Pulsar Slot Gaps and Unidentified EGRET Sources

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Abstract. A new picture of pulsar high-energy emission is proposed that is different from both the traditional polar cap and outer gap models, but combines elements of each. The slot gap model is based on electron acceleration along the edge of the open field region from the neutron star surface to near the light cylinder and thus could form a physical basis for the two-pole caustic model of (Dyks & Rudak, 2003). Along the last open field line, the pair formation front rises to very high altitude forming a slot gap, where the accelerating electric field is unscreened by pairs. The resulting radiation features both hollow cones from the lower-altitude pair cascades, seen at small viewing angles, as well as caustic emission on the trailing-edge field lines at high altitude, seen from both poles at large viewing angle. The combination of the small solid angle of slot gap emission ($\ll 1$ sr) with a high probability of viewing the emission predicts that more gamma-ray pulsars could be detected at larger distances. In this picture, many of the positional coincidences of radio pulsars with unidentified EGRET sources become plausible as real associations, as the flux predicted by the slot gap model for many of the pulsars would provide the observed EGRET source flux. The expected probability of seeing radio-quiet gamma-ray pulsars in this model will also be discussed.

Keywords: neutron stars, pulsars, acceleration, gamma-rays

1. Introduction

The number of rotation-powered pulsars with detected emission at X-ray and $\gamma$-ray energies has been steadily growing (Thompson, 2001; Becker & Aschenbach, 2002). Although the theory of pulsar acceleration and high-energy emission has been studied for over thirty years, the origin of the pulsed non-thermal emission is a question that remains unsettled. The observations to date have not been able to clearly distinguish between an emission site at the magnetic poles (Daugherty & Harding, 1996) and emission in the outer magnetosphere (Cheng, Ho & Ruderman, 1986; Hirota & Shibata, 2001). In the case of polar cap (PC) models, while the energetics and pair-cascade spectrum have had success in reproducing the observations, the predicted beam size of radiation emitted near the neutron star (NS) surface is too small to produce the wide pulse profiles that are observed (Thompson, 2001). However, Arons (1983) first noted the possibility of a high-altitude acceleration region or “slot gap” along the last open field line where the electric field is lower. The slot gap forms because the pair for-
formation front, above which the accelerating field is screened, occurs at increasingly higher altitude as the magnetic colatitude approaches the edge of the open field region (Arons & Scharlemann, 1979 [AS79]). We have re-examined the slot-gap model (Muslimov & Harding, 2003 [MH03]) with the inclusion of two new features: 1) the acceleration due to inertial-frame dragging (Muslimov & Tsygan, 1992) and 2) the additional decrease in the electric field near the boundary at the edge of the polar cap due to the narrowness of the slot gap. These two effects combine to enable acceleration to altitudes approaching the light cylinder in the slot gap at all azimuthal angles around the polar cap. These features result in the production of a larger high-energy emission beam with small solid angle, both favorable for producing high fluxes for γ-ray pulsars.

2. Formation of the Slot Gap

In the space-charge limited flow acceleration model AS79, electrons are freely emitted from the neutron star surface near the magnetic poles and accelerated in steady-state. When the electrons achieve a sufficient Lorentz factor they radiate curvature and inverse Compton photons that can produce electron-positron pairs in the strong magnetic field. Some of the positrons turn around and accelerate downward toward the neutron star, while the electrons accelerate upward. This pair polarization screens the electric field above a pair formation front (PFF). These models assume a boundary condition that the accelerating electric field and potential are zero at the last open field line. Near the boundary, the electric field is lower and a larger distance is required for the electrons to accelerate to the Lorentz factor needed to radiate photons energetic enough to produce pairs. The PFF thus occurs at higher and higher altitudes as the boundary is approached and curves upward, approaching infinity and becoming asymptotically parallel to the last open field line. If the electric field is effectively screened above the PFF, then a narrow slot surrounded by two conducting walls is formed (see Figure 1). Within this slot gap, the electric field is further screened by the presence of the second conducting boundary and acceleration occurs at a reduced rate. Pair production and pair cascades therefore do not take place near the neutron star surface in the slot gap, as do the pair cascades along field lines closer to the magnetic pole (core), but occur at much higher altitudes.

There are several important differences between the revised slot-gap model of MH03 and the original slot-gap model of AS79. The inclusion of general relativistic frame dragging enables particle acceleration on
both “favorably” curved (curving toward the rotation axis) and “unfavorable” curved (curving away from the rotation axis) field lines and also at all inclination angles. MH03 also consider the radiation from pair cascades occurring along the interior edge of the slot gap. The cascade radiation emission beam from the slot gap is thus a full hollow cone centered on the magnetic axis. A narrower emission beam from field lines interior to the slot gap will form a core component of pairs and high-energy emission.

Since the potential in the slot gap is unscreened, electrons on field lines which thread the slot gap will continue accelerating to very high altitudes. Muslimov & Harding(2004, [MH04]) have derived the potential
and accelerating electric field at high altitude in the extended slot gap by considering the effect of deviation of stream lines from the magnetic field lines of a static dipole. In the absence of this effect, the difference between the actual charge density along field lines and the corotation (or Goldreich-Julian) charge density, which grows with altitude above the polar caps, would become comparable to the Goldreich-Julian charge density itself, a situation which cannot be supported since it would disrupt the steady-state charge flow within the magnetic flux tube. However, long before this would occur, the drift of electrons in the slot gap across the magnetic field will largely damp the growth of the charge deficit and the large electric field which would be induced perpendicular to the magnetic field. The residual parallel electric field is small and constant, but still large enough at all altitudes up to nearly the light cylinder to maintain a flux of electrons with Lorentz factors exceeding $10^7$ in the slot gap.

MH04 matched the high-altitude slot gap solution for the parallel electric field to the solution found at lower altitudes (MH03). The result, for most inclination angles, is a continuously accelerating field from the neutron star surface to near the light cylinder along the last open field lines. The derived properties of the extended slot gap closely match the geometrical properties required for the two-pole caustic model of Dyks & Rudak (2003). Such a model can reproduce the double-peaked profiles seen in many $\gamma$-ray pulsars like the Crab, Vela and Geminga. MH04 demonstrated through numerical simulation of slot gap acceleration and radiation, that the extended slot gap radiation will produce the caustic peaks and pulse profiles similar to those of the two-pole caustic model.

The existence of a slot gap requires a dense enough pair plasma on interior field lines to fully screen the parallel electric field, so that the inside walls of the gap have vanishing electric field. Harding & Muslimov (2002, HM02) found that pairs produced by CR are always able to fully screen the $E_{||}$ whereas pairs from ICS were only able to screen locally, if at all. Therefore we can conclude that only those pulsars which can produce CR pairs will have slot gaps. Figure 2 reproduces the death lines for CR pairs in $P-P$ space from HM02, showing the region of pulsar parameter space required for slot gap formation. Generally, the younger pulsars, with ages less than $10^7$ yr and with higher magnetic fields fall into this region, although one or two millisecond pulsars may also have slot gaps.
3. Slot Gap Energetics

The electrodynamics of the slot gap is primarily dependent on a single parameter, the slot gap width, $\Delta \xi_{sg}$. The ratio of the electric field in the slot gap to the electric field in the core region of the PC is $E_{sg}/E_{core} \propto \Delta \xi_{sg}^2/4$ and the luminosity of particles accelerated in the slot gap is $L_{prim} \propto \Delta \xi_{sg}^3 L_{SD}$ where $L_{SD}$ is the spin-down luminosity of the pulsar (for full details see Muslimov & Harding, 2003). One can
Figure 3. Observed flux above 1 keV, $\Phi_\gamma$, times distance squared (from Thompson (2001)) (solid circles) and theoretical values of specific high-energy luminosity from the slot gap, $\varepsilon_\gamma L_{\text{prim}}/\Omega_\gamma$ from eq. (4) (upside-down triangles) vs. spin-down luminosity for known $\gamma$-ray pulsars. An efficiency of $\varepsilon_\gamma = 0.3$ was assumed. Also $\lambda = 0.1$, $\eta_\gamma = 3$ and the stellar parameters $R_6 = 1.6$ and $I_{45} = 4$ were used.

estimate the width of the slot gap as the magnetic colatitude where the variation in height of the curvature radiation PFF becomes comparable to a fraction $\lambda$ of the stellar radius $R$, or

$$\Delta \xi_{SG} \approx \begin{cases} 0.2 P_{0.1}(\lambda B_{12})^{-4/7} I_{45}^{3/7} & B_{12} \leq 4.4 \\ 0.1 P_{0.1}(\lambda B_{12}^{3/4})^{-4/7} I_{45}^{-3/7} & B_{12} \geq 4.4 \end{cases}$$

$$I_{45} = I/10^{45} \text{ g cm}^2, I$$

is the neutron star moment of inertia, $P_{0.1} = P/0.1$ s and $B_{12} = B_0/10^{12}$ G are the neutron star rotation period and surface magnetic field. Here, $\Delta \xi_{SG}$ is in units of the polar cap half-angle, $\theta_0 = \sin^{-1}(2\pi R/PC)^{1/2}$. The emission solid angle of radiation from the
slot gap can be estimated by integrating over the thin annulus defined by the slot gap width (Eqn [1]).

\[ \Omega_{SG} \approx \frac{9}{2} \pi \theta_0^2 \eta \Delta \xi_{SG} \text{ ster}, \quad (2) \]

where \( \eta \equiv r/R \) is the dimensionless radius of emission. Electrons accelerating in the slot gap will radiate curvature-radiation \( \gamma \)-rays, becoming radiation-reaction limited at Lorentz factors

\[ \gamma \approx 3 \times 10^7 \left[ \kappa_{0.15} B_{12} R_6^3 \frac{\eta}{\eta_{lc}} \nu_{SG} \cos \chi \right]^{-1/4}, \quad (3) \]

where \( \kappa_{0.15} = \kappa/0.15 \approx I_{45}/R_6^3 \), \( \nu_{SG} = 0.25 \Delta \xi_{SG}^2 \), \( R_6 = R/10^6 \text{ cm} \) is the neutron star radius, \( \chi \) is the pulsar inclination angle and \( \eta_{lc} \) is the dimensionless light cylinder radius. Based on the luminosity of the primary electrons and the above solid angle estimate, we may derive the quantity,

\[ L_{SG}(\Omega_{SG}) = \frac{\varepsilon_{\gamma} L_{\text{prim}}}{\Omega_{SG}} = 3 \times 10^{34} \varepsilon_{\gamma} L_{\text{sd,35}}^{3/7} R_6^{5/7} \eta^{-1} \lambda^{-8/7} I_{45}^{-6/7} \kappa_{0.15} \cos^2 \chi \text{ erg s}^{-1} \text{ ster}^{-1}. \quad (4) \]

where \( L_{\text{prim}} \) is the luminosity in primary electrons accelerated in the slot gap, \( \varepsilon_{\gamma} \) is the radiation efficiency and \( L_{\text{sd,35}} \equiv L_{\text{sd}}/10^{35} \text{ ergs}^{-1} \) is the spin-down luminosity. The above expression for \( L_{SG}(\Omega_{SG}) \) is equivalent to the observed quantity \( \Phi_{\gamma} d^2 \), where \( \Phi_{\gamma} \) is the high-energy bolometric flux observed at the Earth, and \( d \) is the distance to the pulsar. Figure 3 shows the observed (solid circles with error bars) and theoretical (upside-down triangles) values of \( \Phi_{\gamma} d^2 \) as a function of spin-down luminosity, \( L_{\text{sd}} \) for the 10 known \( \gamma \)-ray pulsars. The theoretical values are calculated for the parameters \( \varepsilon_{\gamma} = 0.3 \) and \( \lambda = 0.1 \) (see eq. [4]). Note that parameter \( \varepsilon_{\gamma} \) can range from 0.2 to 0.5 in cascade simulations, and \( \eta = 3 \). In Figure 3 the dashed line represents the limit, where the spin-down luminosity is radiated into the unit solid angle, i.e. where \( \Phi_{\gamma} d^2 = L_{\text{sd}}/1 \text{ ster} \). One can see that there is good agreement for most high-energy pulsars except several of the pulsars, Geminga and PSR B0656+14, having low \( L_{\text{sd}} \), and for J0218+4232, which is a millisecond pulsar. These pulsars are near or below the curvature radiation pair death line (see Figure 2 and HM02), and therefore have either very wide slot gaps or no slot gaps at all. All other high-energy pulsars depicted in Figure 3 are well above the curvature radiation death lines and are expected to have slot gaps.
4. Slot Gap Emission and EGRET Unidentified Sources

There are presently 53 radio pulsars in the error circles of 28 EGRET unidentified sources (Kramer et al., 2003; Grenier, 2004). Nearly all of these pulsars have been discovered by surveys such as the Parkes Multibeam (Manchester et al., 2001) and by deep pointed searches by Arecibo and GBT radio telescopes (Camilo, 2004) after the end of EGRET operation. The pulsars coincident with EGRET sources are plotted in \( P-\dot{P} \) space in Figure 2. Most of them are young (\( \tau \lesssim 10^7 \) yr), high-field pulsars above the CR pair death line and many are expected to have slot gaps. There are unfortunately too few photons in any of the sources to do credible pulsation searches of the EGRET archival data, so such searches must await AGILE or GLAST. Many of the coincident EGRET sources contain multiple radio pulsars within the error circles. These are shown in Figure 4 with their observed average fluxes from the 3rd EGRET catalog (Hartman, 1999).
We have computed the $\gamma$-ray fluxes predicted by the slot gap model (Eqn [4]) for the EGRET source-coincident radio pulsars and the results are plotted in Figure 4. The fluxes of the pulsars, $L_{SG}(\Omega_\gamma)/d^2$, where $d$ is the distance, are shown as dark bars alongside the coincident EGRET source fluxes shown as light bars. In about 18-22 out of the 28 sources, the predicted slot gap flux from either an individual pulsar or several pulsars combined could account for the EGRET source flux. Thus more than two thirds of these associations are physically plausible, making the pulsars viable counterparts for the EGRET sources. In contrast, the predicted fluxes from the standard polar cap model (e.g. HM02), assuming a solid angle of 1 sr., would be comparable to the EGRET source fluxes in only about 5 of the cases.

5. Conclusions

In the slot gap model, pulsar high-energy emission comes from high altitudes, between 2-3 stellar radii above the neutron star surface to nearly the light cylinder. Two resulting characteristics of radiation from the slot gap: small solid angle and a wide emission beam, combine to provide a significantly larger flux for $\gamma$-ray pulsars than in the standard polar cap model. The small solid angle allows the radiation from $\gamma$-ray pulsars to be seen by any given detector at larger distances, and many of the spatially coincident pulsars are at large distances, as determined from their dispersion measure. Thus, a larger number of the recently detected radio pulsars that are in or near EGRET source error circles become plausible candidates for the $\gamma$-ray sources. It is possible that half of the non-variable unidentified EGRET sources in the galactic plane are radio loud $\gamma$-ray pulsars. A population synthesis study of radio-loud and radio-quiet pulsars in the galaxy (Gonthier et al., 2004a; Gonthier et al., 2004b) have found that in the slot gap model one expects that many more radio-loud than radio-quiet pulsars are counterparts to EGRET sources. This result is due to the fact that the radio emission occurs along the same open field lines as the $\gamma$-ray emission, in contrast to outer gap models where the radio emission is assumed to originate from open field lines on the opposite pole of the neutron star from the high-energy emission. The ratio of radio-loud to radio-quiet $\gamma$-ray pulsars detected by EGRET, and eventually by GLAST, will be a good discriminator between emission models.


References

Arons, J., Pair creation above pulsar polar caps: Geometrical structure and energetics of slot gaps. ApJ, 302, 301, 1983.
Arons, J. & Scharlemann, E. T., Pair formation above pulsar polar caps - Structure of the low altitude acceleration zone. ApJ, 231, 854, 1979.
Becker, W. & Aschenbach, B., X-ray Observations of Neutron Stars and Pulsars: First Results from XMM-Newton., in Neutron Stars, Pulsars, and Supernova Remnants, Max-Plank-Institut fr extraterrestrische Physik, Garching bei Mnchen, p. 64, 2002.
Camilo, F., Searches for Young Pulsars, in Young Neutron Stars and Their Environments, IAU Symposium no. 218, Edited by Fernando Camilo and Bryan M. Gaensler. San Francisco, CA: Astronomical Society of the Pacific, 2004., p.97
Cheng, K. S., Ho, C. & Ruderman, M. A., Energetic radiation from rapidly spinning pulsars. I. Outer magnetospheric gaps., ApJ, 300, 500, 1986.
Daugherty, J. K. & Harding, A. K., Gamma-Ray Pulsars: Emission from Extended Polar Cap Cascades ApJ, 458, 278, 1996.
Dyks, J. & Rudak, B., Two-Pole Caustic Model for High-Energy Lightcurves of Pulsars., ApJ, 598, 1201, 2003.
Grenier, I. A., Gamma-ray sources as relics of recent supernovae in the nearby Gould Belt, A & A, 364, 93, 2000.
Grenier, I. A., Galactic Gamma-Ray Sources in The Multiwavelength Approach to Unidentified Gamma-Ray Sources, Hong Kong, 2004.
Gonthier, P. L., Van Guilder, R. & Harding, A. K., Role of Beam Geometry in Population Statistics and Pulse Profiles of Radio and Gamma-Ray Pulsars, ApJ, 604, 775, 2004.
Gonthier, P. L., Harding, A. K., Grenier, I. A. & Perrot, C., Radio-Loud and Radio-Quiet Pulsars in the Galaxy and the Gould Belt, in The Multiwavelength Approach to Unidentified Gamma-Ray Sources, Hong Kong, 2004.
Harding, A. K. & Muslimov, A. G., Pulsar Polar Cap Heating and Surface Thermal X-Ray Emission. II. Inverse Compton Radiation Pair Fronts., ApJ, 568, 862, 2002.
Hartman, R. C. et al., Third EGRET catalog., ApJS, 123, 79, 1999.
Hirotani, K. & Shibata, S., One-dimensional electric field structure of an outer gap accelerator - III. Location of the gap and the gamma-ray spectrum., MNRAS, 325, 1228, 2001.
Kramer, M. et al., The Parkes Multibeam Pulsar Survey - III. Young pulsars and the discovery and timing of 200 pulsars., MNRAS, 342, 1299, 2003.
Manchester, R. N. et al., The Parkes multi-beam pulsar survey - I. Observing and data analysis systems, discovery and timing of 100 pulsars., MNRAS, 328, 17, 2001.
Muslimov, A. G. & Tsygan, A. I., General relativistic electric potential drops above pulsar polar caps., MNRAS, 255, 61, 1992.
Muslimov, A. G. & Harding, A. K., Extended Acceleration in Slot Gaps and Pulsar High-Energy Emission., ApJ, 588, 430, 2003.
Muslimov, A. G. & Harding, A. K., High-Altitude Particle Acceleration and Radiation in Pulsar Slot Gaps., ApJ, 606, 1143, 2004.
Thompson, D. J., Gamma-ray Pulsars: Observations., in High Energy Gamma-Ray Astronomy, American Institute of Physics (AIP) Proceedings, volume 558., Edited by Felix A. Aharonian and Heinz J. Vlk. AIP, Melville, New York, 2001.