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GAMMA RAY PULSARS: MODELS AND OBSERVATIONS

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ABSTRACT

Data from the EGRET instrument on the Gamma Ray Observatory will be useful in examining predictions made by models of gamma-ray pulsars. The high-energy spectra of pulsars and the luminosities of pulsars other than the Crab and Vela can be used to study and possibly differentiate such models.

I. INTRODUCTION

The two known gamma-ray pulsars, the Crab and Vela, have been used as guides for the development of models of high-energy radiation from spinning neutron stars. Two general classes of models have been developed: those with the gamma radiation originating in the pulsar magnetosphere far from the neutron star surface (outer gap models) and those with the gamma radiation coming from above the polar cap (polar cap models). The goal of this paper is to indicate how EGRET can contribute to understanding gamma ray pulsars, and especially how it can help distinguish between models for emission.

In the outer gap model (Cheng, Ho, and Ruderman, 1986a, 1986b; Ruderman, 1990), electron acceleration in a pulsar magnetosphere takes place in a charge-depleted region well away from the neutron star surface. Model calculations show that the Crab and Vela pulsars are different from one another. For a Crab-type gap, the primary photons are produced by curvature radiation of the electrons. The primary photons annihilate with X-rays to produce secondary electrons. These secondary electrons produce X-rays by synchrotron radiation and also inverse Compton scatter these X-rays up to gamma ray energies. The radiation in the EGRET energy range will originate from inverse Compton scattering.

The Vela pulsar for the outer gap model is different in that the primary photons are inverse Compton scattered infrared photons with much higher energy than those of the Crab. These photons also produce electron secondaries, and the gamma rays which are seen are synchrotron radiation from the secondary electrons.

In a polar cap model (e.g. Daugherty and Harding, 1982),the particle acceleration takes place just above the polar cap of the neutron star. Here the magnetic field is much stronger than in the outer gap. The accelerated particles form a cascade. Electrons produce curvature radiation photons, which annihilate. The secondary electrons produce photons by both curvature and synchrotron radiation. These photons may also annihilate, until the cascade reaches the point where the photons (gamma rays) can escape. The Crab and Vela in this model are similar.

With a reasonable choice of assumptions, either of these models can reproduce the observations of the Crab and Vela. They are fundamentally different models, however. The polar cap model sees gamma ray emission as a general property of young radio pulsars, with the Crab and Vela working by similar mechanisms (Harding, 1981). The outer gap model, on the other hand, not only views the Crab and Vela as different from each other, but suggests that gamma-ray emission is limited to a subset of all pulsars, and that gamma-ray pulsars do not evolve into older radio pulsars (Ruderman and Cheng, 1988).

II. ENERGY SPECTRA OF GAMMA RAY PULSARS

One characteristic of EGRET compared to previous high energy gamma-ray telescopes like SAS-2 and COS-B is its broader energy range (about 20 MeV to 30,000 MeV) and better energy resolution (Hughes, et al., 1986). Features not seen previously in the Crab and Vela energy spectra might be visible to EGRET.

For the outer gap model, the feature in the gamma-ray range is a break in the spectrum above a few GeV. In the case of Vela, this results from the maximum energy that the secondary electrons can have in the outer gap (10^{13} eV), assuming that the synchrotron radiation occurs in a field of about 5000 gauss (Cheng, Ho, and Ruderman, 1986b). The Crab spectrum in the outer gap model shows a similar fall-off in the few GeV range, in this case resulting from the combination of the upper limit on the secondary electron energies and the energies of the X-rays which are being inverse Compton scattered to the gamma-ray range (Ho, 1989).

The polar cap model also shows a fall-off in the few GeV range for both the Crab and Vela pulsars (Harding, 1981, Daugherty and Harding, 1982). This turnover in the cascade model results from two factors: 1. the curvature radiation gamma-ray spectrum has a maximum for a given set of conditions; and 2. the higher energy gamma rays are more likely to convert to pairs in the magnetic field, because they can convert farther out where the field is lower. Both these effects serve to suppress the high energy gamma rays.

These two models predict such similar high-energy spectral shapes that EGRET cannot expect to distinguish them. Nevertheless, EGRET can address the question of whether there is such a turnover in the spectrum. Figure 1 shows the COS-B data for the Crab spectrum (Lichti, et al., 1980), along with a model calculation (Harding, 1981) and a power law fit to the COS-B data. Although the final analysis of the EGRET response above a few GeV is not complete, the estimated sensitivity (Hughes, et al., 1980; Thompson, 1986) can be used to calculated the relative response to the different spectra. For a two week exposure, a continuing power law spectrum would yield about 30 photons above 5 GeV detected by EGRET. Under similar conditions, a spectrum with a break near 2 GeV would produce fewer than 10 photons above 5 GeV. Although the numbers are small, the difference is significant, because at these energies the angular resolution of EGRET allows the source to be separated clearly from any galactic or extragalactic diffuse gamma radiation. A similar change of spectral shape would be even more significant for Vela, because it is a factor of 3 more intense than the Crab. If the spectrum extends in a near power law beyond 10 GeV, however, a higher energy cutoff would probably not be visible to EGRET.

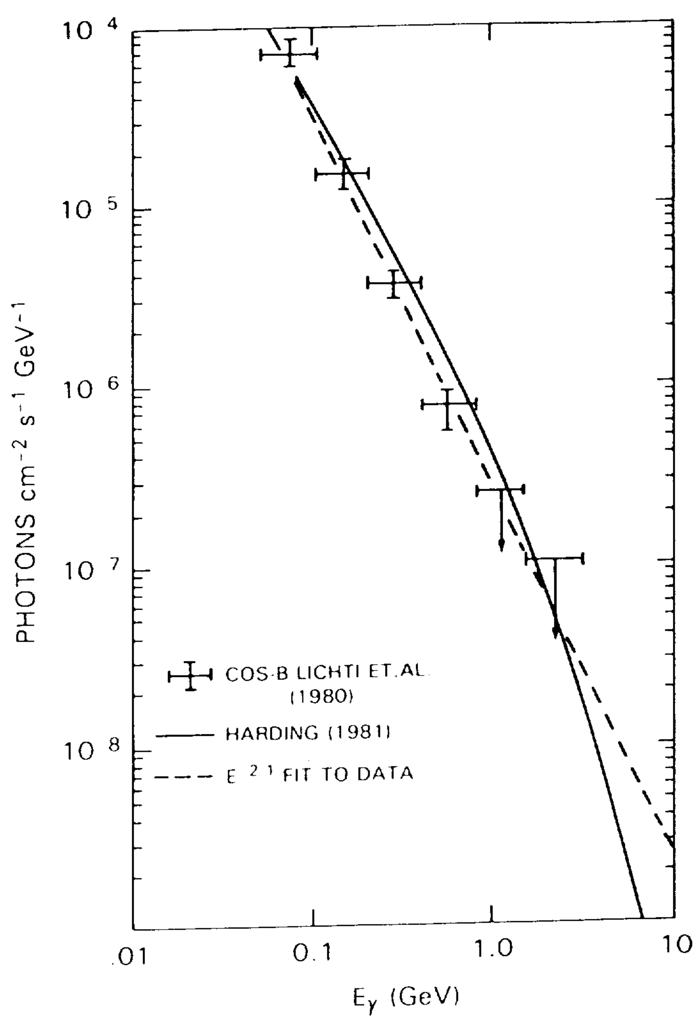

Figure 1 -- High-energy spectrum of the Crab pulsar. Data points from COS-B: Lichti, et al. (1980). Solid curve: model of Harding (1981). Dashed curve: $E^{-2.1}$ fit to data.

III. MODEL PREDICTIONS FOR OTHER PULSARS

Another approach to distinguishing models is to look at the model predictions for other pulsars. It is, of course, possible that the Crab and Vela are so different from other pulsars that they are the only gamma-ray pulsars, but there are enough other candidates around that that seems unlikely. Ruderman and Cheng (1988) suggested, for example, that some of the other COS-B sources might be undiscovered pulsars. The concept used in the present work is to start from the radio pulsar direction, looking for characteristics which might indicate gamma ray emission from some sources which are already known to be pulsars.

The solid line in Figure 2 (based on the work of Ruderman and Cheng 1988) shows the estimated gamma ray luminosity for short-period pulsars with characteristics like those of the Crab and Vela. This figure has been normalized to the Crab and Vela observations, assuming radiation into approximately one steradian. Pulsars with periods shorter than about 50 msec are Crab-like, while those with longer periods are similar to Vela. In the outer gap model, the luminosity function cuts off at about 125 msec for Vela-like pulsars. This occurs when the outer gap essentially fills the magnetosphere and is quenched. Pulsars with longer periods are expected to have no gamma-ray emission.

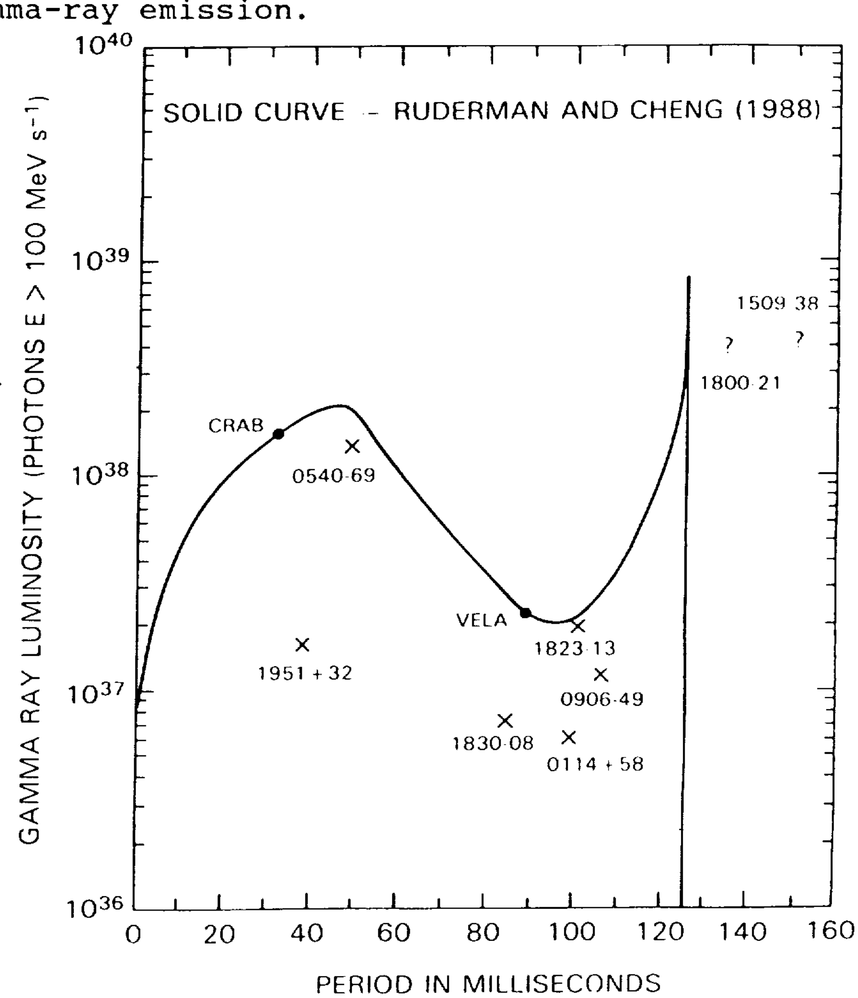

Fig. 2 Gamma-ray pulsar luminosities in the outer gap model. Solid line: calculation of Ruderman and Cheng (1988) Data points: present calculation. The ? for 1800-21 and 1509-38 indicate the large uncertainty.

Following Cheng, Ho, and Ruderman (1986b), the luminosity for other pulsars should be proportional, at least in first approximation, to B/P^2 , where P is the pulsar period and B is the calculated magnetic field at the surface. This comes from the fact that the potential drop in the outer gap and the particle flow are both proportional to this quantity. For pulsars with a given period, this implies that the luminosity should be proportional to the surface magnetic field, calculated from the standard formula

$$B = (10^{30} \; I \; P \; \dot{P} \; / \; a^6)^{1/2} \text{ gauss} \qquad (1)$$

where P is the pulsar period, $\dot{P}$ the period derivative, and a the pulsar radius, generally assumed to be $1 * 10^6$ cm. Parameters for the other pulsars shown on this figure are drawn from a recent update (Taylor, 1988) of the Manchester and Taylor (1981) compilation.

Two pulsars in this figure are shown with periods just beyond the 125 msec cutoff. These are pulsars with calculated fields greater than those of the Crab and Vela. Such pulsars should be able to sustain an outer gap out to longer periods, and should fall somewhere on the rising part of the curve. Clearly, estimates for these two pulsars are very uncertain, but they are potentially luminous gamma-ray pulsars.

The polar cap model is in some sense easier, because it is based on the idea that pulsars follow a common evolutionary path. This means that the Crab and Vela parameters can be used to extrapolate to other pulsars in the context of the model. Harding's (1981) fit to the observations gave

$$L\ (>100) = 1.2 * 10^{35}\ B12^{0.95}\ P^{-1.7} \text{ photons s}^{-1}. \qquad (2)$$

where B12 is the pulsar field in units of 10^{12} gauss. This fit is also based on an assumption of radiation into about one steradian.

In the polar cap model, there is no explicit mechanism which limits the gamma-ray emission (as the quenching of the outer gap does), but the ultimate limiting factor is still the same: the power source for the pulsar is its rotational energy loss, and no process can expect to extract all that energy in the form of gamma rays. In applying this formula, it is important to look at what fraction of the total energy loss it represents, and realize that too large a fraction is not physically meaningful.

Table 1 shows the results of both model calculations for some of the most interesting pulsars, including the Crab and Vela for reference. Luminosities have been converted to flux values, using the estimated pulsar distances and the same 1 steradian emission solid angle assumed in the model calculations.

Table 1
PULSAR PARAMETERS

NAME	P(s)	P($*10^{-15}$ s/s)	d(kpc)	B(gauss)	F(>100) ph s^{-1} cm^{-2} Polar cap	Outer gap
0531+21 (Crab)	.033	422.4	2	$3.7*10^{12}$	$3.*10^{-6}$	$3.*10^{-6}$
0833-45 (Vela)	.089	124.7	.5	$3.3*10^{12}$	$1.0*10^{-5}$	$1.0*10^{-5}$
0114+58	.101	5.8	1.5	$7.8*10^{11}$	$2.1*10^{-7}$	$4.0*10^{-7}$
0540-69.3	.050	509.2	55	$5.0*10^{12}$	$3.0*10^{-9}$	$4.0*10^{-9}$
0906-49	.107	13.9	3.2	$1.2*10^{12}$	$6.6*10^{-8}$	$1.8*10^{-7}$
1823-13	.101	76.0	5.5	$2.8*10^{12}$	$5.4*10^{-8}$	$1.1*10^{-7}$
1830-08	.085	9.0	8.5	$8.9*10^{11}$	$1.0*10^{-8}$	$1.4*10^{-8}$
1951+32	.039	5.9	2.5	$4.8*10^{11}$	$2.5*10^{-7}$	$4.2*10^{-7}$
1509-58	.150	1520.0	6.7	$1.5*10^{13}$	$9.3*10^{-8}$	$9.3*10^{-7}$?
1800-21	.134	125.0	5.2	$4.1*10^{12}$	$5.4*10^{-8}$	$1.5*10^{-6}$?
0355+54	.156	4.4	1.6	$8.4*10^{11}$	$9.6*10^{-8}$	----
0740-28	.167	16.8	1.5	$1.7*10^{12}$	$1.9*10^{-7}$	----
1055-52	.197	5.8	0.9	$1.1*10^{12}$	$2.5*10^{-7}$	----

The pulsars in addition to the Crab and Vela fall into three groups:

The first six are ones for which both models predict gamma-ray emission at about the same level, within a factor of three. These are the ones most like the Crab and Vela and should tell if the Crab and Vela are really different from other radio pulsars in some feature relevant to gamma-ray emission.

The second two are those near the limit of the outer gap model. If this model is correct, then they may be on the upward part of the curve and be strong sources, or they may be over the edge and non-sources. The question marks indicate the high degree of uncertainty in these estimates.

The third group contains pulsars with periods and fields which should not be able to sustain an outer gap, but which might be gamma ray sources in the polar cap model. This group in particular could be much larger if equation (2) extrapolates to pulsars with longer periods. The pulsars shown are some which are relatively fast (periods shorter than 200 msec), relatively nearby (distances less than 2 kiloparsecs), and energetically reasonable (less than 10% of their rotational energy loss appears in the form of gamma rays).

IV. OBSERVATIONAL CONSIDERATIONS

The next question is: Which of these might EGRET see? Based on simple counting statistics, the estimated EGRET sensitivity, and the known diffuse galactic and extragalactic radiation, here are some guidelines:

1. EGRET should be able to see any pulsar with a flux above 100 MeV of a few $* 10^{-7}$ photons cm^{-2} s^{-1} in a single good two week exposure. This is an intensity about 0.1 of the Crab pulsar. Figure 3 is a simulation of a phase plot of a pulsar with this flux (and a Crab-like double peak structure) seen in the galactic center region.

2. In a two week exposure, EGRET will have trouble detecting pulsars at the $1 * 10^{-7}$ photons cm^{-2} s^{-1} level in the galactic center region, due to the high intensity galactic radiation, but should be able to see pulsars with this intensity in regions away from the center. Away from the high intensity portion of the galactic ridge, the galactic radiation is a factor of five or more less intense.

3. Even under the best of circumstances, EGRET will be unlikely to detect pulsars with a flux less than 10^{-8} photons cm^{-2} s^{-1}.

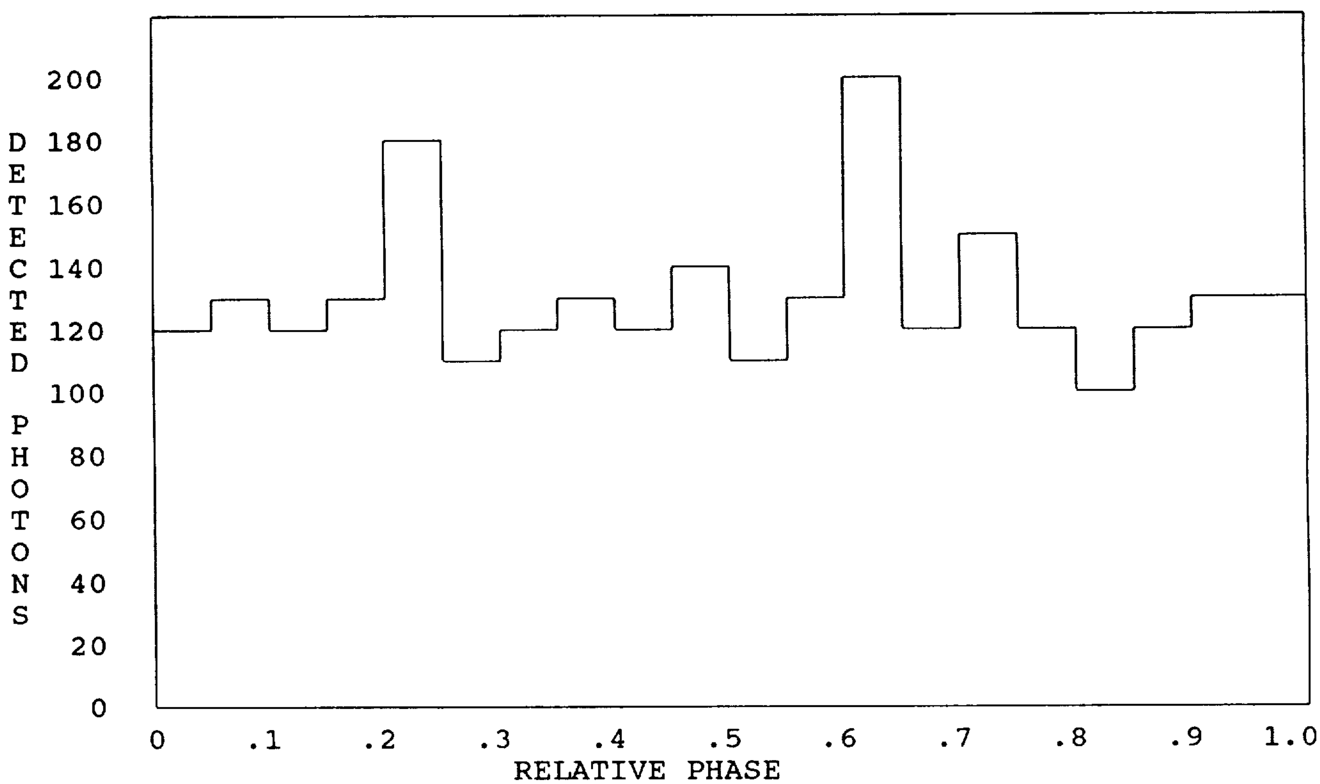

Figure 3 - Simulated phase plot of a pulsar with 0.1 the Crab flux and a double-peak emission, in the high-intensity region near the galactic center. Two week exposure with EGRET, with the pulsar on-axis.

From these guidelines and Table 1, it is clear that these model predictions span this range -- pulsars 0114+58 and 1951+32 should be detectable if either model is a good description of the gamma-ray emission process; 0540-69 (which is in the Large Magellanic Cloud) and 1830-08 are not likely candidates due primarily to their distance; and all the rest are in between. If the outer gap model is an accurate representation of the gamma-ray emission process, then pulsars 0906-49, 1509-38, and 1800-21 could all be detectable. In light of the large uncertainty at the limit of the outer gap model, however, the best discriminator between the models will probably be the longer period pulsars 0355+54, 0740-28, and 1055-52. Detection of any of these (which should not be able to support an outer gap) would suggest particle acceleration and gamma-ray production in some other region of the magnetosphere, such as the polar cap model predicts.

In summary, EGRET should be able to contribute to an improved understanding of gamma ray pulsars. It should be able to look for the predicted turnover in the high energy spectrum of the more intense pulsars. More significant is the prospect of being able to detect additional pulsars which may distinguish models of gamma ray emission.

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DISCUSSION

Alice Harding:

The polar cap model predicts a sharp cutoff in the gamma-ray spectrum above a few GeV, which is due to pair production in the strong magnetic field. Thus, the break in the spectrum would have a different shape from that predicted by the outer gap model.

R.J. Slobodrian:

I am glad that ions have been mentioned. A recent review article on double layers has suggested that they are relevant as astrophysical accelerators to 10^{14} - 10^{15} eV -- for example, in pulsars (young), where both ions and electrons are available. I would like to know the opinion of experts on the, possible relevance of such double layers in young pulsars (only thus far proven gamma-ray emitters).

Mal Ruderman:

Wherever the magnetic field is very strong, e.g. near the surface of a magnetized neutron star, there is copious pair production if the potential drop (along B) exceeds 10^{12} volts. This would be expected to keep such accelerator potentials there well below the 10^{14} - 10^{15} volt range. Far away, e.g. in the outer magnetosphere, an accelerator "gap" is a kind of double layer in this range.

Chip Meegan:

In the gap model, what distinguishes the gamma ray pulsars, which turn off, from pulsars that evolve into longer-period radio pulsars?

Mal Ruderman:

A growing charge depletion region in the outer magnetosphere may be limited by $e^{\pm}$ production there as proposed for the Crab and Vela pulsars, but also by transport into that region of $e^{\pm}$ made elsewhere. These may be separated far from the star by electric fields much weaker than those needed to make them in the outer magnetosphere. It is very much easier to make pairs in the very large B above a part of the polarcap than in an accelerator near the light cylinder. Possible transport of such pairs to where they are needed in the outer magnetosphere depends upon the magnetic field structure around the neutron star; it would not generally occur for a pure dipole but may for somewhat more complicated fields. Another possibility is a switching to real pair production from quasi-pair production from ion stripping above the polarcap as a neutron star cools with age.