High-energy Emission from Pulsar Outer Magnetospheres

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ABSTRACT

We investigate particle accelerators in rotating neutron-star magnetospheres, by simultaneously solving the Poisson equation for the electrostatic potential together with the Boltzmann equations for electrons, positrons and photons on the poloidal plane. Applying the scheme to the three pulsars, Crab, Vela and PSR B1951+32, we demonstrate that the observed phase-averaged spectra are basically reproduced from infrared to very high energies. It is found that the Vela's spectrum in 10-50 GeV is sensitive to the three-dimensionally magnetic electric field configuration near the light cylinder; thus, a careful argument is required to discriminate the inner-gap and outer-gap emissions using a gamma-ray telescope like GLAST. It is also found that PSR B1951+32 has a large inverse-Compton flux in TeV energies, which is to be detected by ground-based air Cerenkov telescopes as a pulsed emission.

Subject headings: gamma-rays: theory { magnetic fields { methods: numerical { pulsars: individual (B1951+32, Crab, Vela)}

1. Introduction

Pulsars form the second most numerous class of objects detected in high-energy γ-rays. To date, six have been detected by the Energetic Gamma Ray Experiment Telescope (EGRET) aboard the Compton Gamma Ray Observatory. The γ-ray pulsations observed from these objects are particularly important as a direct signature of non-thermal al processes in rotating neutron-star magnetospheres, and potentially should help to discriminate among different emission models.

The pulsar magnetosphere can be divided into two zones: The closed zone, filled with a dense plasma corotating with the star, and the open zone in which plasma flows along the open electric field lines to escape through the light cylinder. The last-open electric field lines form the border of the open magnetic electric field line bundle. In all the pulsar emission models, particle acceleration takes place in this open zone. In inner-gap (IG) models, which adopts particle acceleration within several neutron-star radii above the polar-cap surface, the energetics and pair cascade spectrum have had success in reproducing the observations (e.g., Daugherty & Harding 1982, 1996). However, the predicted beam size is too small to produce the wide pulse profiles that are observed from high-energy pulsars. Seeking the possibility of a wide hollow cone emission due to arcing electric field lines, Muslimov and Harding (2004) extended the idea of Arons (1983) and proposed a slot-gap (SG) model, in which emission takes place very close to the last-open electric field line from the stellar surface to the outer magnetosphere. Since the SG model is an extension of the IG model into the outer magnetosphere, a negative magnetic electric field-aligned electric field, E_k, arises if the magnetic moment vector points in the same hemisphere as the rotation vector. However, the electric current induced by the negative E_k does not have a self-consistent closure within the model (Hirotani 2006, hereafter H06).

To construct an accelerator model that predicts
ions from the star as space-charge-limited conditions, we obtain

\[ c^2 \nabla g + \nabla g = S \quad (r; c, \beta, \gamma, \delta, \kappa) \]  

where the wave numbers \( k^2 \) and \( k \) are given by the ray path, \((r, \beta)\) are the polar coordinates, and the dimensionless photon distribution function \( g \) is normalized by the GJ number density at the stellar surface. ICS, synchro-curvature emission, and the absorption are contained in \( S \). In H06, the rate of synchrotron emission by secondary pairs created outside the gap, was calculated assuming a constant pitch angle. However, it turns out that only 17% of the initial particle energy is converted into radiation. In this letter, we corrected this problem by computing the pitch angle evolution of radiating particles, which increases the synchrotron cooling time and hence recovers the time-integrated, radiated energy to 100% of the initial particle energy. Note that the gap electrodynamicics investigated in H06 remains correct, despite the ins client secondary synchrotron uses in H06.

To solve the Poisson equation, we impose \( \psi = 0 \) at the lower, upper, and inner \((s = 0)\) boundaries, and \( E_k = 0 \) at the outer boundary. Ion extraction rate is regulated by the condition \( E_k = 0 \) at \( s = 0 \). We parameterize the transverse thickness of the gap with \( h_n \). If \( h_n = 1 \) the gap exists along all the open field lines, while if \( h_n = 1 \) the gap becomes transversely thin.

3. Application to Individual Pulsars

We apply the theory to three X-ray pulsars, Crab, Vela, and B1951+32, focusing on their photon spectra. Even near and outside the light cylinder, photon emission and absorption occur actively; thus, equations [1] and [2] are solved in \( 0 < s < 16S_{LC} \), where \( E_k = 0 \) in \( S > 0.9S_{LC} \); \( S_{LC} \) denotes the light cylinder radius, the stellar rotation frequency, and \$ \) the distance from the rotation axis. The field line geometry in the force-free magnetosphere (Cotopoulus et al. 1999; Gruzinov 2005). In \( S > 2S_{LC} \), the field lines are assumed to be straight so that they connect smoothly at \( S = 2S_{LC} \).
3.1. Crab pulsar

We present the results for the Crab pulsar in figure 1, adopting a magnetic inclination of \( i = 75 \) and a dipole moment of \( 4 \times 10^6 \text{G cm}^3 \), which is close to the value \((3.8 \times 10^6 \text{G cm}^3)\) deduced from the dipole radiation formula. It follows that the observed pulsed spectrum from IR to VHE can be reproduced, provided that we observe the photons emitted into \( 75 < < 103 \), where denotes the photon propagation direction measured from the rotational axis. Because of the aberration of light, it is reasonable to suppose that photons emitted in a certain range of \( \nu \) into our line of sight in an obliquely rotating three-dimensional magnetosphere (e.g., RY 95). The \( \nu \) rapidly decreases with decreasing \( \nu \) for \( 75 < < 93 \), because \( E_\nu \) is highly screened in the inner part of the gap. Nevertheless, an average over \( 75 < < 103 \), which includes negligible \( \nu \) between \( 75 < < 89 \), achieves the current objective, because the spectral normalization can be fitted with a factor of a few without changing the spectral shape, by adjusting \( h_m \).

ICS takes place closely near and outside the light cylinder (Aharonian & Bogovalov 2003), because the magnetic IR photons, which are emitted along convex \( \epsilon_\nu \) lines, collide with the gap-accelerated positrons near the light cylinder, where the \( \epsilon_\nu \) lines are concave. Most of such upscattered photons, as well as some of the high-energy tail of the curvature component, are absorbed by the \( \nu \) collisions. As a result, there is a gradual turnover around \( 10 \text{G eV} \), which forms a striking contrast with the steep turnover predicted in IG models due to a magnetic pair creation. The primary curvature component appears between \( 100 \text{M eV} \) and \( 100 \text{G eV} \), while the secondary synchrotron component appears below a few \( \text{M eV} \). Between a few \( \text{M eV} \) and \( 100 \text{M eV} \), the ICS component dominates, because the secondary pairs that have been cooled down below a few hundred \( \text{M eV} \) energetically up-scatter magnetic UV and X-rays to lose energy. Similar spectral shapes are obtained for different values of \( \nu \), \( h_m \), provided that the created current is super-G J, by virtue of the negative feedback e effects (G 06).

3.2. Vela pulsar

Next, we present the results for the Vela pulsar in figure 2 (left). Taking an angle average over \( 75 < < 103 \) (solid line), we can reproduce the observed pulsed spectrum, except for the RXTE results. The primary curvature component appears between \( 100 \text{M eV} \) and \( 10 \text{G eV} \), while the secondary and tertiary synchrotron components appear below \( 100 \text{M eV} \). ICS is negligible for the Vela pulsar because of its weak magnetic emission. Similar spectral shapes are obtained for super-G J solutions, even though we have to adjust \( h_m \) to obtain an appropriate \( \nu \).

In the right panel, we compare the present results with IG (dotted) and OG (dashed) models, where the dash-dotted line denotes the averaged \( \nu \) for \( 75 < < 107 \). It follows that the spectrum between 10 and \( 100 \text{G eV} \) crucially depends on the angles in which the photons that we observe are emitted. Thus, to quantitatively predict the \( \nu \) spectrum from the outer magnetosphere, it is essential to examine the three-dimensional magnetic field structure near and outside the light cylinder.

3.3. PSR B1951+32

Thirdly, we present the spectral model of B1951+32 in figure 3 (left). It follows that the ROSAT and EGRET results are reproduced by taking the \( \nu \) average in \( 75 < < 103 \) (solid line), except for \( 17 \text{G eV} \) \( \nu \), which was derived from only two photons. Because of its weak magnetic field, less energetic synchrotron photons reduce the absorption of the ICS component. The reduced absorption results in a small synchrotron \( \nu \), which further reduces the absorption outside the light cylinder, leading to a large, unabsorbed TeV flux. It also follows that the spectrum turns over at lower energy than the IG model prediction (dotted curve in the right panel, Harding 2001).

It should be noted that the predicted ICS \( \nu \) (above \( 100 \text{G eV} \)) represents a kind of upper limits, because it is obtained by assuming that all the magnetic synchrotron photons illuminate the equatorial region in which gap-accelerated positrons are migrating. Some of such VHE photons materialize as energetic secondary pairs, emitting the synchrotron component between a few \( \text{keV} \) and \( 100 \text{M eV} \). Between \( 100 \text{M eV} \) and
30 GeV, the primary curvature component dominates, which represents the absolute ux (instead of upper limits). Some of such curvature photons have energies above 10 GeV and are clcely absorbed to materialize as less energetic pairs, which emit synchrotron radiation below a few keV. Thus, the spectrum below a few keV also represents the absolute ux.

4. Summary and Discussion

To sum up, the self-consistent gap solutions basically reproduce the observed power-law spectra below a few GeV for the three pulsars examined. The cut-off spectra between 10 GeV and 100 GeV strongly reflect the three-dimensional magnetic ekl configuration near the light cylinder; thus, a discrimination between IG and OG models (e.g., using GLAST) should be carefully carried out. If pulsations are detected above 100 GeV, it undoubtedly indicates that the photons are emitted via ICs near the light cylinder, because VHE emissions cannot be expected in IG models.

Since our analysis is limited within the two-dimensional plane formed by the magnetic ekl lines that thread the stellar surface on the plane containing both the rotational and magnetic axes, azimuthal structure is still unknown. Thus, we cannot present pulse profiles, phase-resolved spectra, or the polarization angle variations in this letter. Since the gap is most active in the outer part of the magnetosphere (unlike previous OG models, which adopt the vacuum solution of the Poisson equation and hence a uniform emissivity), and since the photons will be emitted along the instantaneous particle motion measured by a static observer (unlike the treatment in the OG model of RY 95, who assume a very strong aberration of light near the light cylinder), it is possible that the predicted pulse profiles and so on are quite different from previous OG models. These topics will be discussed in the subsequent paper, which deals with the three-dimensional gap structure near the light cylinder.

The pulsed TeV ux from PSR B1951+32 can be predicted to be above 5 $10^5$ Jy Hz, provided that a certain fraction (more than 30%) of the magnetospheric soft photons illuminate the equatorial region. However, if the poloidal ekl lines are more or less straight near the light cylinder, as demonstrated by Spitkovsky (2006, $g$2) for an oblique rotator, the equatorial region may not be clcely illuminated. In this case, the VHE ux will decrease from the current prediction. There is room for further investigation how to extend the present analysis into three dimensions, and to combine it with time-dependence three-dimensional force-free electrodynamics.

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Fig. 1. | Phase-averaged spectrum of the magnetospheric emissions from the Crab pulsar for $i = 75\degree$, $\rho = 4 \times 10^6$ G cm$^3$ and $h_m = 0.12$. The thick dashed, dash-dotted, dotted and dash-triple-dotted lines represent fluxes into $93 < \theta < 97$, $97 < \theta < 101$, $101 < \theta < 105$, $105 < \theta < 109$; the thin dashed, dash-dotted, dotted ones $109 < \theta < 113$, $113 < \theta < 117$, $117 < \theta < 121$. The thick solid line represents the averaged flux in $75 < \theta < 103$. See Eikenberry et al. (1997) for IR-UV data; Knight (1982), Weisskopf et al. (2004), and Mineo et al. (2006) for X-rays; Nolan et al. (1993), Ulmer et al. (1995), Mouchet al. (1993), Fierro et al. (1998), Kuiper et al. (2001) for 10 MeV (20 GeV); Borione et al. (1997), Tanigori et al. (1998), Hillas et al. (1998), Lessard et al. (2000), and de Naurois et al. (2002) for the upper limits above 50 GeV.
Fig. 2. | Phase-averaged Vela spectrum for $\mu = 4 \times 10^3$ G cm$^3$, $i = 75$ and $b_m = 0.21$. See Manchester et al. (1980) for optical data (open squares), Harding et al. (2002) for X-rays (filled triangles), Kanbach et al. (1994), Ramamurthy et al. (1995b), Fierro et al. (1998), Thompson et al. (1999) for $\gamma$-rays (open circles). Left: Same figure as figure 1. Right: Close up above 100 MeV to compare with IG (Harding & Daugherty 1993) and traditional OG (Romani 1996) models. The solid line is same as the left panel.
Fig. 3. Phase-averaged spectrum of PSR B1951+32 for $i = 2 \times 10^9$ G cm$^{-3}$, $i = 75$ and $h_0 = 0.39$. Lines represent same quantities as figure 2 unless noted. See Clifton et al. (1988) for IR upper limits (open squares), Becker & Trumper (1996), Sa Haib et al. (1995) and Chang & Ho (1997) for X-ray data (open triangles), Ramanamurthy et al. (1995a), for 100 MeV-15 GeV data (open circles), Srinivasan et al. (1997) for VHE upper limits.