



The Gamma-Ray Pulsar Phenomenology in View of 3D Kinetic Global Magnetosphere Models

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Abstract

We develop kinetic plasma models of pulsar magnetospheres with magnetic-field-line-dependent plasma injection that reveal the importance of various magnetosphere regions in regulating the γ -ray emission. We set different particle injection rates for the so-called open, closed, and separatrix zones. Moderate particle injection rates in open and closed zones ensure a global field structure close to the force-free structure, while the dissipation occurs mainly in and around the equatorial current sheet. The particles that are injected into the separatrix zone affect the particle populations that enter the equatorial current sheet region, and therefore the corresponding accelerating electric fields, particle energies, the spectral cutoff energy, and γ -ray efficiency. The separatrix zone models reproduce the recently discovered fundamental plane of γ -ray pulsars consistent with curvature radiation emission, the γ -ray light-curve shapes, and the radio-lag versus peak-separation correlation reported in the Fermi second pulsar catalog. The model beaming factors indicate that the pulsar total γ -ray luminosities listed in the Fermi catalogs are overestimations of the actual ones. We find that the radiation reaction limited regime starts ceasing to govern the high-energy emission for $\dot{E} \lesssim 10^{34} \text{ erg s}^{-1}$. Our results also indicate that toward high magnetic inclination angles, the V point around the rotational equator migrates well inside the light cylinder, sparking additional peaks in the γ -ray pulse profiles. We find that an equivalent enhanced particle injection beyond the V point strengthens these features, making the model γ -ray light curves inconsistent with those observed.

Unified Astronomy Thesaurus concepts: Pulsars (1306); Gamma-rays (637); Gamma-ray telescopes (634); Computational methods (1965); Neutron stars (1108)

1. Introduction

Over the past decade, the Fermi Large Area Telescope (LAT) has greatly increased the number of γ -ray rotation-powered pulsars detected between 30 MeV and 300 GeV. The LAT has detected over 270 new γ -ray pulsars to date, 117 of which were compiled in the Second Fermi Pulsar Catalog (2PC; Abdo et al. 2013) and more are expected later this year in the forthcoming Third Pulsar Catalog (3PC).

The Fermi data largely ruled out the possibility that the observed γ -rays originate from near the stellar surface, implicating the outer magnetosphere as the region of the pulsar γ -ray emission in most pulsars. Moreover, the patterns of the γ -ray light curves show clear dependence of the γ -ray pulse peak separation Δ on the phase-lag between radio and γ -ray emission δ . This important multi-wavelength correlation sets strict constraints on the pulsar emission physics and geometry (Bai & Spitkovsky 2010; Contopoulos & Kalapotharakos 2010; Kalapotharakos et al. 2014). These studies indicated that the equatorial current sheet (ECS), a characteristic feature of the force-free (FF) global magnetosphere solutions (Contopoulos et al. 1999; Spitkovsky 2006; Timokhin 2006) emerging at and beyond the light cylinder (LC), was a prime candidate region for the observed γ -ray pulsar emission.

Kalapotharakos et al. (2017), assuming curvature radiation in the radiation reaction limited (RRL) regime that occurs at the ECS region near the LC, demonstrated that the LAT data imply

the corresponding accelerating electric-field components, E_{acc} , and their dependence on the spin-down power \dot{E} , uncovering the corresponding operational regime, i.e., the dissipation degree of the emitting region.

More recently, Kalapotharakos et al. (2019), using 88 γ -ray pulsars from the 2PC, showed that the entire γ -ray pulsar population, i.e., millisecond pulsars (MPs) and young pulsars (YPs), lie on a fundamental plane (FP)

$$L_{\gamma} \propto \epsilon_{\text{cut}}^{1.38 \pm 0.24} B_{\text{st}}^{0.17 \pm 0.05} \dot{E}^{0.41 \pm 0.08} \quad (1)$$

that relates their total γ -ray luminosity, L_{γ} , spectral cutoff energy, ϵ_{cut} , stellar surface magnetic field, B_{st} , and spin-down power, \dot{E} . Remarkably, the observed FP is consistent with the theoretically expected behavior

$$L_{\gamma} \propto A_{\text{cut}}^{1/3} B_{\text{st}}^{1/6} \dot{E}^{5/12} \quad (2)$$

that attributes the pulsar γ -ray emission to curvature radiation in the RRL¹ by particles accelerated in the ECS just outside the LC.

Kalapotharakos et al. (2022)² expanded the pulsar sample by more than two-fold to 190, which they used to update the FP

¹ Kalapotharakos et al. (2022) showed that the RRL regime is a sufficient but not necessary condition for the derivation of the FP theoretical scaling, i.e., Equation (2).

² They adopted the spectral analysis data from the 12 yr incremental version of the fourth Fermi-LAT catalog of point γ -ray sources (4FGL, Abdollahi et al. 2020; 4FGL-DR1, for Data Release 1, Fermi-LAT collaboration et al. 2022) combined with data from the Australia Telescope National Facility (ATNF) Pulsar Catalog (Manchester et al. 2005).



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