THE ATTENUATION OF GAMMA-RAY EMISSION IN STRONGLY-MAGNETIZED PULSARS

Matthew G. Baring,1 Alice K. Harding1 and Peter L. Gonthier2

1Lab. for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.
2Deptartment of Physics, Hope College, Holland MI, U.S.A.
†Compton Fellow, Universities Space Research Association

ABSTRACT

Gamma-rays from pulsars can be efficiently attenuated in their magnetospheres via the mechanism of single-photon pair production and also the exotic QED process of photon splitting, which become prolific in fields approaching the quantum critical value of $B_{cr} = 4.41 \times 10^{15}$ Gauss. Recently we have published results of our modelling of strongly-magnetized $\gamma$-ray pulsars, which focused on the escape or attenuation of photons emitted near the pole at the neutron star surface in dipole fields, in a Schwarzschild metric. We found that pair production and splitting totally inhibit emission above around 10–30 MeV in PSR1509-58, whose surface field is inferred to be as high as $0.7B_{cr}$. Our model pulsar spectra are consistent with the EGRET upper limits for PSR1509-58 for a wide range of polar cap sizes. Here we review the principal predictions of our attenuation analysis, and identify how its powerful observational diagnostic capabilities relate to current and future gamma-ray experiments. Diagnostics include the energy of the gamma-ray turnover and the spectral polarization, which constrain the estimated polar cap size and field strength, and can determine the relative strength of splitting and pair creation.

Keywords: pulsars; neutron stars; gamma-rays; strong magnetic fields.

1. INTRODUCTION

Magnetic one-photon pair production, $\gamma \rightarrow e^+e^-$, has traditionally been the only gamma-ray attenuation mechanism assumed to operate in polar cap models for radio (e.g. Sturrock, 1971) and gamma-ray pulsars (Daugherty & Harding 1982, 1996; Sturmer & DERmer 1994). Such an interaction can be prolific at pulsar field strengths, specifically when the photons move at a substantial angle $\theta_{kB}$ to the local magnetic field. Pair creation has a threshold of $2m_e c^2 \approx 1.02$ MeV for $\theta_{kB} = 90^\circ$. The exotic higher-order QED process of the splitting of photons in two, $\gamma \rightarrow \gamma\gamma$, will also operate in the high field regions near pulsar polar caps and until very recently, has not been included in polar cap model calculations. Magnetic photon splitting has recently become of interest in neutron star models of soft gamma repeaters (Baring 1995, Baring and Harding 1995, Thompson & Dun-can 1995), mainly because of their purportedly extreme fields ($\geq 10^{14}$ Gauss). Splitting becomes more effective in competition with pair creation as a photon attenuation mechanism at higher field strengths (Baring 1991).

The key property of photon splitting that renders it relevant to neutron star environments is that it has no threshold, and can therefore attenuate photons below the threshold for pair production, $\gamma \rightarrow e^+e^-$. Hence the importance of photon splitting in gamma-ray pulsar models clearly needs to be assessed because (i) it is an additional attenuation process for gamma-ray photons that can produce cutoffs in the spectrum, and (ii) when it is comparable to pair production, it will diminish the production of secondary electrons and positrons in pair cascades while effectively softening the emission spectrum. Such “quenching” of pair creation can potentially provide a pulsar “death-line” at high field strengths. About a dozen radio pulsars have magnetic fields, determined from dipole spin-down, above $10^{13}$ Gauss. This group includes PSR1509-58, the gamma-ray pulsar having the lowest high-energy spectral turnover of $\sim 1$ MeV (Matz et al. 1994, Wilson et al. 1993, Bennett et al. 1993). Little attention was paid to $\gamma \rightarrow \gamma\gamma$ in pulsar contexts prior to the launch of the Compton Gamma-Ray Observatory (CGRO) in 1991 because until then, the three known gamma-ray pulsars had estimated field strengths of less than a few times $10^{12}$ Gauss. The detection of PSR1509-58 by the OSSE and Compel experiments on CGRO provided the impetus to focus on high-field neutron star systems.

Recent investigations of the role of $\gamma \rightarrow \gamma\gamma$ in gamma-ray pulsar polar cap models have been performed by Harding, Baring and Gonthier (1996, 1997) and Chang, Chen and Ho (1996). In this paper, we outline the importance of photon splitting for gamma-ray pulsar models, focusing on the major features presented in Harding, Baring and Gonthier (1997), and identifying powerful observational diagnostic capabilities of our attenuation model and their relationship to current and future gamma-ray experiments. Principal diagnostics include the maximum energy of gamma-ray emission, and the spectral shape and the polarization below this maximum. These constrain the estimated polar cap size and/or field strength (i.e. location of emission on or above the stellar surface), and can further determine the relative strength of splitting and pair creation, which becomes salient for some subtle physics issues pertaining to splitting. As such, phase-resolved spectral measurements in the soft gamma-
ray band can provide a wealth of diagnostic information, a goal that is readily achievable by the Integral mission. Future instrumentation with polarization sensitivity will further enhance our understanding of gamma-ray pulsars.

2. SPECTRAL ATTENUATION IN GAMMA-RAY PULSARS

Before discussing the attenuation of gamma-rays in pulsar magnetospheres, it is instructive to briefly review photon splitting. Since pair creation is widely invoked in pulsar models, it is appropriate here to omit a detailed discussion of its properties, referring the reader to Daugherty and Harding (1983). While $\gamma \rightarrow \gamma \gamma$ is forbidden in field free regions, it becomes quite probable in neutron star fields, where $B$ becomes a significant fraction of the quantum critical field $B_{cr} = m^2 c^3 / \hbar = 4.413 \times 10^{13}$ Gauss. Splitting is polarization-dependent in the birefringent, magnetized vacuum, implying that polarized photons emerge from an emission region. The three polarization modes permitted by CP-invariance in QED are $\perp \rightarrow \perp ||$, $\perp \rightarrow \perp \perp$ and $|| \rightarrow \perp$. However, Adler (1971; see also Usov and Shabad 1983) devised additional restrictions, called polarization selection rules, by demanding absolute four-momentum conservation and solving the dispersion relations for photons in the polarized vacuum in the limit of weak dispersion. This limits splitting to just one polarization mode ($\perp \rightarrow ||$) below pair creation threshold and for $B \leq B_{cr}$. Such selection rules are well-defined only in cases of very weak linear dispersion, and could well be modified in regimes of moderate or strong dispersion ($B \gtrsim B_{cr}$), or by non-linear dispersion and field non-uniformity effects; these modifications are not yet fully understood.

The study of the physics of $\gamma \rightarrow \gamma \gamma$ has at times had a tumultuous history (Baring 1991, Harding, Baring and Gonthier 1997); the first reliable calculations of its rate were performed in the early 70s (e.g. Adler 1971, Papanyan and Ritus 1972), and splitting is still the subject of some controversy. For photon energies $\varepsilon mc^2$ with $\varepsilon \ll 1$, and fields $B \ll B_{cr}$, the splitting rate (e.g. Adler 1971) averaged over photon polarizations (e.g. Papanyan and Ritus 1972; Baring 1991) can be expressed as an attenuation coefficient $T_{sp}$, which is the function of splitting divided by $c$:

$$T_{sp}(\varepsilon) \approx \frac{\alpha_i^3}{10 \pi^2} \left( \frac{19}{315} \right) \frac{2 \varepsilon^5}{mc^2} \left( \frac{B \sin \theta_{KB}}{B_{cr}} \right)^6 , \quad (1)$$

where $\alpha_i \approx 1/137$, and $\theta_{KB}$ is the angle between the photon momentum and the magnetic field vectors; $\varepsilon$ is in units of $mc^2$. Note that $\tau_{sp}(\varepsilon) = T_{sp}(\varepsilon) R$ is the optical depth for an emission region of size $R$, when $B$ is spatially uniform. Reducing $\theta_{KB}$ or $B$ dramatically increases the photon energy required for splitting to operate in a neutron star environment, a property that also holds for pair creation. High field ($B \gtrsim 0.3 B_{cr}$) corrections to the above formula (e.g. see Harding, Baring and Gonthier 1997, hereafter HBG97) for splitting diminish its dependence on $B$, causing the attenuation coefficient to saturate above $B \sim 4B_{cr}$.

In this paper, the attenuation of photons is determined as in HBG97 by following photon paths in the dipole geometry of a neutron star field, determining where they split or create pairs. The photons originate at different magnetic colatitudes $\theta$ on the neutron star surface and propagate outwards, initially more-or-less parallel to the magnetic field. We choose the neutron star radius to be $10^6$ cm, and a neutron star mass of $1.4 M_\odot$. Opting for periods of emission on the stellar surface maximizes the average field strength along a photon path, thereby producing the highest possible optical depths for $\gamma \rightarrow \gamma \gamma$ and $\gamma \rightarrow e^+ e^-$. Emission from above the stellar surface, as would occur for processes such as curvature radiation (e.g. Daugherty and Harding 1994) or magnetic Compton upscattering (e.g. Sturmer and Dermer 1994), pushes the threshold for spectral opacity (i.e. the turnover) up in energy, since the rates for splitting and pair creation are increasing functions of $B$ and energy. An important development in HBG97 was the inclusion of the general relativistic effects of curved spacetime in a Schwarzschild metric, following the treatment of Gonthier and Harding (1994). These included curved photon trajectories, affecting the angles photons make to the field, the gravitational redshift of photon energy as a function of distance above the neutron star surface, and an increase in the dipole field strength (by about a factor of 1.4 at the pole) above flat spacetime values. These effects all act to increase splitting and pair creation optical depths and lower the maximum energies for radiation transparency in the magnetosphere, typically by a factor of 2–3 below flat spacetime values. Kerr metrics were not considered since gamma-ray pulsar periods are much longer than their light crossing times.

2.1. Photon Escape Energies

If a photon is attenuated via either absorption process after a distance $L$ along its curved trajectory away from the pulsar surface, then we call $L$ its attenuation length. Clearly from the behaviour in Eq. (1), and also for $\gamma \rightarrow e^+ e^-$, attenuation lengths will be decreasing functions of the photon energy $\varepsilon$; in fact, at high energies they vary as $\varepsilon^{-5/2}$ for splitting and $\varepsilon^{-1}$ for pair creation (HBG97). Generally, they will be reached only after a photon has propagated a sufficient distance to achieve a significant angle to the field. This criterion is easier to accomplish away from the magnetic pole due to greater field curvature. Hence attenuation lengths are expected to be decreasing functions of the magnetic colatitude $\theta$; this is borne out in the detailed calculations of HBG97. Since the rates of the two attenuation processes are strongly increasing functions of energy, $L$ must approach infinity at some finite energy for each process, below which photons are free to escape the magnetosphere. Such energies are called the escape energies, and approximately delineate the energy at which spectral turnovers are anticipated; they always exist due to the $r^{-3}$ decay of the dipole field.

Fig. 1 illustrates escape energies, as determined in HBG97, for photons initially propagating parallel to field lines ($\theta_{KB,0} = 0^\circ$) at the stellar surface. These are strongly decreasing functions of $B$ (roughly as $B^{-6/5}$ for splitting and $B^{-1}$ for pair creation when $B \ll B_{cr}$) and $\theta$ ($\sim \theta^{-6/5}$ for $\gamma \rightarrow \gamma \gamma$ and $\sim \theta^{-1}$ for $\gamma \rightarrow e^+ e^-$). These dependences and their sensitivity are naturally expected to be borne out in spectral turnovers from a population of sources; we argue below the value of this strong diagnostic. HBG97 showed that if the photons are permitted to move at some small angle (at least around $0.57^\circ$) to the field initially, as might be the case for resonant Compton upscattering polar cap models (e.g. Sturmer and Dermer 1994, where particles with Lorentz
factors $\gamma \gtrsim 100$ emit the photons), the sensitivity to colatitude is all but obliterated for $\theta \lesssim 2^\circ$. Also evident in Fig. 1 is that for low fields (below $\sim 0.3B_{cr}$), pair production escape energies are below those for splitting, but in high fields, splitting escape energies are lower at all $\theta$. Hence, one expects photon splitting is irrelevant to the consideration of the Crab and Vela pulsars, whose spin-down fields are $\sim 4 \times 10^{12}$ Gauss, but would be very important for PSR1509-58, which has $B \sim 3 \times 10^{13}$ Gauss. Observe that the pair production escape energies are bounded below by the pair threshold $2mc^2/\sin \theta k_B$, but photon splitting can attenuate photons well below pair threshold.

![Figure 1: The energy (in units of $mc^2$), below which photons escape the magnetosphere without splitting (solid curves) compared to the escape energies for one-photon pair production (dashed curves) as a function of magnetic colatitude $\theta$ of the emission point on the neutron star surface, for different surface dipole magnetic field strengths (the escape energy drops as $B$ increases). The curves, which are for averages over the photon polarizations, diverge near $\theta = 0$ because the photons are almost parallel to the field lines throughout their path. The dots depict the escape energies for the polarization mode $\perp \rightarrow \parallel$.

2.2. Spectral Attenuation in PSR1509-58

Here, the depiction of spectral attenuation caused by splitting and pair creation will be focused on the case of the high field gamma-ray pulsar PSR1509-58. This is because the “GeV” cutoffs and reprocessing in the Crab and Vela spectra are well-studied (e.g. Daugherty and Harding 1982, 1996), and as mentioned above, photon splitting is unimportant in these two sources. We adopt the high revised spin-down estimate $B = 0.7B_{cr}$ for PSR1509-58 following Usov and Melrose (1995). Photons are injected at the stellar surface with a canonical unpolarized power-law continuum that is chosen to be consistent with the OSSE data points (e.g. see Matz et al. 1993), and we determine emergent spectra ignoring (for simplicity) any photon generation by created pairs. Details of pair cascading will be the subject of future work. Fig. 2 shows the differential energy spectrum obtained in the case where both photon polarizations produce pairs, but only one splits ($\perp \rightarrow \parallel$) according to Adler’s (1971) selection rules, so that no cascading of photons ensues.

![Figure 2: Polarized spectra (see HBG97) for partial photon splitting cascades, assuming unpolarized power-law emission (of index $\alpha = 1.6$, the OSSE best-fit value) not parallel to the magnetic field ($\theta_{k_B,0} = 0.57^\circ$), at different magnetic colatitudes, $\theta$, as labelled. Here only photons of polarization $\perp$ split, while those of either polarization produce pairs. The normalization of the spectrum is arbitrary.

![Figure 3: The polarization-averaged spectrum, multiplied by energy squared, for different colatitudes $\theta$ of surface emission, with only one mode of splitting permitted as in Fig. 2. The data points were obtained by the Ginga, Einstein and OSSE instruments, while upper bounds at higher energies belong to Comptel and EGRET viewings (see HBG97 for references).]
Fig. 3 depicts this spectrum in a “ν - \( F_\nu \)” representation, along with observational data and upper limits. A wide range (\( 2^\circ \lesssim \theta \lesssim 25^\circ \)) of polar cap sizes match the observations for the chosen field strength. Restricting splitting to just one polarization mode (\( \perp \rightarrow || \)) below pair creation threshold may be relaxed if modifications to Adler’s (1971) polarization selection rules prove significant, as discussed above. If this arises (e.g. through microscopic momentum non-conservation), and permits all three modes of splitting to proceed, a full cascade ensues with several generations of splitting and polarization state switching, as described by Baring (1995). This pushes the photon spectrum to lower energies since photon splitting tends to dominate pair creation at such high field strengths. Large spectral peaks will result, with strong polarization signatures, as is illustrated in HBG97, and the phase space for polar cap sizes permitted by the observational data diminishes. The concurrent enhanced quenching of pair creation would then be very important for radio and gamma-ray pulsar models.

3. DISCUSSION

In the light of the attenuation results presented here, the diagnostic capabilities of future experiments appear great, and will significantly impact our understanding of gamma-ray pulsars. In observations of individual sources, if polarization measurements are not possible, it will be difficult to pin down the field strength and polar cap size separately; the energy of the cutoff clearly depends on both these quantities. However, if polarization detections yield information such as depicted in Fig. 2, where it becomes possible to observationally determine the ratio of escape energies for splitting and pair creation, then \( B \) and the cap size for emission at any given height above the stellar surface can both be constrained at the same time. The spectral shape below the cutoff is a strong function of the number of modes of splitting that operate in the system. Prominent bumps should appear in source spectra (HBG97) unless the polarization selection rules that are mentioned above restrict photon splitting to just the \( \perp \rightarrow || \) mode. Hence just through a determination of spectral shape, Integral and other gamma-ray instruments may well be able to discriminate between the operation or otherwise of the selection rules in pulsar magnetospheres, thereby impacting our understanding of this aspect of strong field QED, a very enticing prospect.

As a dramatic increase in the number of observed gamma-ray pulsars in the not too distant future is anticipated, we note diagnostic advances can be made with populations of these sources. Firstly, the polar cap scenario considered here makes a definitive prediction that the spectral cutoff energy decreases quickly with increasing spin-down field strength. While the Crab, Vela and PSR1509-58 provide a range of field strengths that suggests this behaviour, it is important to confirm or deny this trend with other sources. The recent marginal detection of PSR0656+14, whose spin-down field is ~ \( 10^{13} \) Gauss, at around 100 MeV (Ramanamurthy et al. 1996) conforms to this trend. A much larger population of detected highly-magnetized gamma-ray pulsars will probe this hypothesis and probably provide the capability to discriminate between the polar cap and outer gap scenarios (e.g. Romani and Yadigaroglu, 1995) are unlikely to produce this correlation with field strength. If this trend is confirmed, we may further have the potential to discern between the physical mechanisms responsible for the gamma-ray emission. Resonant Compton upscattering and curvature radiation produce different angular beaming patterns of radiation, and therefore a different spread of cutoff energies for given \( B \) and distributions of polar cap sizes. Hence distributions of key spectral parameters can refine our modelling of these sources. Furthermore, the future full treatment of pair cascades will reveal the relative importance of curvature (flat) and synchrotron (steep) contributions to the gamma-ray spectra of strongly-magnetized pulsars. This will define a correlation between source spectral index and \( B \), and therefore cutoff energy, trends that can be verified or refuted observationally. In summary, clearly the era of the Integral mission will significantly advance our understanding of gamma-ray pulsars.

REFERENCES

Adler, S. L.: 1971 Ann. Phys. 67, 599
Baring, M. G.: 1991 Astron. Astr. 249, 581
Baring, M. G.: 1995 Ap. J. (Lett.) 440, 69
Baring, M. G. & Harding A. K.: 1995 Astr. Sp. Sci. 231, 77
Bennett, K. et al.: 1993, ApJS 90, 823
Chang, H.-K., Chen, K. & Ho, C.: 1996 Astron. Astr. in press.
Daugherty, J. K. & Harding A. K.: 1982 Ap. J. 252, 337
Daugherty, J. K. & Harding A. K.: 1983 Ap. J. 273, 761
Daugherty, J. K. & Harding A. K.: 1996 Ap. J. 458, 278
Gonthier, P. L. & Harding A. K.: 1994 Ap. J. 425, 767
Harding A. K., Baring, M. G. & Gonthier, P. L.: 1996 Astron. Astr. Supp. in press.
Harding A. K., Baring, M. G. & Gonthier, P. L.: 1997 Ap. J. in press. (HBG97)
Matz, S. M. et al.: 1994 Ap. J. 434, 288
Papanyan, V. O. & Ritus, V. I.: 1972 Soviet JETP 34, 1195
Ramanamurthy, P. V. et al: 1996 Ap. J. 458, 755
Romani, R. W. & Yadigaroglu, I.-A.: 1995 Ap. J. 438, 314
Sturrock, S. J. & Dermer, C. D.: 1994 Ap. J. 420, L79
Sturrock, P. A.: 1971 Ap. J. 164, 529
Thompson, C. & Duncan, R. C.: 1995 Mon. Not. R. astr. Soc. 275, 255
Usov, V. V. and Melrose, D. B.: 1995 Aust. J. Phys. 48, 571
Wilson, R. B. et al.: 1993 in Isolated Pulsars, ed. K. van Riper, R. Epstein & C. Ho, Cambridge Univ. Press, p. 257.