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Perspectives on Gamma-Ray Pulsar Emission

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Abstract. Pulsars are powerful sources of radiation across the electromagnetic spectrum. This paper highlights some theoretical insights into non-thermal, magnetospheric pulsar gamma-ray radiation. These advances have been driven by NASA’s Fermi mission, launched in mid-2008. The Large Area Telescope (LAT) instrument on Fermi has afforded the discrimination between polar cap and slot gap/outer gap acceleration zones in young and middle-aged pulsars. Altitude discernment using the highest energy pulsar photons will be addressed, as will spectroscopic interpretation of the primary radiation mechanism in the LAT band, connecting to both polar cap/slot gap and outer gap scenarios. Focuses will mostly be on curvature radiation and magnetic pair creation, including population trends that may afford probes of the magnetospheric accelerating potential.

Keywords: Pulsars; non-thermal mechanisms; magnetic fields; neutron stars; gamma-rays

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INTRODUCTION

Prior to the launch of the Compton Gamma-Ray Observatory (CGRO) in 1991, the gamma-ray pulsar database was extremely limited. CGRO extended the population to seven sources, all of them young pulsars, and only Geminga had no definitive observation of a radio pulsar counterpart. There were also a few marginal CGRO detections, including the millisecond pulsar PSR J0218+4232. Following the launch of the Fermi Gamma-Ray Space Telescope on June 11, 2008, the gamma-ray pulsar database has grown rapidly, with over 75 sources now observed with high significance. Most of these are again young pulsars with higher spin-down luminosities than the average for radio pulsars. Yet, a sizable millisecond pulsar (MSP) population has emerged, at present numbering more than twenty. Moreover, the improved photon counts captured by the Fermi Large Area Telescope has enabled blind pulsation searches, those without prior knowledge of a radio timing ephemeris. The LAT has discovered over 20 pulsars in blind searches of the gamma-ray data alone, and only a few have since had radio confirmation.

The improved pulse-phase spectroscopy enabled by Fermi has clarified the probable locale of the gamma-ray emission region. The two major competing models for the site of this emission are the polar cap (PC) near the stellar surface (e.g. [10, 12]) and the outer gap (OG) near the light cylinder (e.g. [9, 20]). Super-exponential turnovers due to magnetic pair creation are expected for PC models at the maximum photon energies in the GeV band, as opposed to exponential shapes for OG models. Discrimination by Fermi-LAT between these two shapes was anticipated prior to launch [19]. In the vast majority of LAT pulsar spectra, the turnovers are exponential, thereby favoring the OG scenario [2]. Furthermore, the separation of peaks in pulsars with more than one pulse peak is generally of the order of 0.3–0.5 in phase, indicating a broad radiation
cone that is consistent only with high altitude emission locales for dipolar fields (e.g. [26]). This evidence has ushered in a new era for the $\gamma$-ray pulsar paradigm. Here, some perspectives pertaining to this new era are offered, focusing first on lower bounds to the emission radius from magnetic pair creation physics. In addition, the GeV-band turnover energies $E_{\text{MAX}}$ are assessed in terms of the canonical radiation-reaction-limited curvature emission picture, touching upon population characteristics for $\gamma$-ray pulsars.

**MAGNETIC PAIR CREATION BOUNDS FOR THE MINIMUM ALTITUDE OF EMISSION**

The emergence of gamma-rays from pulsars is probably intimately coupled to the generation of electron-positron pairs in their magnetospheres. Such a connection between radiation emission and pair creation was posited in early radio-pulsar pictures [21, 24]. In the inner magnetosphere of young pulsars, the dominant pair production process involves a single photon interacting with the $B$ field, $\gamma \rightarrow e^+ e^-$, with its non-magnetic, quantum counterpart $\gamma\gamma \rightarrow e^+ e^-$ only becoming competitive at high altitudes. Hence, $\gamma \rightarrow e^+ e^-$ is the preserve of polar cap (PC; [10]) and slot gap (SG; [18]) gamma-ray pulsar models. It is a first-order QED process that is kinematically forbidden in field-free regions, but can take place in an external magnetic field, which can absorb momentum perpendicular to $B$. Its generic physics properties are summarized in [6]. Due to energy conservation, its rate $R_{\text{pp}}$ possesses an absolute threshold energy, $\varepsilon_{\gamma} \geq \frac{2}{\sin \theta_{\text{KB}}}$. Here $\theta_{\text{KB}}$ is the angle the photon momentum vector $k$ makes with the magnetic field $B$, and the photon energy $\varepsilon_{\gamma}$ is in units of $m_e c^2$, a convention adopted hereafter.

Above threshold, $R_{\text{pp}}$, which is averaged here over photon polarizations, exhibits a large number of resonances, corresponding to thresholds for the creation of pairs in excited states; these aggregate to exhibit a characteristic sawtooth structure (e.g. [6, 11]). In pulsar contexts, considerable ranges of field strengths and photon angles $\theta_{\text{KB}}$ are sampled during magnetospheric propagation: the resulting convolution smears out the sawtooth appearance into a continuum. In this regime, the dependence on $\varepsilon_{\gamma}$ can be approximated by a compact asymptotic expression (e.g. [13]; and references in [6]):

$$R_{\text{pp}} \approx \frac{3}{8} \sqrt{\frac{3}{2}} \frac{\alpha_f c}{\lambda_c} \frac{B}{B_{\text{cr}}} \sin \theta_{\text{KB}} \exp \left\{ -\frac{8}{3} \Upsilon \right\}, \quad \Upsilon \equiv \frac{B}{B_{\text{cr}}} \varepsilon_{\gamma} \sin \theta_{\text{KB}} \ll 1 , \quad (1)$$

where $\Upsilon$ is the critical asymptotic expansion parameter. Here, $\alpha_f = e^2/(\hbar c)$ is the fine structure constant, $\lambda_c = \hbar/(m_e c) = 3.862 \times 10^{-11}$ cm is the electron Compton wavelength over $2\pi$, and $B_{\text{cr}} = m_e^2 c^3/(e\hbar) = 4.413 \times 10^{13}$ Gauss is the quantum critical field, where the cyclotron energy equals $m_e c^2$. Near threshold, this asymptotic result is an imprecise description of $R_{\text{pp}}$ [11], and can be improved considerably by careful treatment of the associated mildly-relativistic regimes for the produced pairs (e.g. [4]).

In polar cap pulsar models [10, 21, 24], primary curvature photon emission is emitted at very small angles to the magnetic field, well below pair threshold (e.g. [8]). These photons will convert into pairs only after traveling a distance $s$ that is a fraction of the field line radius of curvature $\rho_c$. Above the polar cap, the radius of field curvature is $\rho_c = [Pr/(2\pi)]^{1/2}$ for a pulsar period $P$, and exceeds the neutron star radius $R_{\text{NS}}$. Pair
creation ensues for small angles such that \( \sin \theta_{kB} \sim s/\rho_c \), and the argument \( \Upsilon \) of the exponential becomes a fraction of unity, i.e., when \( \varepsilon_e B \sin \theta_{kB} \gtrsim 0.2 B_{cr} \). Accordingly, in young pulsars, pair production will usually occur somewhat or well above threshold when \( B \ll 0.1 B_{cr} \), and the attenuation mean free path \( \lambda_{pp} \sim \rho_c/\varepsilon_{cr} \) will then be much less than \( R_{NS} \). Consequently, the optical depth \( \tau_{\Upsilon}(\varepsilon_{gy}) \) for one-photon pair opacity will be a \( \gamma \)-ray emission signature at the escape energy \( \varepsilon_{esc} \), which typically lies above 100 MeV (see [8]).

The upshot is that attenuation by \( \gamma \to e^+e^- \) should impose a \( \text{super-exponential} \) cutoff in pulsar \( \gamma \)-ray spectra of the approximate form \( d n_{\gamma}/d \varepsilon_{\gamma} \propto \exp\{-\alpha \exp[-\varepsilon_{esc}/\varepsilon_{\gamma}]\} \) for some constant \( \alpha \). If \( \varepsilon_{esc} \sim \varepsilon_{\text{MAX}} \equiv E_{\text{MAX}}/m_e c^2 \), the severity of the cutoff should produce [10, 12] a sharp turnover that is distinguishable from those generated by other mechanisms. It was widely anticipated [19] that the Fermi-LAT instrument would discern the precise shape of such cutoffs in Vela and other pulsars, and accordingly discriminate between the polar cap and outer gap models for their high energy emission. It has in fact done so. Early on in the first year of observations by Fermi, the high count rates for Vela permitted the exclusion of super-exponential turnovers at a high level of significance [1]. This has become possible for the pool of 39 young pulsars listed in the Fermi-LAT Pulsar Catalog in [2], all of which reveal significant turnovers in the 1-10 GeV band consistent with simple exponentials. This clearly demonstrates that \( \gamma \to e^+e^- \) is not producing the observed turnovers, proving that \( \tau_{\Upsilon}(\varepsilon_{\gamma}) \lesssim 1 \) for \( \varepsilon_{\gamma} \sim \varepsilon_{\text{MAX}} \).

This undeniable absence of the signature of active magnetic pair creation in gamma-ray pulsar signals can be inverted to provide robust lower bounds to emission altitudes, a protocol that has been adopted in a number of Fermi-LAT pulsar papers. Defining a marginal magnetic pair opacity criterion \( \tau_{\Upsilon}(\varepsilon_{\text{MAX}}) \approx 1 \) near the pulsar surface, rearrangement yields an approximate dependence of pair creation cutoff energies \( \varepsilon_{\text{MAX}} \) on \( B_0 \), \( R_0 \) and pulsar period \( P \) (in seconds). Setting \( E_{\text{MAX}} \equiv \varepsilon_{\text{MAX}} m_e c^2 \), this can be summarized in a relation [5] that corresponds to near-surface emission \((r \lesssim 2R_{NS})\):

\[
E_{\text{MAX}} \sim 0.4 \sqrt{P} \left( \frac{r}{2R_{NS}} \right)^{1/2} \max \left\{ 1, \frac{0.1 B_{cr}}{B_0} \left( \frac{r}{2R_{NS}} \right)^3 \right\} \text{GeV} .
\]

This encapsulates the character of accurate numerics derived from codes employed in [14] and [8], which include pronounced effects of general relativity on spacetime curvature, field enhancement and photon energy. In flat spacetime, the altitudinal dependence is weaker, corresponding to \( \varepsilon_{\text{MAX}} \propto (r/R_{NS})^{5/2} \) (e.g. [16, 27]) above the magnetic poles.

The pair opacity \( \varepsilon_{\text{MAX}} \) trend can be expressed alternatively as a combination of observables appropriate for this inner gap (polar cap) discussion. The form is

\[
\log_{10} \frac{E_{\text{MAX}}}{1 \text{ GeV}} \approx \sigma_{1G} + \frac{7}{2} \log_{10} \chi_{1G} + 0.25 \quad , \quad \sigma_{1G} = -\log_{10} B_{12} + \frac{1}{2} \log_{10} P .
\]

which clearly encapsulates an anti-correlation with \( \dot{P} \), as does Eq. (2), since \( B_0 = 3.2 \times 10^{19}(P \dot{P})^{1/2} \) [17]. Here \( \chi_{1G} = r/R_{NS} \) is the scaling of the radius appropriate for polar cap considerations. Figure 1 plots the phase space corresponding to Eq. (3), using the measured spectroscopic cutoffs \( E_c \) for young Fermi-LAT pulsars in Table 4 of [2] to
The inferred maximum pulsar emission energies $E_{\text{MAX}}$ as a function of the key polar cap (inner gap) magnetic pair creation attenuation parameter $\sigma_{\text{IG}}$ defined in Eq. (3). The spectral parameters used are the cutoff energies $E_c$ listed in Table 4 of [2], the First Fermi-LAT Catalog of Gamma-ray Pulsars. For the 37 pulsars constituting the black points, $E_{\text{MAX}} = 2.5E_c$ was set; for the Crab and Vela, $E_{\text{MAX}} = 3.5E_c$ (see text). The high-field CGRO Comptel pulsar B1509-58 (J1513-5908) is also displayed. No LAT millisecond pulsars are depicted. The fiducial linear relationship in Eq. (3) is displayed as the diagonal lines for four different emission altitudes, $r/R_{\text{NS}} = 1$ (surface), 2, 3, 4, as labelled.

benchmark the maximum energies $E_{\text{MAX}}$. Since these cutoffs are exponential in character, the action of magnetic pair creation can be ruled out at energies below the window around $E_c$. For this reason, a representative setting of $E_{\text{MAX}} = 2.5E_c$ was deployed in the Figure for most of the pulsars, the set of 37 with points in black. This value can be adjusted on a case-by-case basis, depending on the photon counting statistics. Accordingly, the alternative value of $E_{\text{MAX}} = 3.5E_c$ was adopted for the Crab and Vela pulsars. Motivations for these exceptions are as follows: the Crab, possesses high energy emission reflected in its pulsed detection by MAGIC [3], and Vela, because its impressive count rate as the brightest LAT-band pulsar in the sky permits extraordinary spectroscopic determination of its turnover [1]. The uncertainties in $E_c$ were scaled similarly, yielding the $E_{\text{MAX}}$ error bars in the Figure. PSR B1509-58, the young, high-field pulsar detected by Comptel on CGRO, but not by EGRET, was also placed in the Figure using an inferred $E_{\text{MAX}}$ value from the spectral results displayed in [14]. It is the only gamma-ray pulsar that might be consistent with $\gamma \rightarrow e^+e^-$ attenuation operating near the stellar surface. Observe that no millisecond pulsars (with $\sigma_{\text{IG}} < -2$) are exhibited in Fig. 1 as their surface fields are so low that $\gamma \rightarrow e^\pm$ pair creation is exponentially improbable in their magnetospheres. The phase space plot in Figure 3 clearly demonstrates that there is no correlation between $E_{\text{MAX}}$ and $\sigma_{\text{IG}}$ or $\dot{P}$ in the LAT pulsar population.
CURVATURE RADIATION AT HIGH ALTITUDES

Given the above discussion it is evident that the Fermi GeV-band spectral cutoffs in young pulsars are probably related to the primary emission mechanism. Dating from the early models of [24], this mechanism is postulated to be curvature radiation, the elementary dipole radiation resulting from pairs accelerating in the curved magnetospheric fields. The formalism for the curvature radiation emissivity is identical to that for classical synchrotron radiation [15, 22], but with the electron Larmor radius $r_L = \gamma e m_e c^2 / (eB)$ being replaced by the radius of field curvature, $\rho_c$. Accordingly, the characteristic dimensionless (i.e., in units of $m_e c^2$) photon energy scales for curvature radiation, $\varepsilon_c$, and synchrotron emission $\varepsilon_s$, are

$$\varepsilon_c = \frac{3}{2} \gamma^3 \frac{\lambda c}{\rho_c}, \quad \varepsilon_s = \frac{3}{2} \gamma^3 \frac{\lambda c}{r_L} \sin \theta_e \equiv \frac{3}{2} \frac{B}{B_{cr}} \gamma^2 \sin \theta_e .$$

(4)

For curvature emission to seed pulsar gamma-ray signals, $\varepsilon_c$ must exceed a few GeV in the magnetosphere; this is routinely satisfied in polar cap (e.g. [12]), slot gap [18] and outer gap (e.g. [20]) models, for both young pulsars and millisecond ones.

At its characteristic photon energy, the differential emissivity per electron scales as $\alpha f/\lambda c \varepsilon_c^2$ (e.g. see Eq. (2) of [7]) for both the curvature and synchrotron processes. When this emissivity scale is multiplied by the square of the photon energy scale in Eq. (4), the corresponding magnitudes for the curvature radiation and synchrotron cooling rates result; in full form these rates are

$$\dot{\gamma}_{CR} = -\frac{2}{3} \frac{r_0 c}{\rho_c} \gamma^4 , \quad \dot{\gamma}_{syn} = -\frac{2}{3} \frac{r_0 c}{r_g} \gamma^2 \sin^2 \theta_e .$$

(5)

Here $r_g = m_e c^2 / (eB) = \kappa_c B_{cr}/B$ is $c$ divided by the cyclotron frequency, and $r_0 = \alpha f \lambda_c = e^2 / (m_e c^3)$ is the classical electron radius. The precise numerical factors can be derived using the synchrotron formulation of [22]; for the curvature process this requires the specialization to pitch angles $\theta_e = \pi/2$. From Eq. (5) one derives the criterion for the dominance of a synchrotron signal over a curvature one: $\gamma_c \lesssim \rho_c \sin \theta_e / r_g$. While $\theta_e \approx 0$ is presumed for the primary emission, pair creation usually generates secondary photons at significant angles to the field, so that this inequality is almost always satisfied: synchrotron photons therefore abound in subsequent generations of a cascade. Since $\rho_c / r_g \gg 10^{15}$ near the polar cap in young pulsars, only very small $\theta_e$ are required to spawn the swamping of primary curvature emission by a synchrotron component in the inner magnetosphere. This possibility should be borne in mind for future refinements of the gamma-ray pulsar paradigm.

The maximum Lorentz factor of the electrons emitting in gamma-ray pulsars is a function of the accelerating potential adopted in a given model. If the electric field component along the local magnetic field is $E_\parallel$ (presumed positive), then the energy gain rate in the electrostatic gap is $\dot{\gamma}_{acc} m_e c^2 = e E_\parallel c$, i.e. the electron speed $c$ times the force. The maximum possible electron Lorentz factor $\gamma_{MAX}$ is realized when this gain equals the loss rate due to radiative cooling, which is the radiation-reaction limit generally ascribed to curvature emission in gamma-ray pulsar models. Setting $-e E_\parallel / (m_e c)$ equal to
the first result in Eq. (5) yields a maximum $e^-$ Lorentz factor $\gamma_{\text{MAX}} \sim [3 \rho_c^2 E_{\parallel}/(2e)]^{1/4}$, which can then be inserted into Eq. (4) to specify the approximate maximum photon energy (in units of $m_e c^2$) for curvature radiation reaction-limited acceleration:

$$\varepsilon_{\text{MAX}} = \left( \frac{3}{2} \right)^{7/4} \lambda_c \rho_c^{1/2} \frac{E_{\parallel}}{e}^{3/4}.$$  

This form for $\varepsilon_{\text{MAX}}$ is routinely cited in Fermi-LAT publications on gamma-ray pulsars (e.g. [2]). In principal, the observed cutoff energy can be less than this value if attenuation by pair production, magnetic or two-photon, is efficient, or the acceleration is terminated by mechanisms other than curvature cooling. Hence, the observed GeV-band turnovers in dozens of young pulsars in the First Fermi-LAT Pulsar Catalog provide lower bounds to the accelerating potential, modulo the altitude of emission.

A natural, fiducial scale for the parallel electric field can be obtained from Lorentz transformations associated with a rotating magnetosphere. This establishes $r \vec{\Omega} \times \vec{B}/c$ as the co-rotational component of $\vec{E}$, providing the ideal MHD contribution. Yet within the plasmasphere, a non-co-rotational, parallel component $E_{\parallel}$ emerges due to departures from Goldreich-Julian current flow (e.g. [23, 25]): it is putatively of the same order of scaling $\sim r \Omega B/\gamma c$. This is the most optimistic scenario, being adopted for example in the seminal outer gap pulsar model of [9], and leads to $E_{\parallel} \sim e/(r_0 \lambda_c) \chi^{-2} B_{\text{LC}}/B_{\text{ct}}$ for $\chi = r/R_{\text{LC}}$ describing the scaling of the acceleration/emission radius in terms of the light cylinder radius $R_{\text{LC}} = P c/(2 \pi)$ that will be employed hereafter. These define so-called thick outer gaps (e.g. [28]). Here $B_{\text{LC}}$ is the field strength at $r = R_{\text{LC}}$, essentially along the last open field line. Note that the dependence of $E_{\parallel}$, $B_{\text{LC}}$ and the radius of curvature on the obliquity of the rotator, and colatitude $\Theta$, is omitted in this discussion. Using the scaled radius of curvature $v_c = \rho_c/\chi R_{\text{LC}}$, one can then insert this nominal value for $E_{\parallel}$ into Eq. (6). This can be cast in terms of observables $P$ and $\dot{P}$. For a surface polar field $B_0 = 3.2 \times 10^{19}(P \dot{P})^{1/2} \equiv 10^{12} B_{12}$ Gauss and a neutron star radius of $R_{\text{NS}} = 10^6$ cm, since $B_{\text{LC}} = B_0 (R_{\text{NS}}/R_{\text{LC}})^3$, setting $P = 0.1 P_{-1}$ sec yields a result of

$$E_{\text{MAX}} \approx \frac{8.0 v_c^{1/2}}{\chi} (e B_{12})^{3/4} (P_{-1})^{-7/4} \text{GeV}.$$  

This scaling is commensurate with that obtained in Eq. (4) of [20]. Clearly $E_{\text{MAX}}$ rises monotonically as the acceleration locale moves from the light cylinder towards the neutron star surface, due to the rapidly rising inductive $B$-field. An additional electrostatic decrement factor $\varepsilon_{\parallel} \leq 1$ has been introduced in Eq. (7) to facilitate the subsequent discussion. It is an acceleration efficiency factor, representing the departure of $E_{\parallel}$ below the fiducial, optimistic value of $E_{\parallel} \sim r \Omega B/\gamma c$; in general it is a function of the altitude parameter $\chi$, the colatitude $\Theta$ and the rotator obliquity angle $\alpha$.

To interpret this outer magnetospheric curvature radiation cutoff scaling, Figure 2 displays the phase space corresponding to Eq. (7), plotting $\log_{10}E_c$ versus the appropriate combination of observables $P$ and $\dot{P}$; in this graph, the cutoff energy $E_c$ serves as a proxy for $E_{\text{MAX}}$. For the curvature radiation expectation in an outer gap (OG) near the
**FIGURE 2.** Observed *Fermi*-LAT pulsar emission cutoff energies as a function of the key outer gap curvature radiation reaction-limited acceleration parameter $\sigma_{OG}$ defined in Eq. (8). The data come from the First *Fermi*-LAT Pulsar Catalog [2], with classic spinning-down pulsars (SDPs) in black, and millisecond pulsars (MSPs) in blue, as indicated. The Crab pulsar point from the Fermi dataset is highlighted, noting that its $E_c$ from the MAGIC detection [3] is considerably higher. The diagonal lines labelled with $\chi = r/R_{LC}$ values constitute solutions of Eq. (8) for $\epsilon_\parallel = 1$ and $v_c = 1$.

![Graph showing the relationship between $\log_{10}(E_{\text{MAX}})$ and $\sigma_{OG}$ for Fermi-LAT pulsars with SDPs and MSPs distinguished.](image)

The graph is derived from the LAT pulsar data in Tables 1 and 4 of [2]. Since the $E_{MAX}$ values appear in a relatively narrow range, with considerable spread in $\sigma_{OG}$, there appears to be no clear linear correlation, just the suggestion of one. The diagonal lines corresponding to $\hat{\chi} = 1, 0.1, 10^{-2}$ in the Figure provide an approximate guide to read off the scaled altitude. It is clear that this case of maximal $E_\parallel$ cannot quite accommodate the turnover energies of the LAT pulsars being attributed to cooling-limited curvature emission within the light cylinder: the observations mandate that the electrostatic decrement lie in the range $0.05 \lesssim \epsilon_\parallel \lesssim 1$ if $\chi = 1$. This essentially implies acceleration potentials somewhat weaker than the co-rotational benchmark $r\Omega B/c$, or considerably so (i.e., $\epsilon_\parallel \lesssim 10^{-2}$) if the outer gap emission altitude lies well within the light cylinder radius, i.e. $\chi \lesssim 0.1$. This observational diagnostic becomes less constraining if some two-photon pair attenuation is active in the emission region, thereby lowering the observed cutoff energy $E_c$ below the curvature radiation $E_{MAX}$.

\[ \log_{10} \frac{E_{\text{MAX}}}{1 \text{ GeV}} \approx \sigma_{OG} - \log_{10} \hat{\chi} - 0.85 \quad , \quad \sigma_{OG} = \frac{3}{4} \log_{10} B_{12} - \frac{7}{4} \log_{10} P \quad . \]  

(8)
The phase space plot in Fig. 2 exhibits a remarkable property — that the youngish, dipole-torque spin-down pulsars (SDPs) and old, recycled millisecond pulsars (MSPs) occupy the same locale. The \( x \)-coordinate, \( \sigma_{OG} \), is an approximate linear function of \( \log_{10} B_{LC} \), and the field \( B_{LC} \) is fairly similar for the two populations (see Table 1 of [2], and compare Fig. 2 here with their Figure 7 that displays the array of Fermi-LAT pulsar \( \varepsilon_{MAX} \) values versus \( \log_{10} B_{LC} \)). This approximate coincidence of \( B_{LC} \) values in SDPs and MSPs was, of course, well-known for the radio pulsar population. Yet, the clustering of the gamma-ray \( \varepsilon_{MAX} \) around similar values for SDPs and MSPs is a new insight enabled by Fermi. It is strongly suggestive that similar physical acceleration locales and radiative emission mechanisms operate in the two populations.

**Concluding Remarks:** The picture of high altitudes for \( \gamma \)-ray emission in young pulsars is now well-established. Yet questions still remain. Is the primary mechanism curvature emission, or can small-angle synchrotron radiation contribute significantly to the signal? What is the role of two-photon pair creation in controlling the range of observed \( \varepsilon_{MAX} \)? Does magnetic pair production at low altitudes still enhance the multiplicity of pairs being pumped into surrounding pulsar wind nebulae? These issues will capture the focus of theorists in the years to come as the Fermi pulsar legacy further unfolds.

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