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GAMMA-RAY OBSERVATIONS OF PULSARS

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ABSTRACT

We report on *Compton Gamma Ray Observatory* observations of six detected pulsars: the Crab, Vela, Geminga, PSR B1509−58, PSR B1706−44, and PSR B1055−52. We combine these data with radio data and X-ray data to provide an overview of what is known about gamma-ray pulsars. We discuss light curves, spectra, and radio/gamma-ray phase offsets, and present several *tentative* patterns in the data. These include constant phase with γ-ray energy; a correlation between gamma-ray and X-ray luminosity; an anticorrelation between the gamma-ray luminosity and the efficiency in converting rotational energy loss into gamma-ray flux; and a correlation between the pulsar period and radio/gamma-ray phase offset. We also suggest that the emission models that have been proposed to date cannot explain the similarities of the average gamma-ray light curves observed over a wide range of energies. Further, unless a narrow beam is assumed, pulsars such as PSR B1055−52 and Geminga appear to be radiating a significant fraction of their rotational energy loss in the form of gamma rays.

Subject headings: gamma rays: observations — pulsars: general — radio continuum: stars — X-rays: stars

1. INTRODUCTION

Pulsars are believed to be highly magnetized, rotating neutron stars, and, although they were discovered over 25 years ago, it is still not clear how pulsars shine or why some pulsars are bright gamma-ray sources and others are not (for recent reviews on pulsars see Lyne & Graham-Smith 1990; Taylor & Stinebring 1986). This paper reviews the recent results from the instruments on-board the *Compton Gamma-Ray Observatory* (*CGRO*). It also describes how multiwavelength studies can be used to uncover potentially exciting correlations which, if confirmed, should bring us a step closer to understanding the geometry of the pulsar beams and the underlying physics responsible for the gamma-ray emission. Nearly all of the data we present are from published work or work in preparation by the various *CGRO* instrument teams. For details of the observations and analysis the reader is referred to these works, which we will explicitly reference.

2. GAMMA-RAY AND RADIO EMISSION PROFILES

There have now been six reported detections of pulsars by *CGRO:* the Crab pulsar (Nolan et al. 1993; Wilson et al. 1993; Ulmer et al. 1993a, b), the Vela pulsar (Strickman et al. 1993; Kanbach et al. 1993), Geminga (Mattox et al. 1992; Bertsch et al. 1992), PSR B1706−44 (Thompson et al. 1992), PSR B1509−58 (Wilson et al. 1993; Ulmer et al. 1993c), and PSR B1055−52 (Fierro et al. 1993). As can be seen in Figure 1, these gamma-ray light curves can be divided into two categories: "double-peaked" and "single-peaked." This holds for the radio light curves as well; however, the double-peaked gamma-ray sources are not necessarily double-peaked in the radio, and vice versa.

The variety of gamma-ray and radio pulse profiles seen in Figure 1 is intriguing, but it is beyond the scope of this work to try to explain. We therefore only provide the following comments related to Figure 1. Although it is tempting to assume that the lack of radio pulses from Geminga is due to the view angle, the variety of radio and gamma-ray shapes makes this seem doubtful. Rather, it seems more likely that the radio emission from Geminga is simply not produced (see, for example, Ruderman et al. 1993; Halpern & Ruderman 1993).

3. GEOMETRICAL CONSIDERATIONS AND THE CRAB PULSAR

In Figure 2 we show a compendium of the Crab pulsar light curves from the *CGRO* instruments. Although the relative amplitudes of the radio pulses change with energy, the overall phase does not change within the accuracy of the phase determination (1 ms $\lesssim 1/33$ of a cycle). Further, as shown in Figure 3, the normalized pulse shapes are remarkably similar over the energy range 100 keV–100 MeV.

If relativistic beaming were involved in the gamma-ray production, we would expect the beamwidth to be proportional to γ, where γ is the usual relativistic $[1 - (v/c)^2]^{-1/2}$. Or, for gamma rays of different energies, the beaming directions might differ if the radiation were produced by electrons of the same energy but in different parts of the neutron star's magnetic field, or at different pitch angles relative to the magnetic field. In any case, the pulses seen at different energies should not be so similar. Since the pulses at widely different energies are apparently in phase and have nearly the same width, some other process besides relativistic beaming in a magnetic field must be at work. None of the current models (see, for example, Arons 1984; Davila, Wright, & Benford 1980; Daugherty & Harding 1982; Cheng, Ho, & Ruderman 1986a, b and references therein) provide a good explanation for the similarities in the pulse profiles shown in Figure 3.

A potentially controversial point that has been directly related to geometrical considerations is the suggestion that perhaps the Crab pulsar is freely precessing with an $\sim$13.5 yr period. This concept was first presented by Kanbach (1990) and, with the addition of EGRET data, was later published by Nolan et al. (1993). The supposition is that the ratio of the intensities of the second peak (P2) to the first peak (P1) varies

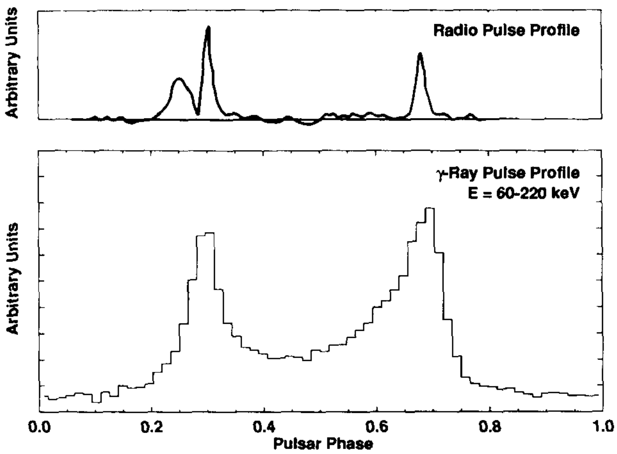

FIG. 1*a*

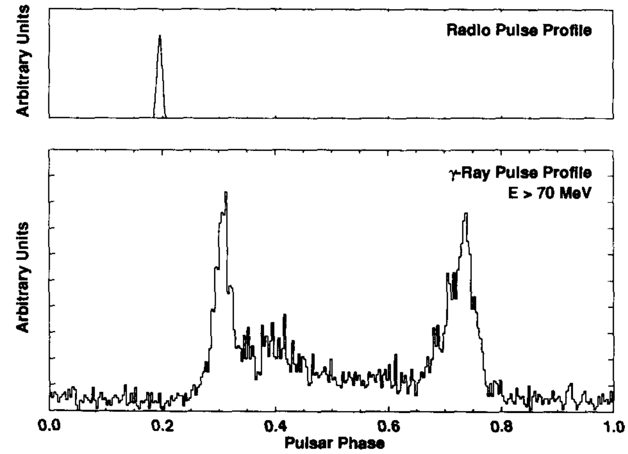

FIG. 1*b*

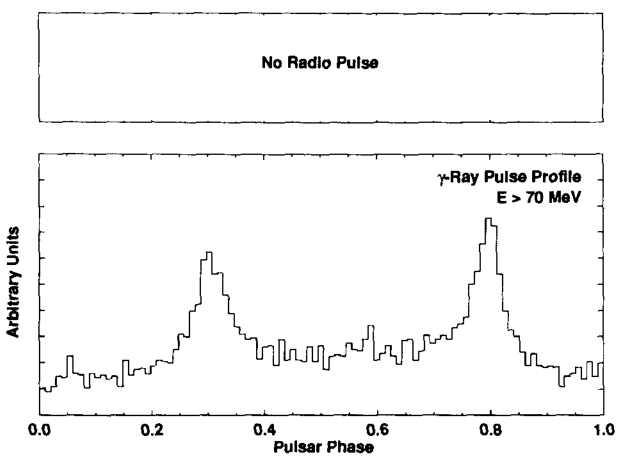

FIG. 1*c*

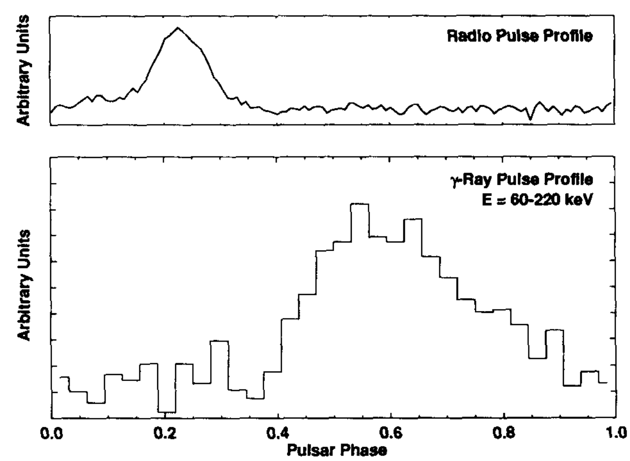

FIG. 1*d*

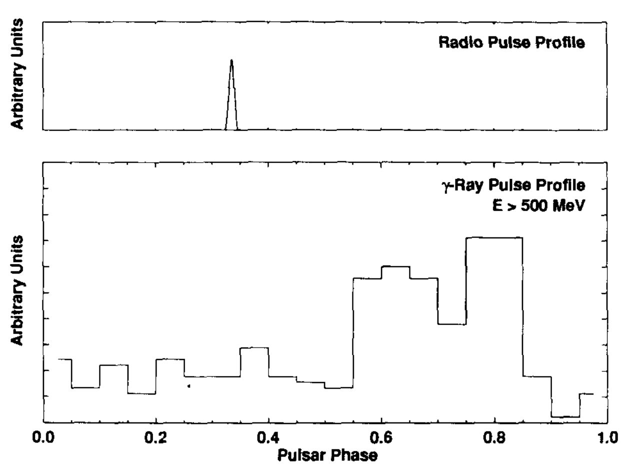

FIG. 1*e*

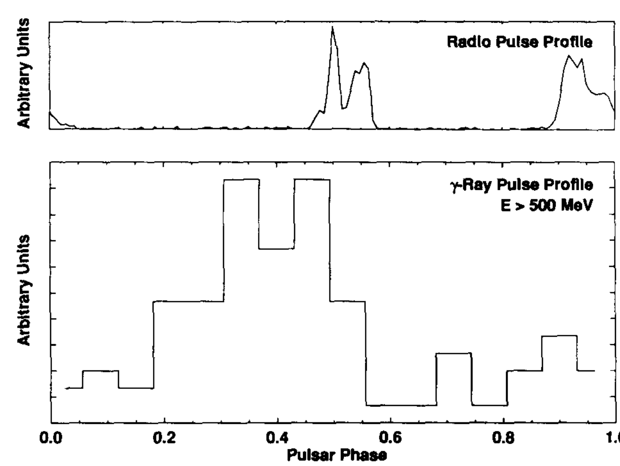

FIG. 1*f*

FIG. 1.—Average gamma-ray and radio light curves shown with their relative phases. (*a*) Crab pulsar; (*b*) Vela pulsar; (*c*) Geminga; (*d*) PSR B1509−58, (*e*) PSR B1706−44; and (*f*) PSR B1055−52. The light curves are presented in arbitrary units. For the Crab pulsar and PSR B1509−58, the relatively high background levels of the gamma-ray data have been suppressed.

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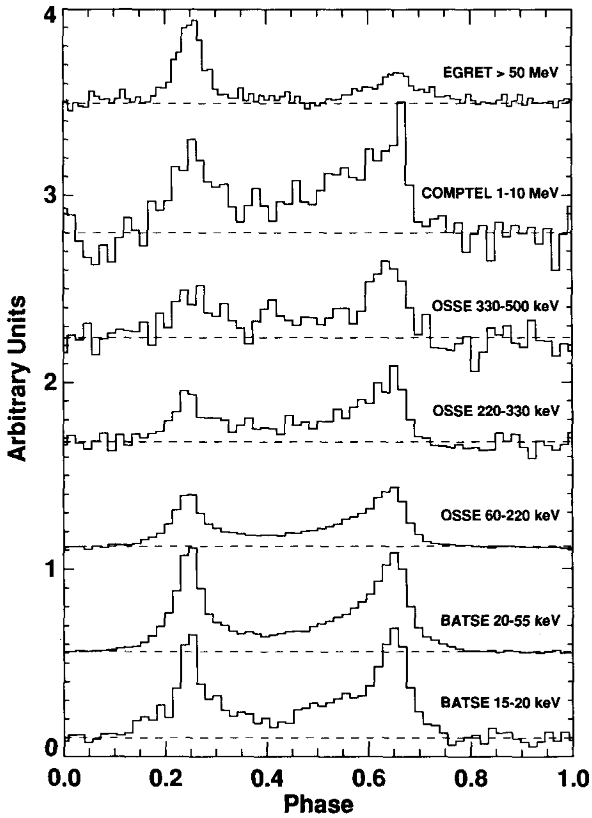

FIG. 2.—Composite of the average Crab pulsar light curves from all the *CGRO* instruments. For plotting purposes we have scaled the various light curves by arbitrary amounts and subtracted a background/constant level per phase bin value when necessary.

periodically due to the free precession of the Crab pulsar (see Fig. 4). If the effect is real and due to a change in the pointing direction of the pulsar beam relative to Earth, then the similarity in pulse shapes and phases at different energies suggests that this effect should be seen at other energies as well.

Therefore, we searched for this effect in the ~50–400 keV energy range, for which both historical as well as OSSE data exist. These data are also shown in Figure 4, where it is shown that a sine wave with the same period (13 yrs) and phase describes both the low- and the high-energy data. The effect is statistically significant: the chi-square for the fit assuming a constant is 70, while the sine wave fit to the data results in a chi-square value of 14. With only about 1 full cycle observed to date, we can only conclude that the result is provocative and that more observations will be needed over the next 5 years to demonstrate or refute the reality of the effect. In the meantime, we hope radio astronomers will analyze their archival data sets to look for a similar effect.

4. CORRELATIONS AND PATTERNS

With the six pulsars that have been detected by the *CGRO* instruments, it is possible to search for patterns and trends. Below we explore just a few of the many possibilities. Because PSR B0540−69 seems similar to PSR B1509−58 (cf. Seward & Harnden 1982; Finley et al. 1993; Seward, Harnden, & Helfand 1984) in terms of spectral shape and pulse shape, we have also included this pulsar in our sample where possible. We have estimated the gamma-ray flux (the object is yet undetected by *CGRO*) by assuming that the ratio of its X-ray to its gamma-ray flux is the same as for PSR B1509−58, but none of our discussion is critically dependent on the inclusion or exclusion of this object.

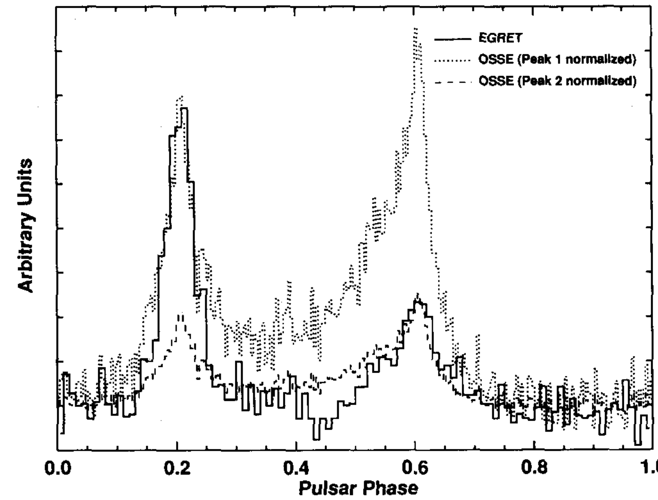

FIG. 3.—Crab pulsar average light curve from *CGRO*/EGRET and *CGRO*/OSSE. The EGRET light curve is represented by the solid histogram. The dotted histogram represents the OSSE light curve as normalized to the first EGRET peak, and the dashed histogram represents the OSSE light curve as normalized to the second EGRET peak.

4.1. *Luminosity and Efficiency*

In order to calculate the absolute luminosity of the gamma-ray sources, some assumptions about beam shape and extent

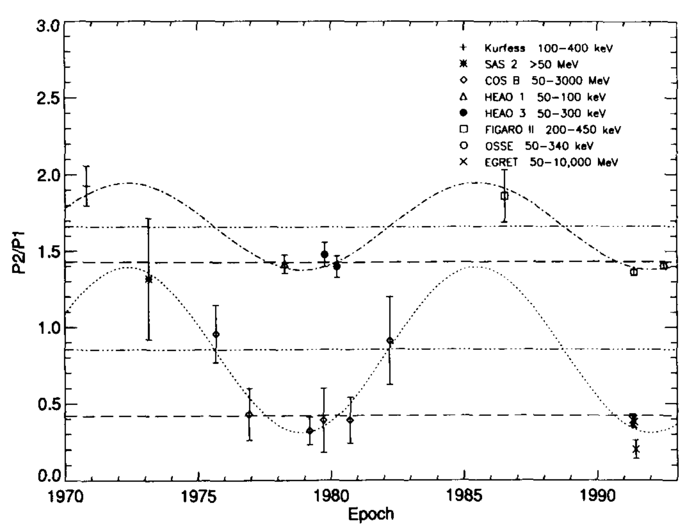

FIG. 4.—For the Crab pulsar, the ratio of the intensity of peak 2/peak 1 vs. time at two different energies. (References for the data are Kurfess 1971; Knight 1982; Mahoney, Ling, & Jacobson 1984; Agrinier et al. 1990; Thompson et al. 1977; Clear et al. 1987; and Nolan et al. 1993.) The dot-dash horizontal lines represent the average of the sine-wave fits, and the other horizontal lines are the best fits to a constant value for each energy range.

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of the gamma-ray spectrum need to be made. In our calculations of the luminosity we multiplied the phase-averaged flux by $2\pi D^2$, where D is the pulsar distance. In other words, we have assumed that the pulse shapes are all $\sim 90°$ wide fan beams, which may not be valid. The data used for Figures 5 and 6 are given in Table 1, where the energy ranges of the gamma-ray data are explicitly given.

In Figure 5 it can be seen that there is an apparent trend for less luminous pulsars to be more efficient in converting rotational energy loss to gamma rays. The apparent efficiency of several pulsars is quite high ($\gtrsim 10\%$), and the possibility that large amounts of energy are radiated away in the gamma-ray regime suggests that the simple dipole radiation model, which assumes that the rotational energy loss is dominated by magnetic dipole radiation (cf. Manchester & Taylor 1977; Pacini 1967, 1968; Ostriker & Gunn 1969), may not accurately estimate the surface magnetic field of the rotating neutron star. However, a model that does not evoke dipole radiation but does predict a similar relationship between the magnetic field strength and pulsar spin-down rate is the model of Goldreich & Julian (1969).

There is an apparent positive correlation between the gamma-ray ($\gtrsim 100$ keV) and X-ray (~ 0.2–4 keV) intrinsic luminosity, as shown in Figure 6. This result might be expected in the naive interpretation that one spectrum is just the extension of the other. However, since some of the X-ray emission is thermal (cf. Ögelman, Finley, & Zimmermann 1993; Halpern & Ruderman 1993) the correlation between the X-ray and gamma-ray emission is not so simple. (The power-law shape of the gamma-ray spectrum suggests that the gamma-ray flux is due to nonthermal radiative processes.) A possibility is that the mechanism responsible for producing the gamma rays may also be responsible for heating the neutron star surface and hence indirectly producing the X-rays. For example, particles could be accelerated both away from the surface (gamma-ray production) and toward the surface (heating/X-ray production).

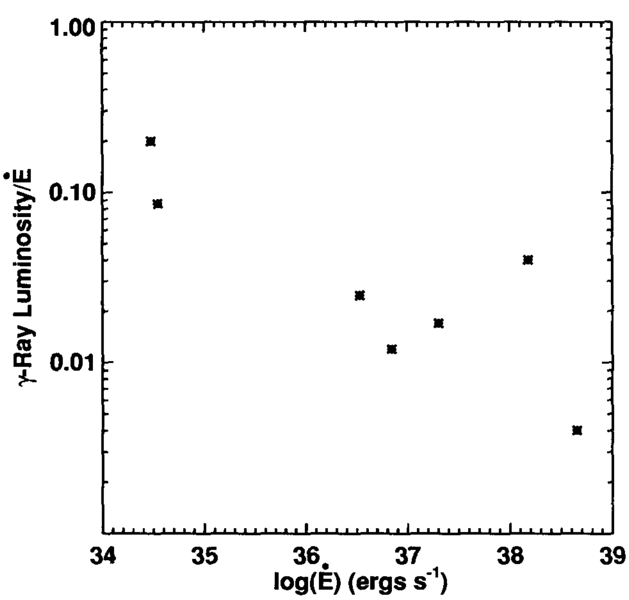


FIG. 5.—Ratio of the gamma-ray luminosity to the rotational energy loss (labeled $\dot{E}$ in the figure). The points are (*from left to right*) PSR B1055−52, Geminga, PSR B1706−44, PSR 1509−58, the Vela pulsar, PSR 0540−69, and the Crab pulsar. See Table 1 and the text.

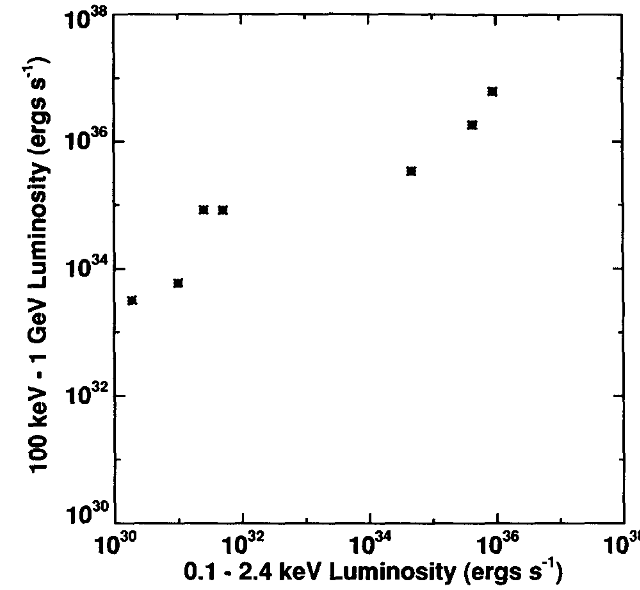


FIG. 6.—X-ray luminosity vs. gamma-ray luminosity. The points are (*from left to right*) PSR B1055−52, Geminga, PSR B1706−44, PSR 1509−58, the Vela pulsar, PSR 0540−69, and the Crab pulsar. See Table 1 and the text.

4.2. *Spectral Breaks*

It is beyond the scope of this work to review the spectra of all the *CGRO*-detected pulsars. Based on preliminary results, however, it seems likely that nearly all (or all) of the *CGRO*-detected pulsars to date will be found to require a break in the power-law spectrum. We demonstrate the "broken" power-law nature of these fits with the spectrum of the Crab pulsar (Ulmer et al. 1993b) as shown in Figure 7. The break energy is about 130 keV, and the photon spectral indices are about −1.8 and −2.2 below and above this energy, respectively. Clearly a single power law cannot fit these data. A future project for *CGRO* and X-ray satellites will be to determine the break energy accurately for all the *CGRO* pulsars and to search for a correlation between the break energy and other pulsar properties (e.g., age, period, etc.).

4.3. *Radio Phases and Gamma-Ray Phases*

With the collaborative efforts of the radio astronomy community, it has been possible to reference the radio and gamma-ray pulse phases. This has led to the suggestion that the longer the period, the larger the separation in phase between the gamma-ray and radio pulses (Ulmer et al. 1993c; Kawai et al. 1991). Those discussions were brief, however; here we elaborate on those discussions and provide some *speculation* about what may be an interesting effect. Pulsed emission that is apparently thermal in origin from pulsars such as Vela (Ögelman et al. 1993) shows statistically significant phase shifts relative to the nonthermal gamma-ray pulse, so that the trend of "the larger the period, the larger the phase offset" is expected to

TABLE 1

PROPERTIES OF GAMMA-RAY PULSARS

Name	F_x[a]	L_x[b]	F_γ[c]	L_γ[d]	$\dot{E}$[e]	D[f] (kpc)	References
Crab	1.9×10^{-9}	4.3×10^{35}	8×10^{-9}	1.8×10^{36}	4.5×10^{38}	2	1, 8
Vela	1.8×10^{-12}	2.5×10^{31}	6×10^{-9}	8.4×10^{34}	7×10^{36}	0.5	1, 5
PSR B1509−58	4.7×10^{-11}	4.7×10^{34}	3.4×10^{-10}	3.4×10^{35}	2×10^{37}	4.2	3
Geminga	1.5×10^{-12}	1.9×10^{30}	2.4×10^{-9}	3×10^{33}	3.5×10^{34}	0.15	2
PSR B1055−52	2.5×10^{-13}	1×10^{31}	1.4×10^{-10}	6×10^{33}	3×10^{34}	0.9	1, 4
PSR B0540−69[g]	5×10^{-12}	9×10^{35}	3×10^{-11} [g]	6×10^{36} [g]	1.5×10^{38}	55	6
PSR B1706−44	4.5×10^{-13}	5×10^{31}	6.6×10^{-10}	8.4×10^{34}	3.4×10^{36}	1.5	4

[a] X-ray flux (0.1–2.4 keV) in units of ergs cm^{-2} s^{-1}.

[b] X-ray luminosity (0.1–2.4 keV) in units of ergs s^{-1} ($2\pi \times$ distance$^2 \times$ flux).

[c] In units of ergs cm^{-2} s^{-1}; 0.1 MeV–1 GeV except for PSR B1706−44 and Geminga (1 MeV–1 GeV).

[d] In units of ergs s^{-1} $2\pi \times$ distance$^2 \times$ flux.

[e] Rotational energy loss based on ν and $\dot{\nu}$, and moment of inertia = 1×10^{45} g cm^2.

[f] Distances from ref. 1 except for PSR B1509−58 (ref. 3), Geminga (ref. 2) PSR B1706−44 (ref. 4), and PSR B0540−69 (ref. 8).

[g] The gamma-ray flux was estimated by assuming that the ratio of gamma rays to X-rays is the same as for PSR B1509−58.

References.—(1) Taylor 1989. (2) Bertsch et al. 1992; Mattox et al. 1992; Halpern & Ruderman 1993. (3) Seward & Harnden 1982; Ulmer et al. 1993c. (4) Thompson et al. 1992. (5) Ögelman et al. 1993; Strickman et al. 1993; Kanbach et al. 1993. (6) Finley et al. 1993; Seward et al. 1984. (7) Fierro et al. 1993. (8) Nolan et al. 1993; Wilson et al. 1993; Ulmer et al. 1993a, b.

apply only to nonthermal X-ray/gamma-ray emission. We first address several points that relate to determining the radio/gamma-ray phase offsets.

By convention, for double-peaked radio or gamma-ray pulses the order of the peaks has been chosen so that the phase difference is less than 0.5. It is not certain that this convention should be used when comparing the phase of the radio pulses to the gamma-ray pulses, i.e., there is a ±0.5 phase ambiguity in the calculation of the radio/gamma-ray phase offsets. Here we assume that the gamma-ray pulse always lags the radio in phase.

For pulsars such as the Crab and PSR B1055−52 the radio pulse shape actually has three peaks (at some frequencies), with the leading peak taking on the appellation of "precursor pulse." We chose the precursor pulse as the radio reference for

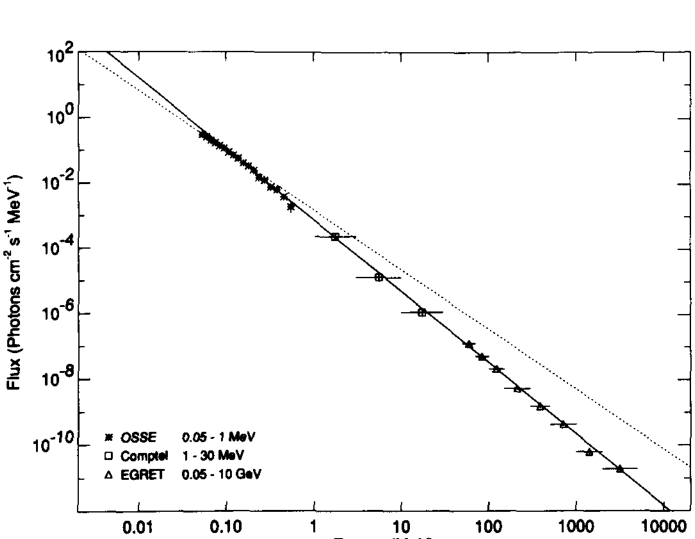
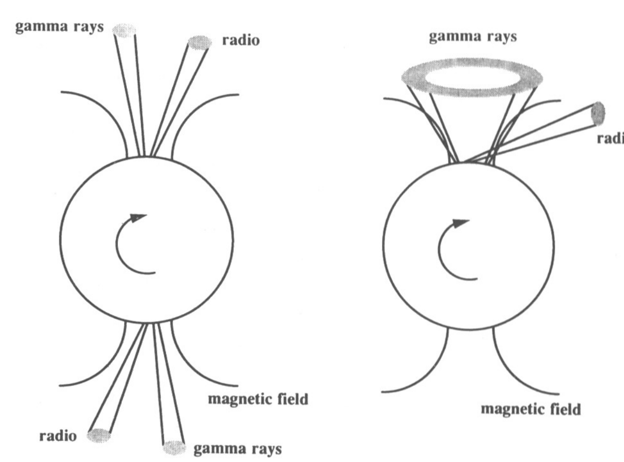


FIG. 7.—The Crab pulsar spectrum based on OSSE, COMPTEL, and EGRET data.

these to be consistent with the choice of the "first" radio pulse for all pulsars.

There is more than one beam geometry that can be used to interpret pulse profiles that we have detected. To provide a framework for our speculations, we provide two geometries. The geometry underlying these two separate models can be seen in Figures 8*a* and 8*b*. In "model 1" (Fig. 8*a*) the emission comes from both polar caps, and we would expect a phase difference of zero between the radio and gamma-ray pulses if the beams are coaligned. In this model, then, the radio/gamma-ray phase offset is taken to be the difference between the first radio peak and the first gamma-ray peak (cf. Fig. 1*a*).



Model 1 FIG. 8*a*

Model 2 FIG. 8*b*

FIG. 8.—Two geometric models for the relationship between a pulsar's γ-ray and radio emission (see text for details). (*a*) Model in which the pulsar emission emanates from both poles. (*b*) Model which the emission comes from just one pole, the gamma-ray emission having an annular beam pattern which, when viewed from Earth, appears as two separate peaks in the light curve.

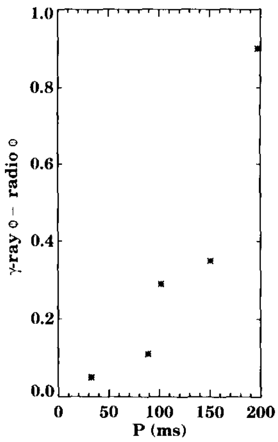


FIG. 9a

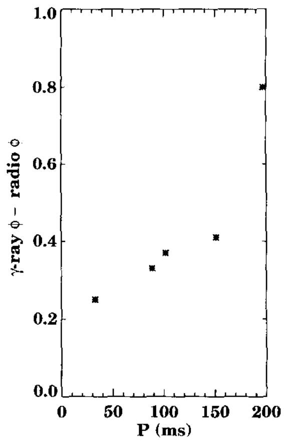


FIG. 9b

FIG. 9.—Correlation of gamma-ray/radio phase offset versus pulsar period, based upon two different methods of referencing the gamma-ray pulse to the radio pulse. (*a*) Model 1; (*b*) model 2; see text for details.

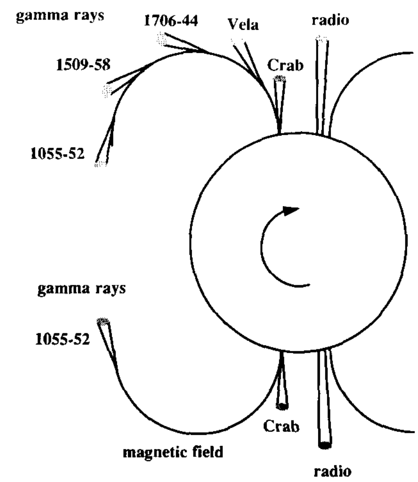


FIG. 10.—This cartoon of a pulsar is based on model 1 and assumes that the gamma-ray beam is emitted tangent to the magnetic field lines, which are depicted by the curved lines. The observer is in the plane of the figure.

In "model 2" we interpret the radio and gamma-ray beams as being "coaligned" if the radio beam emanates from the center of the annular gamma-ray beam pattern. In this model, the radio/gamma-ray phase offset is taken to be the difference between the first radio peak and the *centroid* of the gamma-ray peaks.

With the above assumptions, we have estimated the gamma-ray/radio phase offsets for both model 1 and model 2 (Fig. 9). A detailed explanation of this effect is beyond the scope of this work and is not warranted in view of all the assumptions that were made.

We provide one sample explanation based on the assumption that model 1 applies. In our example, the radio emission remains fixed relative to the magnetic polar cap and the gamma rays come from field lines leaving the polar cap that are on the trailing side of the spin direction. Then, as the period increases, the emission region (which beams the gamma rays tangent to the field line in this model) travels along the magnetic field line away from the neutron star surface. Therefore, the beam naturally trails the radio beam in phase by more and more as the period increases. This is illustrated in Figure 10. Here it can be seen that this model suggests that PSR B1055−52 must have a "reverse" identification, i.e., the gamma-ray beam in the upper part of the figure will appear to be in near-alignment with the radio beam that is coming from the bottom part of the figure, and vice versa.

We acknowledge that the above discussion is speculative and that in it we have ignored relativistic effects which are likely to be important. However, we hope that this discussion will provide impetus for the measurement of more radio/gamma-ray phase offsets and for a theory to explain the offset-period relationship if the effect is found to withstand the test of further observations.

5. SUMMARY AND CONCLUSIONS

Studies of pulsars by *CGRO*, taken in conjunction with work done in radio and X-rays, reveal several interesting patterns and effects: (1) constant phase with energy; (2) the higher the gamma-ray luminosity the higher the X-ray luminosity; (3) the lower the luminosity of the gamma-ray pulsar, the more efficient it is in converting rotational energy loss into gamma-ray flux; and (4) the longer the period, the larger the radio/gamma-ray phase offset. We also suggest that the emission models proposed to date cannot explain the similarities of the average ~100 keV and ~100 MeV light curves. Further, unless a narrow beam is assumed, pulsars such as PSR B1055−52 and Geminga appear to be radiating a very significant fraction of their rotational energy loss in the form of gamma-rays. These patterns and effects are not easily explained by current models. Perhaps it is time to consider an entirely new set of models and ideas that concentrate on geometrical considerations rather than particle acceleration effects.

We gratefully acknowledge help in compiling the data and useful discussions from R. Wilson for the BATSE team; K. Bennett and M. Bussetta for the COMPTEL team; J. Fierro, G. Kanbach, P. Nolan, and D. Thompson for the EGRET team; K. Brown, D. Grabelsky, E. Grove, S. Lomatch, S. Matz, and W. Purcell for the OSSE team; J. Cordes, V. Kaspi, R. Manchester, S. Lundgren, D. Nice, and J. Taylor for the radio data; J. Finley, J. Halpern, N. Kawai, and H. Ögelman for the X-ray data; I. Grenier and E. Massaro for gamma-ray data from instruments other than *CGRO;* and J. Arons, A. Harding, C. Ho, and M. Tavani for information about the theory of pulsars. We also thank the referee for useful comments.

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