper understanding of the pulsar emission mechanism. We have been involved in the observational studies

of soft γ -ray emission from PSR B1509–58 (Gunji et al. 1994), interpulse X-ray/soft γ -ray emission from the Crab pulsar (Sekimoto 1994; Ezawa et al. 1994), and X-ray pulse-to-pulse fluctuation in the Crab pulsar (Sekimoto 1994; Sekimoto et al. 1994) and come to apply the scaling approach in analyzing these data.

In this paper, we will first bring to readers' attention that PSR B1509–58, supposedly a twin of the Vela pulsar in the outer gap model (eg. Ho 1993), emits photons predominantly in much lower energy range than the Vela pulsar (Gunji et al. 1994). We will then find generic formulae prescribing the intensity and energy scale of pulsed high energy emission in the polar cap and outer gap models. We will define two baseline X-ray/ γ -ray emission spectra, one for the polar cap emission and the other for the outer gap emission, and scale their luminosities and characteristic energies according to the generic formulae and the relevant pulsar parameters. The parameters are the radius of the curvature (ρ) and the strength (B_s) of the surface magnetic field, and the rotation period (P).

We note that dependence of the pulsar emission spectrum on age, P , and/or B_s have been studied in recent years in outer gap models (Pacini & Salvati 1987; Chen & Ruderman 1993) and in polar cap models (Harding 1993; Dermer & Sturmer 1994).

2. DIFFICULTIES WITH POLAR CAP AND OUTER GAP MODELS

Polar cap models can be traced back to the works by Sturrock (1971) and Ruderman & Sutherland (1975). Refinements have been made and new ideas have been added to form several variants by Arons & Scharlemann (1979), Arons (1983, 1984); Harding (1981), Daugherty & Harding (1982); Michel (1982, 1991a, 1991b), Harding, Ozerney, & Usov (1993); and Beskin, Gurevich & Istomin (1993). In these models acceleration

regions appear near the magnetic poles of a neutron star where magnetic induction voltage builds up. Electrons and positrons produced in the region or extracted from the boundary surfaces are accelerated to high energies, initiate $e^+ e^-$ cascade showers, and consequently suppress the voltage build up until an equilibrium is reached. These electrons and positrons move around at relativistic speeds and emit high energy photons. The flux, directionality, and spectrum of these photons are determined by the total area of the polar cap region, the energy $e^+ e^-$ attain, and the strength and curvature of the local magnetic field.

An outer gap model was first proposed by Cheng, Ruderman, & Sutherland (1976), and developed later by Cheng, Ho, & Ruderman (1986a; 1986b) to describe high energy emission from the Crab and Vela pulsars. In later discussion we take this version of outer gap model as the outer gap model and refer it as the CHR model. In this CHR model, charged particles ($e^\pm$) are accelerated between the null surface and the light cylinder along the boundary between the closed and open parts of the magnetosphere. The following interrelated processes make up a self-sustaining outer gap accelerator : inverse Compton scattering between accelerated $e^\pm$ and soft photons produces highest energy γ -rays (primary γ -rays); collisions between the primary γ -rays and soft photons produce secondary $e^\pm$ pairs; synchrotron photons from these secondary $e^\pm$ pairs produce tertiary $e^\pm$ pairs; synchrotron radiation from the tertiary $e^\pm$ pairs supplies the soft photons. Observed X-rays and γ -rays are sum of primary γ -rays and synchrotron photons emitted by the secondary $e^\pm$ pairs.

The polar cap region is characterized by strong magnetic field ($B \sim 10^{12 \sim 13}$ G) and small curvature radii of magnetic field lines ($\rho \sim 10^{6 \sim 7}$ cm). Photons with energy higher than ~ 100 MeV will be converted immediately to $e^\pm$ pairs in this strong magnetic field (eg. Arons 1984, Chen & Ruderman 1993) and can not escape the region. The most serious difficulty common to polar cap models lies, therefore, in

explaining observed γ -ray emissions in the energy range above 100 MeV (eg. in the Crab, Vela, and Geminga pulsars). Several attempts have been made to boost up the maximum photon energy to the GeV range (Daugherty & Harding 1982; Arons 1984). These attempts, however, have faced difficulties: in the model by Arons (1984), steady acceleration is said to be difficult. The pulsed X-ray emission from the Crab pulsar has been known to be stable (Harnden & Seward 1984; Sekimoto et al. 1994) and an upper limit of 7.2 % has been set on the pulse-to-pulse fluctuation (Sekimoto 1994; Sekimoto et al. 1994). The model by Daugherty & Harding (1982) assumes a total current flow more than two orders of magnitude higher than Arons' model and is regarded unrealistic by Arons (1984). Chen & Ruderman (1993) argued that the observed pulsed optical emission from the Crab pulsar is hard to understand in polar cap models in the following reason. Firstly they noted that, the processes capable of producing optical photons (synchrotron radiation, curvature radiation, and inverse Compton scattering) are inefficient under strong magnetic field ($B > 10^8$ G). The pulse profile of the optical emission being almost identical to that of the γ -ray emission, suggests a similar emission mechanism for the two emissions at least in the Crab pulsar, that is, an outer gap emission. The breadth of the pulse profile depends on the angle between the line of sight and the rotational axis, the angular distribution of photons relative to local magnetic field lines, and the longitudinal distribution of emission region along magnetic field lines (eg. Smith et al. 1988). The polar cap emission takes most probably a single peak profile, but a double peak profile is also possible if both the line of sight and the magnetic dipole axis are perpendicular to the rotational axis.

In the CHR outer gap model, the highest energy is determined primarily by the mean free path of $e^\pm$ for synchrotron radiation which ends up to be only a small fraction of the total gap voltage (Cheng et al. 1986b). Because magnetic field is weak

in the outer gap region, high energy photons can escape freely once emitted, and hence emission spectra can extend to the GeV range as in the Crab and Vela pulsars. The model predicts the emission spectrum to shift to higher energies and the conversion efficiency of the rotational energy loss to increase for slower pulsars such as the Vela and Geminga pulsars (Ruderman & Cheng 1988). This latter prediction is also in agreement with a recent observation of the Geminga pulsar (Halpern & Ruderman 1993). On the theoretical side, the outer gap model may face a difficulty explaining where and how the inward particle flow terminates. For example, Arons (1990) has criticized that the power of radiative output is overestimated by an order of magnitude in the outer gap model by Cheng et al. (1986b).

A recent observation of soft γ -ray emission from PSR B1509–58 challenges the CHR outer gap model. The emission spectrum of PSR B1509–58 is predicted to be similar to that of the Vela pulsar but its energy range has turned out to be off by 3 orders of magnitude in the study by Gunji et al. (1994).¹

A variety of pulse profiles is predicted in the CHR model. Photon beams point both inward and outward, and the line of sight may intersect widely open emission cones several times (Cheng et al. 1986b), allowing 4 peaks to appear in the pulse profile. If the current flow of $e^\pm$ from the polar cap to the outer gap is roughly conserved, the transverse size of the outer gap will be much thinner than that of the polar cap. The directional divergence of the outer gap emission is therefore expected to be sharper than that of the polar cap emission. A Monte Carlo simulation by Chiang & Romani

¹The luminosity normalized by the rate of the rotational power loss $L_{outer\ gap}/\dot{E}$ was taken to be proportional to $B^2 P^{-5}$ in Gunji et al. (1994) as is suggested in the paper by Cheng et al. (1986b). We have noted that this proportionality relation may not apply to a Vela-type gap with a Vela-like parameter, as will be discussed later in the text. For PSR B1509–58, this change does not affect the discussions and conclusions given in Gunji et al. (1994). We thank K. S. Cheng for discussion on this point.

(1992) has produced, in fact, a sharper peak for the outer gap emission.

3. OUR UNIFIED PICTURE

We propose a unified picture that the pulsed X-ray/ γ -ray emission from young spin-powered pulsars consists of both the polar cap emission and the outer gap emission: the observed pulsed emission from PSR B1509–58 and the interpulse emission from the Crab pulsar (the "broad soft γ -ray emission") are produced in the polar cap region, while the double-peak emission from the Crab and Vela pulsars (the "spiky power-law emission") are produced in the outer gap region. We will argue below that the broad soft γ -ray emission and the spiky power-law emission bear the characteristic features expected for the emissions from the polar cap and outer gap regions, respectively.

Another idea that the two emission regions may co-exist has been proposed by Heyvaerts & Signore (1981) to explain the spiky power-law γ -ray emission from the Vela pulsar. Assuming a parallel rotator ($\vec{\Omega} \times \vec{\mu} = 0$), they interpreted that the pulsed emissions below and above 1 GeV are produced in the outer gap and polar cap regions, respectively. This idea is not widely accepted now because the spectrum and the pulse profile of the Vela γ -ray pulse appears basically unchanged below and above 1 GeV. Our picture differs from that of Heyvaerts & Signore (1981) in that we consider emissions from the two regions to have distinct pulse profiles and spectra. We also note that the global models by Shibata (1991) and by Beskin et al. (1993) expect emissions in the polar cap and outer gap regions. No concrete prediction has been made on the emission in these global models.

4. SCALING RULES

We first assume double-peak emissions extending to the high energy γ -ray band are characteristic of the outer gap emission and take the spiky power-law emission from the Vela pulsar as its baseline. We note here that, in the outer gap model, the emission from the Crab pulsar is considered to be special and not applicable to that from other slower pulsars (Cheng et al. 1986b). Secondly we assume that the interpulse of the Crab pulsar comes from the polar cap region and take this broad soft γ -ray emission as the baseline of the polar cap emission. The Crab interpulse fills between the double peaks and has a harder power-law index (Ezawa et al. 1994) until the spectrum is cut off somewhere below 50 MeV (Nolan et al. 1993). This spectral feature is in general agreement with expected characteristics of the polar cap emission.

The X-ray/ γ -ray luminosity of the polar cap emission ($L_{polar\ cap}$) will be proportional to the number of $e^\pm$ generated within the polar cap per unit time ($\dot{N}$) (eq. 10 in Ruderman & Sutherland 1975), which is determined by plasma density and polar cap area,

$$L_{polar\ cap} \propto \dot{N} \propto B_s P^{-2}. \quad (1)$$

Here B_s is the magnetic field on the neutron star surface. Rotational energy loss rate ($\dot{E}$) by magnetic dipole radiation is proportional to

$$\dot{E} \propto B_s^2 \Omega^4 R_{NS}^6 \propto B_s^2 P^{-4}, \quad (2)$$

where R_{NS} is the neutron star radius. The luminosity normalized by the rotational energy loss rate for the polar cap emission is then,

$$\frac{L_{polar\ cap}}{\dot{E}} \propto \frac{\dot{N}}{\dot{E}} \propto \frac{B_s P^{-2}}{B_s^2 P^{-4}} = B_s^{-1} P^2. \quad (3)$$

The photon energy characterizing the polar cap emission is the maximum energy ($h\nu_{max}$) below which photons can escape from the strong magnetic field. Photons

with energies higher than several MeV will be attenuated by magnetic pair production ($\gamma + B \rightarrow e^+ e^-$) if the magnetic field transverse to the photon momentum ($B_\perp$) is strong ($> 10^{12}$ G) (Toll 1952; Klepikov 1954; Erber 1966). Photons produced parallel to a magnetic field line soon deviate from the field line because it is curved. The attenuation coefficient depends heavily on photon energy and $B_\perp$ (Erber 1966), and the maximum energy of escaping photons is determined by the following formula (eg. eq. 6 in Arons 1984),

$$h\nu_{max} = 50\text{MeV} \left(\frac{1 \times 10^{12} \text{Gauss}}{B_s} \right) \left(\frac{\rho_c}{1 \times 10^6 \text{cm}} \right). \quad (4)$$

The radius of curvature of the magnetic field, ρ_c , near the neutron star surface is difficult to estimate because the field may not be that of a pure dipole located at the center of the neutron star (Ruderman & Sutherland 1975). Nevertheless, we will use ρ_c calculated assuming a pure dipole field

$$\rho_c = \sqrt{cR_{NS}/\Omega}. \quad (5)$$

According to the above formula ρ_c will be 1.3×10^7 , 2.1×10^7 , and 2.8×10^7 cm for the Crab pulsar, Vela pulsar, and PSR B1509–58, respectively. We note here that Ruderman & Sutherland (1975) have argued that ρ_c can be as low as 10^6 cm if multipole components are strong near the neutron star surface. For some slow-rotating pulsars the emission region may be high above the polar surface: then B_s will be weaker and ρ_c larger than our estimate based on a purely dipolar field. These uncertainties will be represented by error bars in our graphic presentations.

As has been described earlier, we generally expect a single broad pulse for the polar cap emission. For soft γ -rays below ~ 1 MeV, attenuation by magnetic pair production will be negligible and the angular distribution of emitted photons will be quite wide ($\sim m_e c^2 / E_\gamma$). The pulse width will not be determined by the opening angle of polar magnetic field lines as in the radio pulse emission. We believe that the pulse profile

observed for PSR B1509–58 is such an example.

The luminosity of the outer gap emission is determined by the total number of primary electrons/positrons in the accelerator and the potential drop of the accelerator (Cheng et al. 1986b). In Cheng et al. (1986b) the luminosity normalized by the rotational energy loss rate is predicted to scale as eq. 6 below. In the paper, however, we see a possibility that if PSR B1509–58 has a Vela-type gap with a Vela-like parameter eq. 4.19 applies instead of eq. 4.19' and the scaling rule takes a different form eq. 7 below.

$$\frac{L_{outer\ gap}}{\dot{E}} \propto B_s^{-2} P^5. \quad (6)$$

$$\frac{L_{outer\ gap}}{\dot{E}} \propto \text{const.} \quad (7)$$

Numerically the difference between eq. 6 and 7 is only 2.5 : 1 for PSR B1509–58 and does not affect our discussion. Since spiky double-peak emissions are known to scale roughly according to eq. 6 (Chen & Ruderman 1993), we adopt eq. 6 for all pulsars with a Vela-type gap.

In the outer gap model, the energy spectrum is characterized by the synchrotron critical frequency ($h\nu_c$) of the most abundant charged particles, that is, the secondary e^+e^- pairs (eq. 3.4 in Cheng et al. 1986b),

$$h\nu_c = \gamma_{\perp}^2 \gamma_{\parallel} \frac{eB_{lc}}{mc} \propto \gamma_{\parallel}^3 \Omega^2 B_{lc}^{-3}. \quad (8)$$

Here, γ is the Lorentz boost factor of the secondary e^+e^- , $\gamma_{\parallel}$ and $\gamma_{\perp}$ are its components parallel and perpendicular to the magnetic field, and B_{lc} is the magnetic field strength at the light cylinder. We note here that the magnetic field strength in the outer gap is taken to be that at the light cylinder, which may be off by a large factor. We will assume this factor to be 5 later. In the CHR outer gap model, voltage developed in a segment of the outer gap accelerator is determined by magnetic induction or the number of field lines the accelerator segment crosses per unit time (Cheng et al.

1976; Cheng & Ruderman 1977; Cheng et al. 1986a; Cheng et al. 1986b). The maximum energy $e^\pm$ pairs can attain is, however, limited by energy loss due to synchrotron radiation and inverse Compton scattering, and consequently, the parallel Lorentz factor ($\gamma_\parallel$) saturates before reaching a small fraction ($< 1/10$) of the total acceleration voltage, at around a constant value almost independent of pulsar parameters (Cheng et al. 1986b). The critical energy (eq. 8) is then proportional to,

$$h\nu_c \propto \Omega^2 B_{lc}^{-3} \propto B_s^{-3} P^7. \quad (9)$$

Luminosities normalized by rotational energy loss rate ($L/\dot{E}$) have been scaled, according to eq. 3, from the observed Crab interpulse emission to predict polar cap emissions, and, according to eq. 6, from the Vela double-peak emission to predict outer gap emissions to make predictions on 6 known pulsars (Table 1). Here we have assumed that the baseline polar cap emission has a power-law spectrum with a photon index of $\alpha = -1.5$ up to the predicted maximum photon energy $h\nu_{max}$ (eq. 4). The baseline outer gap emission, on the other hand, is assumed to have a power-law spectrum with a photon index of $\alpha = -1.8$ up to a cut off energy ($h\nu_{max}$) that scales proportionally to the critical photon energy ($h\nu_c$) (eq. 9). The differential luminosity dL is then related to the total luminosity L as

$$dL \propto E^\alpha E dE. \quad (10)$$

If the minimum emission energy ($h\nu_{min}$) is much lower than $h\nu_{max}$ and $\alpha > -2.0$, the differential luminosity between E_1 and E_2 is

$$L_{\Delta E} \propto \int_{E_1}^{E_2} dL \propto L (h\nu_{max})^{\alpha+2}, \quad (11)$$

where E_2/E_1 is set to be 2. From eqs. 3, 4, 6, and 9 we get the scaling rules for $L_{\Delta E}/\dot{E}$ as

$$L_{\Delta E}/\dot{E} \propto B_s^{-1/2} P^{7/4} \quad (\text{polar cap emission}), \quad (12)$$

$$L_{\Delta E}/\dot{E} \propto B_s^{-7/5} P^{18/5} \quad (\text{outer gap emission}). \quad (13)$$

5. COMPARISON WITH OBSERVATIONS

The fact we do not know the inclination angle between the spin axis and the magnetic dipole axis of a neutron star, the effective solid angle fraction covered by the pulse emission, and the radius of curvature (ρ_c) near the neutron star surface need to be reflected as uncertainties in our predictions. The surface magnetic field (B_s) has been calculated from P and $\dot{P}$ assuming energy loss by magnetic dipole radiation in our estimations (Table 1) assuming the inclination angle to be 90 degree. The inclination angle has been deduced from radio observations by Lyne & Manchester (1988), by Rankin (1990), and by Miller & Hamilton (1993). The inclination angle of the Vela pulsar is, for example, estimated to be 90 degree by Lyne & Manchester (1988) and 65 degree by Halpern & Ruderman (1993). This difference leads to an error of ± 10 % for the surface magnetic field. The effective solid angle fraction is assumed to be 60 %, but probably with an error around ± 30 %. In the polar cap region, the radius of curvature of the magnetic field lines will deviate from the pure dipole approximation if higher multi-pole components exist (Ruderman & Sutherland 1975). We do not have any reasonable way to estimate error but assume an error factor of 5 to represent these uncertainties.

Our predictions are shown in Figure 1 and Figure 2 with the error factor of 5 quoted above. Note that $L_{\Delta E}/\dot{E}$ has been scaled by using eqs. 12 and 13, and its scaling factors are given in the 4th rows of Table 1. We note that $L_{\Delta E}/\dot{E}$ of PSR B1509–58 for the polar cap emission is 7 times higher than that of the Crab pulsar and covers about the same energy band. This is in a good agreement with the observation (Gunji et al. 1994). Our picture predicts polar cap emission in the Vela pulsar to have a

luminosity comparable to or lower than the present upper limits as shown in Figure 2: it may well be observable by Comptel on CGRO in near future.

The interpulse emission from the Geminga pulsar has been detected up to 1 GeV by Mayer-Hasselwander et al. (1994). If we had scaled from the Crab interpulse emission, the prediction would have been comparable to the observation but the energy range would have come out to be higher than the observation. We consider the Geminga pulsar non-standard as far as the polar cap emission is concerned, because radio emission is absent in the Geminga pulsar. It is likely that e^+e^- cascades do not develop and the polar cap accelerator is not shorted out in the Geminga pulsar. In such a case, lower density e^+ or e^- cloud can flow out of the polar cap region and particles can acquire much higher energy as they reach the outer region where magnetic field is much lower. This flow may continue to the outer gap where the self-sustaining accelerator operates. The pulsed soft X-ray emission discovered by ROSAT (Halpern & Holt 1992) is probably not the polar cap emission discussed here and the interpulse emission in the GeV range detected by EGRET (Mayer-Hasselwander et al. 1994) may be due to those e^+ or e^- traveling between the polar cap region and the outer gap region.²

Our unified picture predicts double-peak outer gap emission for PSR B1509–58 at a luminosity level comparable to that of the Vela pulsar. The flux at Earth will be about 1/100 of that of the Vela pulsar, because the distance to PSR B1509–58 is 8 times that to the Vela pulsar (see Table 1): this flux is probably below the present detection limit of EGRET on CGRO. Our scaling rule prediction on the outer gap emission from the Geminga pulsar agrees with the observed luminosity but the predicted energy range is higher than the observation by about two orders of magnitude.

²We benefited from discussion with K. S. Cheng on this point.

6. RELATIVE PHASE BETWEEN THE TWO EMISSIONS

In our picture we assume the relative phase between the polar cap and outer gap emissions to be that in the Crab pulsar. The phase at which a photon is detected depends on the azimuthal and radial position of the emission region (eg. Smith et al. 1988). The polar cap emission region is uniquely defined but the position and orientation of the outer gap emission region is not specified by the model. The phase of the recently observed sinusoidal X-ray pulse from Geminga (Halpern & Holt 1992) falls between the two sharp peaks observed at higher energies (Halpern & Ruderman 1993). If the X-ray pulse is from the polar cap as interpreted by Halpern & Ruderman (1993), we will be led to make a guess that the relative phase between the polar cap emission and the outer gap emission remains constant, roughly independent of the pulse period.

7. CONCLUSION

We have proposed a unified picture for the X-ray/ γ -ray emission from spin-powered pulsars: the double-peak power-law γ -ray emission from the Crab, Vela, and Geminga pulsars comes from the outer gap region, while the broad soft γ -ray emission of the Crab interpulse and PSR B1509–58 comes from the polar cap region. The luminosity and the energy band are expected to scale on P , B_s , and ρ_c , according to the basic equations derived for the outer gap and polar cap emissions. By assuming the interpulse emission from the Crab pulsar and the double-peak emission from the Vela pulsar as the baseline polar cap and outer gap emissions, respectively, we have made predictions on pulsed X-ray/ γ -ray luminosities and energy bands of the two emissions for known pulsars. The predictions are consistent with observations except for the Geminga pulsar. Our predictions are only partially successful for emissions from the Geminga pulsar. For the polar cap emission this may be related to the fact that pulsed

radio emission is absent in the Geminga pulsar.

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TABLE 1

Predictions in the polar cap and outer gap emissions

- ^a Relative to the Crab interpulse
- ^b Relative to the Vela pulsar
- ^c $L_{\Delta E}$ has been calculated by using eqs. 12 and 13 in the text.
- ^c Taken from Seward (1985).
- ^e Taken from Halpern & Ruderman (1993).
- ^f Quoted in Thompson et al. (1992).
- ^g Taken from Ögelman & Finley (1993).

TABLE

Table 1:

		Crab	1509-58	Vela	Geminga	1706-44	1055-52
P (ms)	-	33.4	150.7	89	237.1	102.4	197
$\dot{P}$ (s/s)	-	4.2E-13	1.54E-12	1.3E-13	1.1E-14	9E-14	6E-15
$B_s(1 \times 10^{12} \text{ G})$	-	4.7	19.3	4.2	2.1	3.9	1.4
$\dot{E}_{\text{rot}}(1 \times 10^{35} \text{ erg/s})$	$B^2 P^{-4}$	4.4E+03	1.8E+02	7.0E+01	3.4E-01	3.4E+01	3.0E-01
Distance (kpc)	-	2.0 ^d	4.2 ^d	0.5 ^d	0.25 ^e	1.5 ^f	0.5 ^g
polar cap emissions							
$h\nu_{\text{max}}$ (MeV)	$B^{-1} P^{1/2}$	135.0	70.5	247.5	819.5	286.9	1148.9
$L_{\text{polar cap}}^{\text{a}}$	$B P^{-2}$	1.0E+00	2.0E-01	1.3E-01	8.8E-03	8.9E-02	8.3E-03
$L_{\text{polar cap}}/\dot{E}^{\text{a}}$	$B^{-1} P^2$	1.0E+00	5.0E+00	8.0E+00	1.2E+02	1.1E+01	1.2E+02
$L_{\Delta E}/\dot{E}^{\text{a c}}$	$B^{-1/2} P^{7/4}$	1.0E+00	7.0E+00	6.0E+00	4.7E+01	7.9E+00	4.2E+01
$L_{\text{polar cap}}/\dot{E}/h\nu_{\text{max}}^{\text{a}}$	$P^{3/2}$	1.0E+00	9.6E+00	4.4E+00	1.9E+01	5.4E+00	1.4E+01
outer gap emissions							
$h\nu_c^{\text{b}}$	$B^{-3} P^7$	7.7E-04	4.3E-01	1.0E+00	8.2E+03	3.5E+00	8.2E+03
$L_{\text{outer gap}}^{\text{b}}$	P	5.9E-03	6.7E-01	1.0E+00	5.5E+02	2.3E+00	5.2E+02
$L_{\text{outer gap}}/\dot{E}^{\text{b}}$	$B^{-2} P^5$	9.3E-05	2.6E-01	1.0E+00	1.1E+05	4.8E+00	1.2E+05
$L_{\Delta E}/\dot{E}^{\text{b c}}$	$B^{-7/5} P^{18/5}$	2.5E-02	8.0E-01	1.0E+00	9.2E+01	1.9E+00	8.6E+01
$L_{\text{outer gap}}/\dot{E}/h\nu_c^{\text{b}}$	$B P^{-2}$	1.3E-01	6.3E-01	1.0E+00	1.4E+01	1.4E+00	1.5E+01

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FIGURES

- FIG. 1.— Predictions on the polar cap emission ($\bigcirc$) and the outer gap emission ($\square$) from PSR B1509–58.

Solid lines indicate the broken power laws fitted to the observational data; Crab pulsar (total) (Knight 1982; Nolan et al. 1993), Crab (IP) (Sekimoto 1994; Ezawa et al. 1994), PSR B1509–58 (Kawai et al. 1993; Gunji et al. 1994) Vela (Grenier et al. 1988; Strickman et al. 1993), and Geminga (Mayer-Hasselwander et al. 1994).

See the text for the definition of $L_{\Delta E}$.

- FIG. 2.— Predictions for the polar cap emission from the Vela pulsar ($\bigcirc$) and the outer gap emission from the Geminga pulsar ($\square$).

See the text for the definition of $L_{\Delta E}$.

Figure 1:

Figure 2:

FIGURE 1

FIGURE 2