HIGH-ENERGY EMISSION FROM PULSARS: 
THE POLAR CAP SCENARIO

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ABSTRACT

The study of pulsars in the three and a half decades since their discovery has highlighted a handful of issues critical to their understanding. To date there is no consensus on the physical mechanism for their radio emission, despite a rapid increase in the observed population due to the Parkes Multi-Beam survey and prospects for similar growth in the radio population database in the near future. The small subset of pulsars that emit at X-ray to gamma-ray wavelengths are critical to refining the pulsar paradigm since this energy band (i) is where the vast majority of radiative luminosity is observed, and (ii) is intimately connected to the pair winds that form the dominant mode of energy deposition in the circum-pulsar environment. The most crucial point of contention pertaining to the high energy astrophysics of pulsars is the location of the acceleration region in their magnetospheres: is an outer gap model or a polar cap scenario (or both) the most appropriate picture. Radiative signatures provide the clues to this current enigma. This review focuses on salient characteristics of the polar cap scenario; these form the basis for discriminating observational diagnostics that should drive pulsars studies in the GLAST era just three years away.

INTRODUCTION

Pulsar astronomy is at a fascinating juncture with many exciting new results from the Chandra and XMM X-ray telescopes, and the prospects of next generation gamma-ray experiments, led by space missions INTEGRAL (just launched), GLAST and AGILE, and a number of atmospheric Cerenkov telescopes coming on line in the next few years. These will enable a continuation of ground-breaking discoveries. Pulsars are expected to be detected by GLAST (Gamma-Ray Large Area Space Telescope: http://www-glast.stanford.edu) in profusion, some that are radio-selected, like most of the present EGRET/Comptel pulsars, and perhaps even more that are detected via independent pulsation searches. This theoretical review summarizes relevant characteristics of the polar cap model, emphasizing distinctions from the competing outer gap model. These features include acceleration properties, the X-ray to gamma-ray spectral shape, high energy cutoffs, pulse profiles and flux observabilities in different wavebands, and how these characteristics generally depend on pulsar period and period derivative. The polar cap scenario exhibits definitive signatures that will be readily tested by the detections of GLAST and other experiments, thereby establishing cogent observational diagnostics.

This polar cap review complements the outer gap review by Cheng (2003). The key distinguishing characteristic of the two models that is usually cited is that the acceleration zone for the polar cap model is confined to within a few stellar radii of the pulsar surface, while the region of acceleration in the outer gap model is proximate to the light cylinder. However, in terms of the physical manifestations that are most directly probed by astronomical observations, the presence or absence of an extremely strong magnetic field is the conspicuous feature. In polar cap models, the strong field permits single photon pair creation that attenuates super-GeV photons in Crab and Vela-like pulsars, whereas pair creation in outer gap models is mediated through the more familiar two-photon process involving surface thermal X-rays as targets. It is a principal contention of this paper that the two models will not generate coincident predictions for a large population of pulsars (contrasting isolated sources) that sample a significant range of periods.
and period derivatives. Since such model discrimination will probably be rendered by the gamma-ray observations of GLAST, here the focus is on magnetospheric cascade spectral properties. The reader is referred to the review by Michel (2003), and Mestel (2000) for discussions of pulsar electrodynamics. Recent polar cap model reviews include those of Harding (2001) and Rudak, et al. (2002). The issues of radio pulsar death lines and radio quiescence at high fields are beyond the scope of this paper; discussions can be found in Baring (2001a) and Zhang (2003).

**POLAR CAP MODEL BASICS**

The critical physics ingredient for the polar cap model is the presence of a strong magnetic field in the acceleration and cascade emission region. Such high fields follow from the contention that the induced electric fields that seed particle acceleration in the oblique rotators exists at low altitudes near the neutron star surface at the magnetic poles. Since the earliest polar cap pulsar models of Sturrock (1971) and Ruderman and Sutherland (1975; hereafter RS75), there has been a potpourri of variations and updates, with the primary division being whether or not there is free emission of particles from the neutron star surface. Whether the surface temperature \( T \) of the neutron star exceeds the ion, \( T_i \) and electron, \( T_e \), thermal emission temperatures controls the nature of the acceleration zone.

If \( T < T_i \), ions will be trapped in the neutron star crust (RS75, Usov and Melrose 1995) and a vacuum gap will develop at the surface forming the locale of the region of particle acceleration and radiation. If \( T > T_e \), free emission of particles of either sign of charge will occur. The flow of particles is then limited only by space charge, and since such particle flow all along each open field line is unable to supply the corotation charge that is required to short out the electric field component \( E_\parallel \) along the magnetic field lines, an accelerating potential will develop (Arons and Scharlemann, 1979; Muslimov and Tsygan, 1992). In space charge-limited flow (SCLF) models, the accelerating \( E_\parallel \) is screened at a height where the particles radiate \( \gamma \)-rays that produce pairs. This so-called pair formation front (e.g. Arons, 1983; Harding and Muslimov, 1998; Muslimov and Harding, 2003) can occur at high altitudes above the polar cap, depending on the colatitude of the field line (discussed below in the section on Slot Gaps), a property that may prove necessary to explain the spectral cutoffs in the some or most of the EGRET pulsars. Many surface temperatures have now been measured for canonical X-ray pulsars in the range \( T \sim 10^5 - 10^6 \) K (Becker and Trümpier, 1997), though higher values are obtained \( (T \sim 4 \times 10^6 - 7 \times 10^6 \) K: see Perna et al., 2001) in observations of anomalous X-ray pulsars and soft gamma repeaters, so both vacuum gaps and SCLF models need to be considered depending on the source.

In the strong electric fields, the acceleration of primary electrons is rapid and ceases when one of two types of radiative cooling becomes significant, thereby establishing the maximum Lorentz factor \( \gamma_e \) of these particles, and generating a quasi-monoenergetic primary distribution prior to cascading. The cooling mechanisms are curvature radiation (present in models from the earliest days of pulsar theory; e.g. Sturrock, 1971) induced by the non-uniform magnetic field, and resonant (magnetic) inverse Compton scattering of thermal X-rays from the stellar surface (e.g. Sturrock and Dermer, 1994), a more recent incorporation. Both are strong functions of the magnetic field strength and either the electron’s Lorentz factor or the field geometry. Curvature radiation-initiated cascades generally have \( \gamma_e \sim 10^7 \) (e.g. Daugherty and Harding, 1989; see also Harding and Muslimov, 1998), while inverse-Compton seeded pair cascades yield \( \gamma_e \sim 3 \times 10^5 - 10^6 \) (e.g. Sturrock, 1995; see also Harding and Muslimov, 1998).

The primary photons propagate through the magnetosphere until they achieve sufficient angles \( \theta_{KB} \) with respect to the magnetic field to permit the creation of pairs via \( \gamma \rightarrow e^+e^- \) above the threshold energy of \( 2m_e c^2 / \sin \theta_{KB} \). This propagation is impacted by general relativistic distortions of photon trajectories and field structure (e.g. Gonthier and Harding, 1994; Harding, et al., 1997), as is the magnitude of the field in the local inertial frame, so that curved spacetime properties significantly modify the rates of pair creation. For small polar cap sizes, corresponding to longer pulsar periods, the primary photons fail to acquire sufficient angles \( \theta_{KB} \) at low to moderate altitudes prior to the decline of the dipole field, thereby permitting the photons to escape unattenuated; pair creation is quenched at high altitudes since the rate is a strongly increasing function of \( B \sin \theta_{KB} \) (e.g. Tsai and Erber, 1974). It is this effect that is primarily responsible for the existence of a theoretical death line for radio pulsars (Sturrock, et al. 1976) at longer periods. The inability of simpler curvature radiation-seeded cascades to account for emission from pulsars of the longest periods has lead to recent refinements (Zhang, et al., 2000; Hibschman and Arons, 2001; Harding, et al., 2002) that incorporate the influence of non-resonant inverse Compton scattering of surface X-rays in seeding cascades and subsequent pair creation for significantly smaller polar cap sizes and small period derivatives.

The first generation of pair creation initiates the pair cascade, with pairs generally being created in excited transverse (to the field) momentum states, the so-called Landau levels. Rapid de-excitation via cyclotron and syn-
Spectral and temporal properties can define the most potent means for distinguishing between polar cap and outer gap scenarios. Yet such diagnostics are limited in power because of the significant number of parameters in each of the models. This degree of flexibility renders each model capable of approximately describing the major characteristics presented in a given dataset on an individual pulsar: a classic example is the comparison of polar cap models (e.g. Daugherty and Harding, 1996; Dyks and Rudak, 2000) with outer gap predictions (Romani, 1996) for the Vela pulsar. Such a predictive redundancy of two disparate models for individual sources is a limitation that is lifted when global characteristics of the pulsar population are considered. This provides motive for emphasizing global trends and properties for the entire pulsar population in this paper. The reasonable premise underpinning this tack is that the two scenarios cannot generate identical trends for luminosities, spectral indices, maximum gamma-ray energies, non-thermal X-ray indices, pulse profiles, polarization signatures, etc. as functions of period, period derivative, and viewing perspective for dozens or hundreds of well-measured pulsars. Since such large gamma-ray pulsar databases will be afforded by the GLAST mission, such an approach is both pertinent and timely.

**SPECTRAL AND TEMPORAL SIGNATURES**

In the polar cap model, there are two distinguishing spectral features that serve as indicators of the field strength, namely structure sampling the cyclotron resonance that generally arises in the soft or hard X-ray bands for Crab-like and Vela-like pulsars, and the super-GeV cutoff due to attenuation by $\gamma \rightarrow e^+e^-$ pair creation. In principal, these features are smeared out by distribution of the emission of magnetospheric altitudes and colatitudes; in practice this spectral structure degradation impacts the cyclotron feature much more than it does the high energy cutoff. Moreover, the cyclotronic structure is blue shifted by the minimum Lorentz factor of pairs generated in a synchrotron cascade: in most cases this further broadens the structure rendering field diagnostics difficult if not impossible. In addition, structure in the primary curvature spectrum due to cooling breaks can confuse the situation in the hard X-ray band.

Monte Carlo cascade simulations (e.g. Daugherty and Harding, 1982) generate minimum Lorentz factors $\gamma_{\text{MIN}}$ of around 50–100 for secondary pairs in models of Vela-like pulsars. The synchrotron photon energy for this Lorentz factor is $\varepsilon_{\text{MIN}} \sim \gamma_{\text{MIN}} B/B_{\text{cr}}$, noting that a factor of $1/\gamma_{\text{MIN}}$ is introduced to account for the cascade beaming...
angle. This energy, the energy of cascade cessation, is typically in hard X-rays for Crab-like pulsars, and generally \( \gamma_{\text{MIN}} \) depends on \( B_0, P \), etc. in more or less the same manner (Baring and Harding, 2000) that \( \varepsilon_{\text{MAX}} \) does in Eq. (1) below, since the same pair creation physics applies to both. The result is an \( \varepsilon_{\text{MIN}} \) with a fairly weak field dependence. Note, however, that the reprocessing that leads to the establishment of \( \varepsilon_{\text{MIN}} \) is initiated at slightly lower altitudes (corresponding to more cascade generations) than the ultimate attenuation that defines \( \varepsilon_{\text{MAX}} \), thereby complicating parametric specifications of \( \varepsilon_{\text{MIN}} \). The spectrum possesses a break at \( \varepsilon_{\text{MIN}} \), below which it assumes the flat \( \varepsilon^{-2/3} \) form that signifies curvature or synchrotron emission from quasi-monoenergetic pairs. For the Vela pulsar (see Pavlov et al., 2001 for a spectrum), when such a flat slope is extrapolated from the gamma-ray band, the model flux in the optical band grossly underpredicts that observed, implying that another component is present below X-ray wavelengths. Note that when the surface field becomes sufficiently high, ground state pair creation suppresses the synchrotron component and the \( \varepsilon_{\text{MIN}} \) feature disappears.

The second major spectral feature is the maximum energy of emission, which is controlled by attenuation due to magnetic pair creation \( \gamma \to e^\pm \) during photon propagation through the pulsar magnetosphere. Such attenuation provides a characteristic super-exponential turnover (e.g. Daugherty and Harding, 1996) that contrasts that expected in outer gap models (e.g. see Thompson, 2001, for a comparison). Pair creation occurs at the threshold \( \varepsilon \sin \theta_{\text{KB}} = 2 \) for high fields, i.e. \( B \gtrsim 0.1 B_{\text{ct}} \), and above threshold at \( \varepsilon \sin \theta_{\text{KB}} \sim 0.2 B_{\text{ct}} / B \) for lower fields (e.g. see Daugherty and Harding, 1983). Here, \( \theta_{\text{KB}} \) is the angle of photon propagation relative to \( B \), and hereafter photon energies \( \varepsilon \) are expressed in units of \( m_e c^2 \). Hence, the mean free path for photon attenuation in \textit{curved} fields is \( \lambda_{\text{pp}} \sim \rho_c / \varepsilon_{\text{MAX}} \), i.e. when \( \varepsilon \sin \theta_{\text{KB}} \) crosses above threshold during propagation. The radius of field curvature is \( \rho_c = [P r_c / 2\pi]^{1/2} \) for a pulsar period \( P \). The approximate dependence of pair creation cutoff energies \( \varepsilon_{\text{MAX}} \) on \( B_0, R_0 \) and pulsar period \( P \) (in seconds) can be summarized in the relation (Harding, 2001; Baring, 2001a)

\[
\varepsilon_{\text{MAX}} \approx 0.4 \sqrt{P} \left( \frac{r}{R_0} \right)^{1/2} \max \left\{ 1, \frac{0.1 B_{\text{ct}}}{B_0} \left( \frac{r}{R_0} \right)^3 \right\} \text{GeV}.
\]

Accurate numerical determinations derived from the codes developed in HBG97 and Baring and Harding (2001), are plotted in Figure I; these include the effects of general relativity on spacetime curvature, field enhancement and photon energy in non-rotating systems. At fields \( B_0 \gtrsim 0.7 B_{\text{ct}} \) photon splitting acts to further reduce \( \varepsilon_{\text{MAX}} \), as discussed in Baring and Harding (2001); the operation of splitting proved necessary to account for the turnover inferred from Comptel data and EGRET upper limits to PSR 1509-58 (HBG97). For magnetars, pulsars with fields above \( 4 \times 10^{15} \) Gauss, photon splitting and pair creation should prohibit any emission above \( \sim 100 \) MeV, though prominent signals below \( 100 \) MeV are possible (Baring, 2001b) due to the efficiency of resonant Compton scattering.

There is clearly a strong anti-correlation between the maximum energy and the surface magnetic field, which seems to be augmented by an apparent decline of emission altitude with \( B_0 \). Such a trend is a distinctive characteristic that can be probed by GLAST; there appears to be no prediction of such a trend in outer gap models. The maximum energy is generally in the 1–10 GeV band for normal young pulsars, but can be much lower (e.g. HBG97; BH01) for highly magnetized ones, and also much higher for millisecond pulsars so that sub TeV-band (i.e. \( \sim 50–100 \) GeV) signals are possible (Bulik, et al., 2000) for polar cap models via synchrotron/curvature cascades if the field is low enough. It also should be remarked that the cutoff energy depends on pulse phase, with slightly greater values achieved between the pulse peaks in the case of Vela modelling (Daugherty and Harding, 1996); such a property matches the EGRET observations (Kanbach et al., 1994). Furthermore, there is an asymmetry in \( \varepsilon_{\text{MAX}} \) values between the peaks due to geometrical effects that is discussed in the next Section below. In passing it is noted that it is a generic property of polar cap models that small rotator obliquities (\( < 45 \) degrees between rotation and dipole axes) are usually needed to simultaneously produce the observed \( \varepsilon_{\text{MAX}} \) values and double peaked pulse profiles of phase separation appropriate for gamma-ray pulsars (Harding and Daugherty, 1998).

The gamma-ray spectral index \( \alpha \) extending below \( \varepsilon_{\text{MAX}} \) depends on the details of the cascading, and its behavior can be broadly summarized as follows. The primary photon index from cooling curvature radiation is \( 5/3 \), and should be realized in millisecond pulsars (Bulik, et al., 2000), where the fields are sufficiently low that synchrotron components contribute only below 1 MeV. For Vela-like fields, successive generations of cascading sequentially steepen the index (Wei, et al., 1997; Harding and Daugherty, 1998), saturating at \( \alpha = 2 \). While most gamma-ray pulsars have \( \alpha < 2 \) and can be simply described via such cascading, the Crab possesses a spectrum steeper than \( \alpha = 2 \) that must depend on a spatial convolution in some subtle and obscure manner. When the local field in the emission region exceeds around \( 6 \times 10^{12} \) Gauss, such as should be the case for PSR 1509-58, pair creation occurs only
in the ground state and quenches cascading, yielding just a bare, flat curvature spectrum \( (\alpha = 5/3) \). The contribution from resonant Compton scattering can also be significant in high field pulsars, depending on the proximity of the acceleration region to the surface and the surface X-ray temperature; its extremely flat spectrum is discussed below in the context of magnetars.

The presence of strong fields virtually guarantees a strong polarization signal in polar cap models, and when these couple with spectral structure and temporal information, particularly powerful observational diagnostics are possible. This may be fruitful at the lower end of the cascade continuum in Vela-like objects, but it is an especially valuable tool for highly-magnetized pulsars since the attenuation cutoffs fall in the Comptel band, and should exhibit strong and distinctive polarization signatures. Hard gamma-ray experiments like GLAST are generally not afforded the opportunity to act as polarimeters, being limited by multiple scattering in trackers above 300 MeV. Medium energy gamma-ray experiments, on the other hand, are ideally suited to polarization studies (via their sampling of Compton scattering kinematics). Gamma-ray polarimetry is no longer a distant dream, given the prospects (Lei, et al., 1997) that the recently-launched INTEGRAL mission will detect polarization at the 10% level from the Crab pulsar (at 200–600 keV), and also in a handful of other sources. Polarimetric capability in the hard X-ray and soft gamma-ray bands is a high priority for next-generation advanced Compton telescopes (e.g. see Kanbach et al., 2000, and the Web pages for the MEGA \([\text{http://www.gamma.mpe-garching.mpg.de/MEGA/mega.html}]\) and ACT \([\text{http://gamma.nrl.navy.mil/ngram/}]\) consortia).
Observabilities

Spectral signatures provide the second layer of detail in observational diagnostics of gamma-ray pulsars; the primary layer is clearly the flux of a source at earth, i.e. its observability. This essentially represents the normalization of the model spectrum convolved with the pulsar’s distance. In recent years there has been an evolution in the understanding of what controls the detectability, making way for a further dimension of discrimination between polar cap and outer gap models in the GLAST era, when luminosity trends will not be crimped by small population statistics. The traditional approach of the EGRET community was to use the dipole spin-down power $\dot{E} \propto B_0^2/P^4$ as an indicator of a pulsar’s observability, which is in fact mirrored by the population of field X-ray pulsars (Becker and Trümper, 1997); recent Chandra detections of pulsars in globular clusters indicate (Grindlay et al., 2002) a weaker luminosity dependence on $B_0/P^2$. While theoretically motivated (see just below), the spin-down luminosity choice did not match the trend subsequently established by EGRET: that there is clearly an almost linear correlation between the inferred luminosity $L_{\gamma}$ of gamma-ray pulsars and $B_0/P^2$, i.e. the voltage drop across the open field lines for standard polar caps. There is a very modest scatter in this correlation, largely due to the uncertainty in determining source distance by folding radio dispersion measures into the Taylor and Cordes (1993) galactic electron model (just recently updated in Cordes and Lazio, 2002).

It is interesting to note that such a linear correlation with $B_0/P^2$ of the inferred luminosity of gamma-ray pulsars was predicted (Harding, 1981) in the context of the polar cap model. At the time, only 2 gamma-ray pulsars were known, strengthening the impact of the polar cap model on the understanding of magnetospheric emission in such pulsars. The contention of a $L \propto B_0/P^2$ dependence is based on the premises that the radiative luminosity is proportional to the Goldreich-Julian current, and that the cascade emission is initiated by pairs of Lorentz factor that is almost independent of pulsar $B_0$ and period. Subsequent predictions by competing analyses/models (e.g. Sturman and Dermer, 1994; Romani and Yadigaroglu, 1995; Cheng et al., 1998; Rudak and Dyks, 1999) and revisions (Zhang and Harding, 2000) all post-dated the EGRET database. The current status is that the polar cap expectations (Sturman and Dermer, 1994; Zhang and Harding, 2000) match the data slightly more accurately than their outer gap counterparts (Romani and Yadigaroglu, 1995; Cheng et al., 1998), with each group of researchers offering different $B_0$ and $P$ dependences for the luminosity (see Harding, 2001 for a review). This situation is presently limited by small number statistics, however in the GLAST era such correlations will be established on a firm basis.

Motivations for considering their luminosity dependence are not confined to model discrimination and refinement; assumed luminosity “laws” can dictate period selection in pulsation searches. This is a salient issue for GLAST, since it will be capable of blind period searches on gamma-ray sources with no radio counterparts. The period dependence is the most critical element to the $L_{\gamma}(P, \dot{P})$ relationship. While EGRET observed most pulsars high up on a $B_0^2/P^4/d_{\text{PSR}}^2$ rank-ordered list (where $d_{\text{PSR}}$ is the pulsar distance), certain gamma-ray pulsars (notably the longer period pulsars PSR 0656+14 and PSR 1055-52) are surprisingly low in spin-down luminosity, and millisecond pulsars proved extraordinarily difficult to detect, till the detection of PSR 0218+4212 (see Kuiper et al., 2000).

Clearly, a gamma-ray luminosity dependence $L_{\gamma}(P, \dot{P})$ that differs from the spin-down one will dramatically modify the observability criterion, particularly if the period dependence is substantially different. Accurate determination of $L_{\gamma}(P, \dot{P})$ will influence the weight on different period ranges that will be applied to GLAST source data in pulsation searches. This will be particularly germane to cases where the source is near the galactic plane and pulsations are not evident at the frequencies of known radio pulsars within the GLAST source localization.

The spectral shape also affects the observability (Baring and Harding, 2000), a more subtle influence. This is a consequence of how the luminosity is distributed in the gamma-ray band, specifically that portion that emerges above the threshold sensitivity for a specific gamma-ray detector. The driving parameter for such an apportionment is the maximum emergent energy $\varepsilon_{\text{MAX}}$, and to a lesser extent $\varepsilon_{\text{MIN}}$ and the gamma-ray spectral index $\alpha$, since the spectra are generally flat enough for the bulk of the luminosity to emerge at the highest energies. These parameters control the normalization of the pulsar gamma-ray power-law for a given luminosity. An appropriate definition of a detector’s observability $O(\varepsilon_{\text{TH}})$ is the integral flux above an effective instrumental energy threshold $\varepsilon_{\text{TH}}$. For pulsars with $\varepsilon_{\text{MIN}} \ll \varepsilon_{\text{TH}}$, the usual case for GLAST considerations, this scales as the luminosity divided by the spectral normalization, yielding $O(\varepsilon_{\text{TH}}) \propto L_{\gamma}(P, \dot{P}) \varepsilon_{\text{MAX}}^{\alpha-2}/d_{\text{PSR}}^2$ (Baring and Harding, 2000; Baring, 2001a). Modest modifications to this dependence are possible, in particular if $\varepsilon_{\text{MIN}} \gtrsim \varepsilon_{\text{TH}}$ (see Baring 2001a for a discussion). The essential feature is that the observability is substantially different from that inferred from the spin-down formula, assuming that $\varepsilon_{\text{MAX}}$ scales with $B_0$ and $P$ approximately as the low field alternative offered in Eq. (1). Accordingly, observabilities predicted for GLAST pulsation searches should follow a dependence (Baring, 2001a) somewhere in
between $B_0/P^2$ and $B_0^2/P^{5/2}$. Using the latter possibility, Baring and Harding (2000) generated a revised rank-ordered listing that indicated a dramatic rearrangement from the traditional EGRET ordering. A depiction of this re-ordering in $O(\varepsilon_{TH})$ versus $\dot{E}/d_{PSR}^2$ space is given in Figure 2, where each axis can be used to define a rank ordering.

The limited scatter around a linear dependence in the figure indicates that there are generally only modest changes to the rankings for most pulsars when adopting the observability as an updated criterion for detectability. The most notable changes (see Baring, 2001a) included the much higher ranking of the “outlier” longer period gamma-ray pulsars PSR 0656+14 and PSR 1055-52, and the marked lowering of millisecond pulsars (PSR 1939+2134, PSR 0437-4715, PSR 1744-1134, etc.) in the ranks, specifically out of the top 40. Both of these reflect the weaker dependence of the revised observability on $P$. These refinements of rank-orderings mute questions of why PSR 1055-52 was seen by EGRET. Further revisions are in progress, and largely focus on the details of spectral shape. Only modest influences are expected from new pulsar distance determinations resulting from the updated model for the galactic electron distribution, NE2001 (Cordes and Lazio, 2002).

![Gamma-Ray Observabilities for Radio Pulsars](image)

**Fig. 2.** The GLAST observability phase space for 40 known radio pulsars that are grouped by symbol, as indicated, according to whether they are gamma-ray pulsars, X-ray emitters, ordinary Princeton catalog sources, or new pulsars from the Parkes MultiBeam (MB) survey [Manchester et al., 2001; [http://www.atnf.csiro.au/research/pulsar/pmsurv/](http://www.atnf.csiro.au/research/pulsar/pmsurv/)]. The x-axis represents the canonical dipole spin-down power $\dot{E}$ divided by $d_{PSR}^2$, and the y-axis indicates the fiducial GLAST observability $O(30MeV)$, i.e. integral flux above 30 MeV, as obtained by Baring and Harding (2000). The GLAST integral flux threshold for pulsating sources is around $2 \times 10^{-9}$ cm$^{-2}$ sec$^{-1}$, so that it should comfortably detect all depicted pulsars. The corresponding EGRET value is $3 \times 10^{-7}$ cm$^{-2}$ sec$^{-1}$, above around 100 MeV. Observe that the Parkes MB pulsars do not rank in the top ten for flux due to their typically large distances. Also, the flux specification for the high field pulsar PSR 1509-58 is sensitive to fine-tuning in $\varepsilon_{MAX}$, since this parameter is proximate to the 30 MeV threshold for the GLAST Large Area Telescope.
RECENT DEVELOPMENTS

Slot Gaps

During the Compton Gamma-Ray Observatory era, polar cap modelling focussed mostly on magnetospheric emission processes in order to take advantage of the rapid increase in gamma-ray pulsar data afforded by EGRET. In the last few years, considerable effort has been invested by Harding and Muslimov in the exploration of the acceleration region in order to determine the altitudes and particle energies associated with acceleration in the polar cap potentials (e.g. see Harding and Muslimov 1998, Muslimov and Harding 2003). Such details are essential to forming a self-consistent polar cap model for outward cascade emission as well as for polar cap reheating and subsequent X-ray reprocessing of the cascade power. In particular, a major question was raised by the modeling of Vela data: Daugherty and Harding (1996) ascertained that high altitudes ($\sim 2 - 3$ stellar radii) for the emission region were required to simultaneously explain the pulse phase separation and the $\sim 5$ GeV maximum energy of emission. The altitude of the pair formation front (PFF) was a free parameter in their model, and a concerted effort in studying pulsar electrodynamics was needed to ascertain whether high altitudes could naturally be expected.

The recent work of Muslimov and Harding (2003) has affirmed the altitude choice of Daugherty and Harding (1996). In an extension of their sequence of papers on PFF development and location under the influence of general relativistic frame-dragging effects, they have explored colatitude variations of the PFF height. Their principal result is that there is a large variation in height with colatitude $\theta$ along the surface of the polar cap. This arises because the accelerating potential drops smoothly to zero at the rim of the polar cap, thereby extending the acceleration region to high altitudes in the vicinity of the rim. Pair quenching of the smaller electric field is precipitated more gradually due to the prolongation of acceleration in this confined region, referred to as the slot gap (after Arons, 1983). The result is that the dominant emission region spans a range of altitudes from relatively near the surface at the magnetic axis up to several stellar radii above the surface in the vicinity of the rim. Accordingly, hard X-ray and gamma-ray pulsar emission contains both core and conal components. In addition, the broad distribution of emission altitudes could aid smoothing of the super-exponential turnovers imposed by pair creation attenuation near $\varepsilon_{\text{MAX}}$. The angular width of the slot gap scales approximately as $(P/B)^{1/2}$ for $B_0 \lesssim 4 \times 10^{12}$ Gauss. When this is incorporated in solid angle modifications to the emergent gamma-ray luminosity, the slot gap model of Muslimov and Harding (2003) impressively accounts for the inferred luminosities in most cases; Geminga and the millisecond pulsar PSR 0218+4232 provide exceptions that require refinements to the model.

Pulse Asymmetry

The GLAST experiment will afford phase-resolved spectroscopy at unprecedented statistical significance. It will provide well-defined pulse profiles in much smaller energy bins than were possible with EGRET or Comptel. Such developments enable new diagnostic capabilities. One effect that can be probed by this advance is that of pulse asymmetry, which has been studied in detail by Dyks and Rudak (2002). As the magnetosphere rotates, the photon trajectories slip across the curved field lines slightly. This relative motion differs between the leading and trailing rims of the polar cap, translating to different shapes for the two peaks in the pulse profile. Since pair creation rates are critically sensitive to the angle $\theta_{kB}$ between the photon path and the local field line, one expects significant correlation of pulse asymmetries with photon energy. Dyks and Rudak find that near the pair creation turnover at $\varepsilon_{\text{MAX}}$, the trailing peak dominates since $\theta_{kB}$ is larger on average for the leading rim. Equivalently, $\varepsilon_{\text{MAX}}$ is lower for the leading pulse. Concomitantly, the pair reprocessing is enhanced for the leading peak so that it becomes the more prominent of the two peaks at sub-GeV energies. While $\varepsilon_{\text{MAX}}$ is an increasing function of $P$ for the leading rim, non-monotonic dependence of $\varepsilon_{\text{MAX}}$ on period is exhibited by the trailing rim, providing constraints that will aid isolation of the rotator obliquity for an assumed polar cap size. Note that although Dyks and Rudak explored these asymmetry effects in flat spacetime, they are also present in the curved spacetime magnetospheric models of Muslimov and Harding (2003). Observe also that this rotational effect is a strong function of pulse period, being much more pronounced for fast rotators, as expected. Fortunately, these are the brighter portion of pulsars so such distinctive properties will provide powerful probes of polar cap models in the GLAST era.
In conclusion, this paper has identified key properties that the polar cap (PC) model has that are dependent on high $B$ physics, and that are palpably distinguishable from outer gap model characteristics; these can be summarized as follows. In the PC model there is no pulsed TeV emission in garden-variety pulsars, though millisecond pulsars should exhibit sub-TeV emission. The attenuation of gamma-rays due to one photon pair creation generates super-exponential cutoffs in the 10 MeV – 10 GeV band when the surface polar field is in the range $10^{11}$ Gauss $\lesssim B_0 \lesssim 4 \times 10^{13}$ Gauss; these have been posited as a key pulsar diagnostic for GLAST. Moreover, $\varepsilon_{\text{MAX}}$ should decline with increasing $B_0$ if $B_0 \lesssim 4 \times 10^{13}$ Gauss. At the same time, an increase of $\varepsilon_{\text{MAX}}$ with emission altitude implies a correlation between $\varepsilon_{\text{MAX}}$ and pulse separation. Recent work has also suggested that there should exist a significant pulse asymmetry near $\varepsilon_{\text{MAX}}$ and for lower cascade photon energies. In the special case of magnetars, pulsars with fields above $4 \times 10^{13}$ Gauss, attenuation due to photon splitting and pair creation should prohibit any emission above $\sim 100$ MeV, though prominent sub-100 MeV signals are possible due to the efficiency of resonant Compton scattering, and can be probed by GLAST. The hard X-ray/soft $\gamma$-ray spectral slope is expected to steepen slightly as $B_0$ rises when $3 \times 10^{11}$ Gauss $\lesssim B_0 \lesssim 10^{15}$ Gauss, though flat curvature radiation spectra with $\alpha = 5/3$ are anticipated for both highly-magnetized and millisecond pulsars, i.e. at both ends of the pulsar field range. Most of these features will be probed by new gamma-ray missions INTEGRAL, AGILE, GLAST and ground-based air Čerenkov telescopes (HESS, Veritas, MAGIC, CANGAROO-III), as well as current X-ray missions CHANDRA, XMM, and RXTE. In addition, strong and distinctive polarization signatures are expected in pulsar spectra, which may be explored for the first time by INTEGRAL; positive detections anticipated for the Crab pulsar would break new ground in for the astrophysics of gamma-ray pulsars.

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