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# Gamma-Ray Pulsars

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**Abstract.** Various observations of γ-ray pulsars are summarized briefly and related to outer-magnetosphere accelerator models.

## 1. Introduction

The charged particles on the closed magnetic field lines of a pulsar magnetosphere are expected to be "charge separated" (Michel 1991): because of gravitational and inertial forces the charge density needed to maintain $\boldsymbol{E} \cdot \hat{\boldsymbol{B}} \sim 0$ in the corotating magnetosphere (Goldreich and Julian 1969) consists in any region exclusively of positively charged particles or of negatively charged ones, but not a mixture of both. Relativistic current along open $\boldsymbol{B}$-field lines results in charge deficient regions where $\boldsymbol{E} \cdot \hat{\boldsymbol{B}} \neq 0$ if the current is carried by the flow of charge separated plasma (Scharlemann *et al.* 1978). In such regions $e^- / e^+$ would be accelerated to large relativistic energies and become powerful sources of high energy γ-rays. The materialization of some or all of that γ-ray emission could produce enough $e^{\pm}$ pairs to supply the charge needed to sustain magnetospheric current flow and quench further accelerator growth. These accelerators and the γ-ray emission which they power may be relatively close to the surface of a neutron star ("polar cap accelerators" (Sturrock 1971; Ruderman and Sutherland 1975; Michel 1991), "slot-gap" accelerators (Arons and Scharlemann 1979), or very far from the surface at a good fraction of the way to the corotation speed-of-light-cylinder ("outer-gap" accelerators (Cheng, Ho and Ruderman 1986a, Chiang and Romani 1992), or at both locations. The mechanism for $e^{\pm}$ pair production by the accelerator is quite different in the two locations. When the local magnetic field is as strong as that found near the stellar surface, γ-rays can be converted to pairs by the field itself (Sturrock 1971; Ruderman and Sutherland 1975; Daugherty and Harding 1982, 1983, 1989). In the outer-magnetosphere the local magnetic field is much too weak for such a mechanism to be effective and local $e^{\pm}$ pair production would have to be maintained by collisions of energetic γ-rays on X-rays or other γ-rays (Cheng, Ho and Ruderman 1986b); (or conceivably even on electron-volt photons if the initial γ-ray energies were high enough).

Seven solitary pulsars with strong energetic non-thermal emission have now been observed (Table 1). Many of the long known but still unidentified "COS-

| | Pulsar | $L_\gamma$ (erg s$^{-1}$) | $I\Omega\Omega$ (erg s$^{-1}$) |
|---|---|---|---|
| **A** | Crab | $3 \cdot 10^{35}$ | $3 \cdot 10^{38}$ |
| | 1509 | $\sim 1 \cdot 10^{35}$ | $2 \cdot 10^{37}$ |
| | 0540 | ? | $2 \cdot 10^{38}$ |
| **B** | Vela | $4 \cdot 10^{34}$ | $7 \cdot 10^{36}$ |
| | 1706 | $3 \cdot 10^{34}$ | $3 \cdot 10^{36}$ |
| | Geminga | $2 \cdot 10^{34}$ | $3 \cdot 10^{34}$ |
| | 1055 | $1 \cdot 10^{34}$ | $3 \cdot 10^{34}$ |

Table 1: Spin-down power ($I\Omega\dot{\Omega}$) and approximate luminosity of γ-ray pulsars (Thompson *et al.* 1994). PSR 1509 has not been detected much above several MeV. PSR 0540 in the LMC so far has been observed only at optical and X-ray energies. The assumed Geminga distance is 500 pc (Halpern and Ruderman 1993; Helfand 1993).

B sources" may also be γ-ray Pulsars. In several cases, and plausibly in all, the accelerators which power this radiation seem to be far from the neutron star surface (in the outer-magnetosphere) e.g., the very large ratio of γ-ray accelerator power to total spin-down power (unless there is very narrow beaming (Dermer and Sturner 1994) in PSR 1055 (and probably in Geminga) cannot be sustained if the accelerator magnetic field exceeds about $10^9$ G; similarly it is difficult to find an origin for the Crab pulsar's powerful optical radiation other than ynchrotron emission $e^-$ / $e^+$ in the relatively weak field ($B < 10^8$ G) of the Crab pulsar's outer-magnetosphere.

The pulsars of Table 1 fall into two groups. The pulsars of group A all have strong non-thermal X-ray emission and very much larger spin-down power. A model which was developed to describe the 1 – $10^9$ eV Crab pulsar emissions (Cheng, Ho and Ruderman 1986a,b) also seems able to accommodate the other Group A spectra and pulse geometries (Chiang and Romani 1992). In this kind of outer-magnetosphere accelerator model, $e^-$ / $e^+$ passing in opposite directions through the accelerator lose almost all of their energy to curvature radiation with $E_\gamma \sim$ several GeV. However almost all of these γ -rays are converted to $e^\pm$ pairs in the intense local X-ray flux (synchrotron radiation by the pairs created in this way just outside of the accelerator). The observed emission is the synchrotron and inverse Compton radiation from these same $e^\pm$ pairs. In such models, the observed $L_\gamma$ power (mainly inverse Compton) is reduced relative to $L_x$ (synchrotron emission with $E_x \lesssim 1$ MeV) as the accelerator magnetic field is increased (Cheng and Ruderman 1994). PSR 1509 is the most strongly magnetized radiopulsar known. The Crab pulsar and PSR 0540 have strong outer-magnetosphere fields because their outer-magnetospheres are closer to the star. In the group A γ-ray pulsars the very energetic primary curvature γ-rays from the accelerator itself are absorbed and unobserved.

The group B pulsars of Table 1 have more distant outer-magnetospheres than those of group A pulsars (except, in some cases, for PSR 1509). Because of the consequently very much weaker fields magnetic fields around group B outer-magnetosphere accelerators, their secondary $e^{\pm}$ pairs do not give enough local synchrotron X-ray emission to sustain an outer-magnetosphere accelerator which works in this Crab-like mode. An alternative long ago proposed for Vela-like magnetospheres (Cheng, Ho and Ruderman 1986b) has difficulties in describing Vela's spectral break at γ-ray energies near or above 10 MeV, may predict too much $10^{12}$ eV γ-ray flux (Nel et *al* 1993), and seems to give too much optical-UV radiation from Geminga (Usov 1994). An outer-magnetosphere accelerator model for group B γ-ray pulsars, outlined below, which crucially utilizes the observed surface thermal X-ray emission from the group B pulsars, seems much more promising.

## 2. Soft Thermal X-rays and Group B. γ-ray Pulsars

Despite a variation in spin-down power by more than a factor of $10^2$, the group B pulsars are roughly similar in $10^2$ MeV – several GeV γ-ray spectra and power. It has been proposed that they all have essentially the same accelerators, (i.e., very similar potential drops, current flows and distances from their neutron stars) but differ among themselves mainly in their magnetic dipole inclination angles (Ruderman *et al.* 1993). They are also similar to the total soft thermal X-ray emission shown in Table 2, which includes, for comparison, two pulsars *not* observed as γ-ray pulsars. The soft thermal X-rays of Table 2, presumably from the heated neutron star surface, should also illuminate and pass through an outer-magnetosphere accelerator. Although they are not abundant and energetic enough to absorb many of the accelerator produced curvature γ-rays, they can materialize enough of the highest energy γ-rays to supply the new $e^{\pm}$ pairs needed to self-sustain the accelerator current. The group B γ-ray pulsars' primary curvature γ-ray emission should be directly observable, unlike that from the group A pulsar outer-magnetosphere accelerators. Therefore, the non-thermal part of the emission from the group B γ-ray pulsars should consist of (a) directly observable curvature γ-rays from $e^- / e^+$ inside of outer-magnetosphere accelerators ($E_\gamma \sim 10^2$ MeV – 10 GeV); (b) inverse Compton scattering by the same $e^- / e^+$ of radio-photons from any of the low frequency canonical radioemission which passes through the accelerator ($E_\gamma \lesssim 10^2$ MeV). Preliminary work on such a model (Cheng and Ruderman 1994) supports optimism for matching observed spectra. Independently, there are provocative questions about the origin of the soft quasi-thermal X-rays upon which the model depends.

## 3. Thermal X-rays and $e^{\pm}$ Annihilation from γ-ray Pulsars

Because the effective emission areas for group B γ-ray pulsars' soft X-ray emissions (Table 2) are near the stars' total surface areas rather than those of their stellar polar caps, it may indeed be the case that these emissions are just those from normal stellar cooling (Ögelman and Finley 1993; Ögelman, Finley and Zimmermann 1993). Moreover, the observed thermal $L_x$ are suggestively close to that expected from an outer-magnetosphere accelerator heating its parent neutron star (Helfand 1993) and, at least for Geminga, 10% of the flux is otherwise too hot. The extreme relativistic $e^-$ (or $e^+$) from the starward end of the accelerator will flow down onto

| | Pulsar | log Age (yrs) | $L_x$ (erg $s^{-1}$) | $T(K)$ |
|---|---|---|---|---|
| B | PSR 1706 | 4.2 | $8 \cdot 10^{32}$ | |
| | Vela | 4.1 | $4 \cdot 10^{32}$ | $1 \cdot 10^6$ |
| | Geminga | 5.5 | $3 \cdot 10^{32}$ | $5 \cdot 10^5(90\%); 3 \cdot 10^6(10\%)$ |
| | PSR 1055 | 5.7 | $3 \cdot 10^{32}$ | $7 \cdot 10^5$ |
| | PSR 1929 | 6.5 | $\sim 7 \cdot 10^{29}$ | |
| | PSR 0950 | 7.2 | $\sim 7 \cdot 10^{29}$ | |

Table 2: Very soft (thermal) emission from group B pulsars (Halpern and Ruderman 1993; Halpern and Holt 1992; Ögelman and Finley 1993; Ögelman, Finley and Zimmermann 1993) and two radiopulsars which have not been detected in γ-rays (Helfand 1993). As in Table 1 the Geminga distance is taken as 500 pc (Halpern and Ruderman 1993; Helfand 1993). The distance to PSR 1055 is uncertain and may be up to twice that used here.

the star's polar caps. On the way they will synchrotron radiate away any kinetic energy perpendicular to $\boldsymbol{B}$. The particle flow through Geminga's or PSR 1055's outer-magnetosphere accelerators must be near the maximum possible open field line flow to give such a high $L_\gamma / I\Omega\dot{\Omega}$(minus losses to synchrotron radiation after leaving the accelerator)Then the power brought down to Geminga's stellar surface should be $\sim 3 \cdot 10^{32}$ erg $s^{-1}$ (Halpern and Ruderman 1993). However, instead of such radiation coming back out from small hot ($6 \cdot 10^6$ **K**) polar caps, most of this power seems to come from a large fraction of the surface area of the B group pulsars. One possible cause of this is the large density of $e^{\pm}$ pairs near these neutron stars. Their effectiveness in reflecting KeV X-rays from a hot polar cap is enormously increased wherever their cyclotron resonance frequency in the circumstellar magnetic field matches the X-ray frequency. The scattering cross section

$$\sigma = \sigma_T(\hat{e} \cdot \hat{\boldsymbol{B}})^2 + \frac{2\pi^2 e^2}{mc} \mid \hat{e} \times \hat{\boldsymbol{B}} \mid^2 \delta(\omega_B - \omega),$$

where $\sigma_T$ is the Thomson cross section, $\omega_B$ the resonance frequency, $\hat{e}$ the X-ray polarization and $\hat{\boldsymbol{B}}$ the magnetic field direction. An $e^{\pm}$ density exceeding $10^{13}$ $cm^{-3}$ at $r \sim 3R$ would make an optically thick cyclotron-resonant backscattering layer there. Local pair densities greatly in excess of this seem plausible from the conversion of some of the Geminga-family inward directed curvature γ–rays from particles within the outer-magnetosphere accelerator and, especially, from its starward directed extreme relativistic particle flow. Gamma-rays which pass near these stars will make pairs which backscatter most hot polar cap X-rays to the stellar surface where they will be reradiated, but at lower energies and from larger areas. For the Crab pulsar a strong, narrow, gravitationally red-shifted $e^{\pm}$ annihilation line should be marginally observable (Massaro *et al.* 1991).

## 4. Comments

An outer-magnetosphere accelerator seems a plausible ultimate power source for a γ-ray pulsar's main emission and, perhaps, also its soft X-rays. Both are needed for the accelerator current to be self-sustained. Such bootstrapped accelerators would grow in size (i.e., in the fraction of the open **B**-field lines which they subtend) until they are self-sustained, but no larger since more $e^{\pm}$ pair production within the accelerator would begin to quench the needed $\boldsymbol{E} \cdot \hat{\boldsymbol{B}}$ there. These accelerators might indeed be expected to be rather similar among γ-ray pulsars, as is observed for group B and implied for group A. But what happens when even spanning all available open field lines is insufficient to give accelerated $e^{-}$ / $e^{+}$ enough energy for curvature radiation γ–rays to reach the needed multi-GeV? Equivalently, what happens when pulsar spin-down power ( $-I\Omega\dot{\Omega}$)drops below the $L_\gamma$ of Table 1? Does the pulsar turn off as a strong γ-ray source or does it manage to continue with an $L_\gamma \sim -I\Omega\dot{\Omega}$? At present the answer is unclear.

Most of the difficulty in constructing a quantitative model for outer magnetosphere accelerators arises from the lack of a reliable description of just how the corotating magnetosphere with mainly dipolar **B**, almost certainly an adequate model for the relevant part of the magnetosphere which begins many radii from the neutron star, changes as the light cylinder is approached. Since much, and perhaps most, of an outer-magnetosphere accelerator probably lies in this region, this lack is crucial. For example, the accelerator magnetic field structure is uncertain there in shape and orientation because it is so heavily loaded with relativistic plasma (e.g., the accelerated $e^{\pm}$ which it has created) whose energy density can be comparable to that of the magnetic field which would otherwise control the plasma flow. Some models assume the accelerator is still close enough to the star that **B** can be approximated as the non-retarded one of a rotating dipole (Cheng, Ho and Ruderman 1986a,b). Others assume that the accelerator is nearer the light cylinder, but that the exact retarded magnetic field in an empty magnetosphere is still an adequate approximation (Chiang and Romani 1992). Both seem capable of giving pulse shapes which resemble those observed – especially the prevalence of those consisting of a pulse and a widely separated interpulse with comparable intensity.

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