Rotationally-induced asymmetry in the double-peak lightcurves of the bright EGRET pulsars?

J. Dyks* and B. Rudak†

*Nicolaus Copernicus Astronomical Center, Toruń, Poland
†Nicolaus Copernicus Astronomical Center, also TCF@NCU, Toruń, Poland

Abstract. Pulsed emission from the bright EGRET pulsars - Vela, Crab, and Geminga - extends up to \(<\sim 10\) GeV. The generic gamma lightcurve features two peaks separated by 0.4 to 0.5 in phase. According to Thompson (2001) the lightcurve becomes asymmetrical above \(<\sim 5\) GeV in such a way that the trailing peak dominates over the leading peak. We attempt to interpret this asymmetry within a single-polar-cap scenario. We investigate the role of rotational effects on the magnetic one-photon absorption rate in inducing such asymmetry. Our Monte Carlo simulations of pulsar gamma-ray beams reveal that in the case of oblique rotators with rotation periods of a few millisecond the rotational effects lead to the asymmetry of the requested magnitude. However, the rotators relevant for the bright EGRET pulsars must not have their inclination angles too large in order to keep the two peaks at a separation of \(<\sim 0.4\) in phase. With such a condition imposed on the model rotators the resulting effects are rather minute and can hardly be reconciled with the magnitude of the observed asymmetry.

INTRODUCTION

High quality gamma-ray data for three pulsars - Vela, Crab, and Geminga - provided by EGRET aboard the CGRO enable an analysis of properties of pulsar high-energy radiation as a function of both, photon energy and phase of rotation. The spectra of pulsed radiation from these sources (as well as from three other EGRET pulsars: B1706-44, B1951+32, and B1055-52) extend up to \(<\sim 10\) GeV. All three pulsars feature gamma lightcurves characterised by two strong peaks separated by 0.4 to 0.5 in rotational phase. The pulses are asymmetrical in the sense that their leading peaks exhibit lower energy cutoffs (about \(<\sim 5\) GeV) than their trailing peaks. In other words, the trailing peaks dominate over the leading peaks above \(<\sim 5\) GeV [6].

The high-energy cutoffs in pulsar spectra are interpreted within polar cap models as due to one-photon absorption of gamma-rays in strong magnetic field with subsequent $e^\pm$-pair creation. A piece of observational support for such an interpretation comes from a strong correlation between the inferred ‘spin-down’ magnetic field strength and the position of the high-energy cutoff [6]. This, in turn, opens a possibility that the observed asymmetry between LP and TP, i.e. the dominance of LP over TP above \(<\sim 5\) GeV, is a direct consequence of propagation effects (which eventually lead to stronger one-photon absorption for photons forming LP than TP) rather than due to some inherent property of the gamma-ray emission region itself. The aim of this research note is to investigate
the role of rotation in the built-up of such asymmetry.

We consider the purely rotational effects: due to the presence of the rotation-induced electric field $\vec{E}$, aberration of photon direction and slippage of magnetosphere under the photon’s path. All these effects are of the same order of magnitude: $\propto \beta$, where $\beta$ is a local corotation velocity $v$ expressed in units of the speed of light $c$. We assume that the magnetic field within the radius of a few pulsar radii has a shape of a rigidly rotating static-like dipole. In reality the rotation distorts this shape because of both retardation effects as well as toroidal currents due to plasma dragging. Fortunately, these are higher order effects ($\propto \beta^2$) and will be ignored below. Another expected disturbance of the magnetic field structure comes from longitudinal currents suspected to flow within the region of open field lines. No self-consistent solution of this problem has been found so far (see [1] and references therein). Nevertheless, the longitudinal currents are expected to modify the dipole magnetic field by a factor of $\propto \beta^{3/2}$, and therefore they will be neglected too.

**IS THE LEADING PEAK ABSORBED MORE EFFICIENTLY?**

Let us consider the photon propagation in the equatorial plane of an orthogonal rotator with rotation period $P = 1.5$ ms (this case is ideal for instructive purposes, and it is shown
in Fig 1). For definiteness, we constrain to its northern magnetic hemisphere. Then, at any point in the plane, photons propagating upwards cross the magnetic field $\vec{B}$ at angles $\theta_B < 90^\circ$ and the rotation-induced electric field $\vec{E} = -\vec{\beta} \times \vec{B}$ is directed towards the reader, at right angle to the page.

One of the striking features of one-photon magnetic pair production is that its rate $R$ is not axisymmetric around a local $\vec{B}$ direction if a weak electric field $\vec{E} \perp \vec{B}$ is present [3]. Within the accessible range of angles $\theta_B$ the rate vanishes in the unique direction which lies in the plane perpendicular to $\vec{E}$ and deviates from $\vec{B}$ by angle $\sim \frac{E}{B}$ towards the rotation direction. In local coordinate frame with $\hat{z} \parallel \vec{B}$, $\hat{y} \parallel \vec{E}$, and $\hat{x} \parallel \vec{E} \times \vec{B}$ this "free propagation" direction is given by $\hat{\eta}^{FP} = [\eta_x^{FP}, \eta_y^{FP}, \eta_z^{FP}] = [\frac{E}{B}, 0, (1 - \frac{E^2}{B^2})^{1/2}]$. If $E \ll B$ the pair production rate $R$ is approximately symmetric around the free propagation direction $\hat{\eta}^{FP}$ instead of around $\vec{B}$. Moreover, $R$ increases monotonically for angles which depart from $\hat{\eta}^{FP}$. Accordingly, the projection of photon momentum on $\hat{\eta}^{FP}$ is a better measure of $R$ than its projection on $\vec{B}$. The directions of $\hat{\eta}^{FP}$ at various points within the magnetosphere are shown in Fig. 1 as solid arrows. Note that the free propagation direction deviates from the local $\vec{B}$ by an angle $\theta_B = \arcsin(\frac{E}{B}) \sim \frac{E}{B}$ which increases with altitude.

High-energy photons are emitted from the outer rim of standard polar cap tangentially to the magnetic field in the corotating frame (dashed arrows at the star surface in Fig. 1). In the observer frame (OF) the photons propagate at the aberrated direction (dotted lines) which at the emission point is just the free propagation direction (at this point the angle between the photon direction and the magnetic field line equals $\theta_B \sim \frac{E}{B}$, and therefore $R = 0$ [5], [7]). Initially, therefore, the rate $R$ is symmetric for photons in the leading and in the trailing peak both in the corotating and in the observer frame. As the photons propagate outward, however, the free propagation direction starts to deviate from the photon direction $\hat{\eta}$ and this occurs in a different way for photons of the leading and the trailing peak. The reasons for which the local $\hat{\eta}^{FP}$ diverges from $\hat{\eta}$ include: (1) the magnetic field line curvature, (2) the increase in $E/B$ ratio with altitude, and (3) the slippage of magnetic field lines under a photon’s path. For photons in the leading peak the effects (1) and (2) cumulate whereas for the trailing peak they effectively tend to cancel out each other. In consequence, the photons in the leading peak suffer stronger absorption than the photons of the same energy in the trailing peak. This is why the high energy cutoff in the LP spectrum occurs at a slightly lower energy than the cutoff for the TP. The difference becomes more pronounced for smaller curvature of magnetic field lines. The slippage (3) does not change this picture.

Photon propagation direction $\hat{\eta}$ as seen in the observer frame (dotted lines) and the local free propagation direction $\hat{\eta}^{FP}$ in the OF (solid arrows) are shown in Fig. 1 for a few positions along the photon trajectory in the corotating frame. The stronger absorption of the leading peak is evident (for the TP, $\hat{\eta}$ nearly coincides with $\hat{\eta}^{FP}$).

Another way to understand the asymmetry in the pair production rate is to follow photon trajectories in a reference frame where $\vec{E}' = 0$ is fulfilled\(^1\) and the pair pro-
duction rate $R'$ can be approximated by the well-known formula for the pure-$\vec{B}$ case: 

$$R'(\varepsilon', \vec{B}', \sin \theta'_{\vec{B}}) = c_1 \sin \theta'_{\vec{B}} \exp \left[-c_2 / (\varepsilon' \sin \theta'_{\vec{B}})\right]$$

where $\theta'_{\vec{B}} = \angle(\hat{n}', \vec{B}')$ and $\varepsilon'$ is photon energy. If a frame of local $\vec{E} \times \vec{B}$ drift is chosen, with $\vec{B}' = \vec{B} / \gamma_D$, the rate $R$ in the observer frame can be expressed as

$$R = \gamma_D (1 - \eta_x \beta_D) \cdot R'(\varepsilon', \vec{B}', \sin \theta'_{\vec{B}})$$

where $\varepsilon' = \varepsilon \gamma_D (1 - \eta_y \beta_D)$, $\vec{B}' = \vec{B} / \gamma_D$, and $\sin \theta'_{\vec{B}} = \left(\eta_x (1 - \beta_D^2) + \eta_y^2 (1 - \beta_D^2)\right)^{1/2} (1 - \eta_x \beta_D)$. In the equatorial plane of the orthogonal rotator $\eta_y = 0$ so that $\eta_x = \pm \sin \theta_B$ where the signs 'minus' and 'plus' correspond to the leading and the trailing peak, respectively. Typically $\eta_x \ll 1$ which implies that the difference between the pair production rates in the locally drifting frame and in the observer frame results primarily from the aberration of photon direction whereas the change in $\varepsilon$ or $\vec{B}$ is a second order effect. Obviously, the aberration is asymmetric for the leading and the trailing peak ($\eta_x < 0$ and $\eta_x > 0$ respectively). Fig. 1 presents this “aberration effect” in the rigidly corotating frame where

FIGURE 2. Evolution of double peak pulse profile with photon energy. For details see text.
\( \vec{E}' = 0 \) is assumed. Photon trajectories in this frame are marked with dashed lines which indicate clearly that photons of the leading peak encounter larger \( B'_\perp \) than photons of the trailing peak of the same energy.

We have performed Monte Carlo simulations of radiative processes above polar cap, including the emission of curvature radiation with subsequent one-photon pair production (for description of the model see [2]). We find that a difference by a factor of \( \sim 2 \) in the position of high-energy cutoffs for the leading and the trailing peak can be generated for Vela-like objects with emission regions placed a few stellar radii above the surface provided the inclination angle \( \alpha \) of the magnetic dipole exceeds \( \sim 45 \) degrees. However, for such large \( \alpha \) the observed peak-to-peak separation of about 0.4 cannot be reproduced [4]. Therefore, we now turn to the case of nearly aligned rotators. As an example we choose the model with parameters of the Vela pulsar \( (B_{\text{dip}} = 3.4 \, \text{TG}, P = 0.0893 \, \text{s}) \) and we take the inclination angle \( \alpha = 7.6^\circ \). We then place the polar accelerator at the altitude of \( \sim 4 \, R_{\text{NS}} \) to ensure that the magnetosphere is not entirely opaque to curvature photons of energy \( \lesssim 10 \, \text{GeV} \). The numerical results are presented in Fig. 2. The three columns of Fig. 2 present: 1) the photon distribution in the observer’s colatitude-phase space \( (\zeta_{\text{obs}}, \phi) \) (left), 2) pulse profiles for \( \zeta_{\text{obs}} = 7.7^\circ \) integrated above a photon energy \( \varepsilon \) (middle), and 3) the phase-integrated spectrum with \( \varepsilon \) marked with the dotted vertical line (right). Four rows correspond to increasing energy of \( \varepsilon = 4.0, 6.4, 8.0, \) and \( 10 \, \text{GeV} \) (top to bottom). The peak-to-peak asymmetry (middle column) does agree qualitatively with the observed data even in this nearly aligned case. However, the really strong fading of the leading peak LP occurs only at the very end of the curvature spectrum, where its level drops below the detectability level of EGRET.

Therefore, the rotational effects alone probably cannot account for the asymmetries observed in the bright EGRET pulsars. However, the photon statistics at the highest energy bins is too low to treat this conclusion as being firm. Alternatively, the asymmetries may be generated by some properties inherent in the region of the gamma-ray emission.

**ACKNOWLEDGMENTS**

We are grateful to V.S. Beskin for useful comments on the issue of magnetospheric distortions. This work was supported by KBN grant 2P03D02117 and NCU grant 405A.

**REFERENCES**

1. Beskin, V. S., *Physics-Uspekhi*, **42**, 1071–1098 (1999)
2. Daugherty, J. K., and Harding, A. K., *ApJ*, **252**, 337–347 (1982)
3. Daugherty, J. K., and Lerche, I., *ApSS*, **38**, 437–445 (1975)
4. Dyks, J., and Rudak, B., *MNRAS*, **319**, 477–483 (2000)
5. Harding, A. K., Tademaru, E., Esposito, L. W., *ApJ*, **225**, 226–236 (1978)
6. Thompson, D. J., astro-ph/0101039 (2001)
7. Zheng, Z., Zhang, B., and Qiao, G. J. *A&A*, **334**, L49–L52 (1998)