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GAMMA RAYS FROM THE GEMINGA PULSAR: VARIATIONS WITH TIME AND PHASE

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ABSTRACT

Pulsed γ radiation from the Geminga pulsar was recorded by the *COS B* satellite from 50 MeV to 5 GeV between 1975 and 1982. It has been analysed to derive the source spectral properties as a function of time and phase. The two main peaks are separated by 0.50 ± 0.01 in phase. Significant pulsed emission has also been detected in both phase regions between the two main peaks. Significant spectral differences with phase have been found; the emission from the first peak is slightly softer than from the second one and the Interpeak 2 radiation is extremely soft. The first peak emission remained stable within the statistics over 7 years while the flux from the other phase intervals changed significantly with time. The phase dependence of the variability implies that all the observed source emission should be pulsed and that it consists of four discrete beams with different apertures and spectra. The beams characteristics are strikingly similar to those of four γ-ray beams generated by the Vela pulsar.

Subject headings: gamma rays: observations — pulsars: individual (Geminga, Vela)

1. INTRODUCTION

Although it is the second brightest GeV source in the sky, Geminga has denied us a firm identification for 20 years. Evidence for its pulsar nature was steadily accumulated: excessive blue colour, very high L_γ/L_X and L_X/L_V ratios (Bignami, Caraveo, & Paul 1988; Halpern & Tytler 1988), γ-ray spectrum and variability similar to the Vela pulsar (Grenier, Hermsen, & Hote 1991). In 1992, Halpern & Holt discovered a periodicity at 237 ms in the *ROSAT* data from the 1E 0630+178 X-ray source that was later confirmed in the Geminga γ-ray data recorded by *EGRET, COS B, SAS 2,* and *GAMMA* 1 (Bertsch et al. 1992; Hermsen et al. 1992; Mattox et al. 1992; Akimov et al. 1993). This paper presents the first results from a detailed study of the pulsed γ-radiation from Geminga as a function of phase, energy, and time throughout the 7 years of *COS B* observations. A similar study of the Vela pulsar has shown that its pulsed γ-radiation was not homogeneous, but composed of five discrete beams with different apertures, spectra, and long-term evolutions (Grenier, Hermsen, & Clear 1988). We find strikingly similar properties for Geminga.

2. PULSAR EPHEMERIS

Photons with energies higher than 100 MeV have been taken from five *COS B* observations (namely, periods 0, 14, 39, 54, and 64), between 1975 August and 1982 April. The UTC arrival times have been transformed to the Solar System Barycentre using the *Einstein* HRI position of the 1E 0630+178 source ($\alpha_{1950} = 6^h30^m59^s.15$, $\delta_{1950} = 17°48'33''$). We have searched for a periodic signal around the period and period derivative values published by Halpern & Holt (1992) and have found an extremely stable law of variation of the pulsation frequency, which is valid for the entire *COS B* lifetime: $f = 4.21775012277 \pm 2.4\ 10^{-10}$ Hz, $df/dt = -1.952379\ 10^{-13} \pm 2.4\ 10^{-18}$ Hz s^{-1}, and $d^2f/dt^2 = (2.8 \pm 1.6)\ 10^{-25}$ Hz s^{-2}, at the epoch t_0 = J.D. 2,443,946.500115741 (with the timescale in atomic time TAI at the Solar System Barycentre and the MIT ephemerides). The new epoch t_0 with respect to that quoted by Hermsen et al. (1992) renders the absolute phase shown in Figure 1. When using the position of the proposed optical counterpart G″ for Geminga (Halpern & Tytler 1988), the timing solution slightly improves, mainly in the value of d^2f/dt^2, although it remains statistically consistent with that reported above.

Despite the long time spans between the observations, the remarkable stability, within 5 ms, of the absolute phases of the peaks from one observation to the next strongly suggests that no glitch affected the star rotation. The recent ephemeris obtained by the *EGRET* team (Mayer-Hasselwander et al. 1993) further supports the idea of a very stable Geminga neutron star.

Light curves have been generated for the sum of the five observations by folding the data with the parameters applicable to each epoch and by selecting photons from within a cone of half angle $\theta = 12.5\ E_{\rm MeV}^{-0.16}$ degrees about the pulsar position. This cone maximizes the signal-to-noise ratio for the energy-dependent point spread function of the *COS B* detector (Buccheri et al. 1983). Figure 1 shows the light curves obtained in three energy bands. As for the Crab and Vela pulsars, a double-peak structure can be seen, but with a phase separation of 0.50 ± 0.01.

Four phase intervals have been selected to study the spectral and temporal characteristics of the pulsed emission as a function of phase. The choice of boundaries is displayed in Figure 1. It results from a comparison of the *COS B, EGRET,* and

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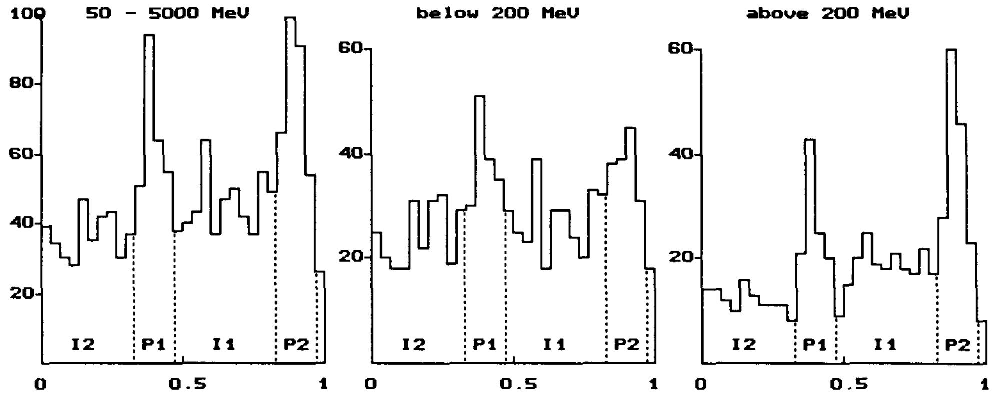

FIG. 1.—Light curves of the pulsed γ radiation from Geminga summing five *COS B* observations

SAS 2 light curve shapes. The phase intervals have been named Peak 1 (from 0.33 to 0.47 in phase), Interpeak 1 (0.47 to 0.83), Peak 2 (0.83 to 0.97), and Interpeak 2 (0 to 0.33 and 0.97 to 1), after the names of four of the five components of the Vela pulsed emission because of strong phenomenological similarities that are discussed below.

3. SPECTRAL PROPERTIES

The spectral deconvolution of the emission in each phase interval and for each epoch has been performed using the maximum-likelihood method developed for the *COS B* data (Grenier et al. 1988). Given the instrumental responses for position and energy determination, the procedure maximizes the likelihood of detecting the individual photons recorded by *COS B* at measured energies and positions, by adjusting the parameters of a source model. To describe the bulk of the γ rays detected in the large *COS B* field-of-view, the model includes several sources: the point-sources of the Crab pulsar and nebula with stable spectra as measured by Clear et al. (1987); an isotropic instrumental background and a structured Galactic emission, both of free intensity and spectral index (the spatial structure of the latter is traced by H I and CO maps of the region); and the point-source Geminga at its X-ray position for which we examined various spectral distributions.

The spectral deconvolution was already applied to the entire emission from Geminga before the discovery of the pulsar period. The detailed results were described in Grenier, Hermsen, & Henriksen (1993). Below a few hundred MeV, the spectrum flattened notably (5 σ) during four observations, while in the remaining observation, it followed a single power law of index -2.02 ± 0.10 down to 50 MeV (see Fig. 2). The implied spectral variability at low energy had a statistical significance of 4 to 5 σ and was further supported by the stability of the simultaneously derived background spectra (instrumental and Galactic). A stable $E^{-2.07\pm0.09}$ spectrum was found above 200 MeV. The source emission may be composite, so it has been analysed in each phase interval. As a first step, single-power-law spectra have been fitted to the 50–5000 MeV data. As expected from the bridge of emission between the main peaks in the *EGRET* light curve (see Mattox et al. 1992), highly significant emission has been detected from the Interpeak 1 interval in the *COS B* data. The confidence probabilities $\bar{p}$ (i.e., likelihood probability of being a random fluctuation of the background emissions) lie well below 10^{-25}. Of greater importance is the discovery, in the Interpeak 2 interval, of a point-source at the position of Geminga during four observations, with confidence probabilities $\bar{p}$ of $<10^{-25}$, 3×10^{-12}, 2×10^{-7}, and 5×10^{-14} for periods 14, 39, 54, and 64, respectively. During period 0, the Interpeak 2 emission was not detected. To study the time-averaged spectra and their phase dependence, all five observations have been combined. The results are given in Table 1. The probability that the pulsed emission be represented by a

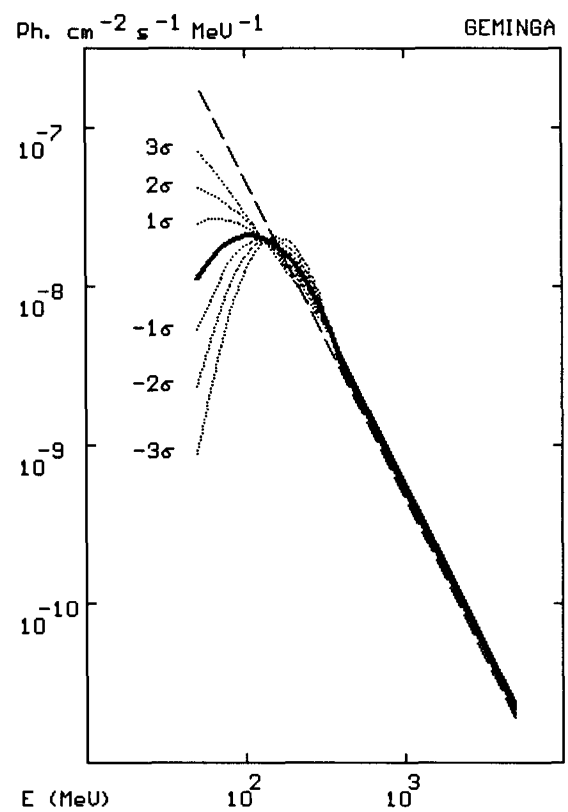

FIG. 2.—Spectral fit to the whole pulsed emission in a low state (*thick line*) from the sum of *COS B* observations 0, 39, 54, and 64. The distribution couples a smooth parabolic function to an E^{-2} law above 380 MeV. The dotted curves give the related confidence regions. The dashed line shows the high-state spectrum obtained in period 14.

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TABLE 1

TIME-AVERAGED SINGLE AND DOUBLE POWER-LAW SPECTRA[a]

PHASE INTERVAL	k	α	50–200 MeV k	50–200 MeV α	200–5000 MeV (k for $\alpha = -2.07$)
Peak 1	$(2.19^{+1.21}_{-0.79}) \times 10^{-4}$	-1.79 ± 0.08	$(6.9^{+28.2}_{-5.8}) \times 10^{-6}$	$-1.08^{+0.36}_{-0.32}$	$(1.3 \pm 0.1) \times 10^{-3}$
Peak 2	$(8.75^{+5.04}_{-3.24}) \times 10^{-5}$	-1.62 ± 0.08	$(1.9^{+25.5}_{-1.8}) \times 10^{-8}$	$+0.08^{+0.64}_{-0.52}$	$(1.6 \pm 0.1) \times 10^{-3}$
Interpeak 1	$(1.92^{+1.05}_{-0.69}) \times 10^{-4}$	-1.83 ± 0.08	$(1.5^{+7.0}_{-1.3}) \times 10^{-6}$	$-0.85^{+0.40}_{-0.34}$	$(9.7 \pm 0.7) \times 10^{-4}$
Interpeak 2	$(1.5^{+3.9}_{-1.0}) \times 10^{-2}$	$-2.93^{+0.24}_{-0.27}$	...	...	...

[a] In γ cm^{-2} s^{-1} MeV^{-1} phase unit^{-1}, fitted to the Geminga emission recorded between 50 MeV and 5 GeV by *COS B*: $k \times E^{\alpha}_{\rm MeV}$.

common power law over all phases is below 10^{-25}. Hence, there are significant spectral differences with phase. Of particular interest is the extreme softness of the Interpeak 2 component and the mild hardness of the second peak relative to the first one (see Fig. 1).

To study which phases contribute to the spectral flattening seen at low energies for the total emission (Grenier et al. 1993), double-power-law spectra with a break at 200 MeV have been tested for three phase intervals. Interpeak 2 was not tested because of its extreme softness. The index below 200 MeV and the overall intensity were treated as free parameters. The index above 200 MeV was forced to the time-averaged value of −2.07 measured for the entire pulsed emission and which remained stable over the years. This constraint reduced our number of degrees of freedom to match the low statistics. The comparison of the single and double power-law fits results indicates that this constraint is reasonable. The Geminga results are displayed in Table 1. The existence of a spectral break was clearly established (5 σ) for the total pulsed emission despite the softness of the Interpeak 2 component (Grenier et al. 1993). For the other separate phases, however, the indication for a break is weak due to the reduced statistics. A single power law of index -1.79 ± 0.08 can represent the first peak emission with a confidence level of 76%. The break significance levels obtained for Peak 2 and Interpeak 1 are 2.3 and 3.1 σ, respectively. These numbers slightly improve when looking at individual observations. The results of the various fits as a function of time and phase will be fully described in a forthcoming paper (Grenier et al. 1994).

To show the long-term evolution of the pulsar radiation and its phase dependence, 50–5000 MeV fluxes have been integrated from the double–power-law spectra for each epoch and phase interval. The fluxes are displayed in Figure 3. The observed variations result both from changes in the overall inten-

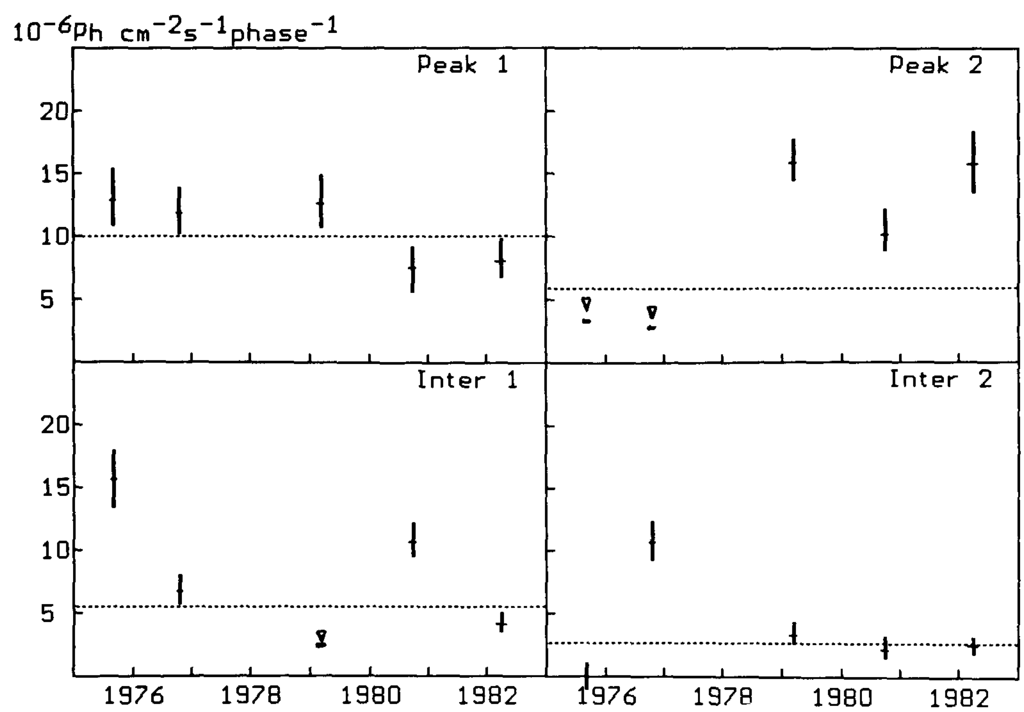

FIG. 3.—Time evolution in four phase intervals of the 50–5000 MeV pulsed flux integrated from the double-power-law spectra. Dots indicate fluxes measured above 200 MeV when no emission was detected below. The related arrows show the level reached by adding the 1 σ upper limit of the low-energy flux.

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sity and from spectral distorsions below 200 MeV of the same type as displayed in Figure 1. The emission from the first peak remained stable over seven years. As in the case of Vela, this stability demonstrates that the large fluctuations seen at other phases do not have an instrumental origin.

4. DISCUSSION

The lack of correlation between the temporal evolutions of the emission in the separate phase intervals and their spectral differences imply that Geminga emits four independent beams of γ rays. In particular, a high Interpeak 2 flux was recorded in 1976 while both Peak 2 and Interpeak 1 yielded lower fluxes. It is therefore unlikely that the radiation seen outside the main peaks should be a soft, underlying DC emission that would cover all phases, as interpreted by Cheng & Ma (1994) from an independent analysis of the *COS B* data. Interpeak 2 emission is rather pulsed. The statistics are, however, too low to test its actual extent in phase. Emission from the Interpeak 2 interval has been recently confirmed between 10 and 30 MeV by a combined timing and spatial analysis of COMPTEL data. The measured flux is consistent with an extrapolation of the soft *COS B* spectrum (Hermsen et al. 1993). The soft and variable, $E^{-2.93\pm0.27}$, Interpeak 2 component strongly resembles its namesake from Vela that also exhibits a soft and variable, $E^{-2.55\pm0.19}$, spectrum below 300 MeV that may have been seen by COMPTEL down to 1 MeV (Bennett et al. 1993).

In conclusion, significant pulsed γ radiation has been observed from Geminga at most phases. The phase dependence of both the time variability and spectral shape implies that the pulsed emission consists of four beams with different apertures, spectral distributions and long-term evolutions. Their properties strongly resemble those of the four Vela γ-ray beams bearing the same names: emission in the first peak is soft and stable, with an index of -1.79 ± 0.08 for Geminga and -1.98 ± 0.05 for Vela; emission from the second peak is harder; Interpeak 2 radiation is extremely soft; Interpeak 1 and Interpeak 2 emissions are highly variable. They appear, however, in phase in a different order. The Geminga observations were too sparse to constrain the timescale of the variability. The stability of the pulsar rotation, however, indicates that the γ-ray variations are not triggered by any glitch activity. In Vela too, γ-ray fluctuations and glitches were not correlated. The striking analogy we find between the two pulsars suggests that similar acceleration sites work in both magnetospheres despite their different rotation rates, sizes, and ages. The independent evolutions of the components suggest distinct origins inside the magnetosphere. The 0.5 phase separation between the Geminga main peaks indicates that they originate relatively closer to the star than in the case of Vela where aberration near the light-cylinder can explain the 0.42 phase separation between the peaks. In their present state, however, neither the polar cap nor the outer gap models (Harding & Daugherty 1992; Halpern & Ruderman 1993) account for the existence of the two broad and variable beams of Interpeak 1 & 2, independent of the bright and highly focused radiation from the main peaks.

The flattening of the whole pulsed spectrum below 200 MeV, which characterized four observations out of five, provides an explanation for the difficulties of detecting Geminga below 30 MeV with COMPTEL (Strong et al. 1993; Hermsen et al. 1994). The low-energy variability may be caused by a variation in energy of an abrupt break in the spectrum of the radiating particles. A suppression of soft γ photons seems more unlikely since the γ rays are too scarce to suffer from self-absorption at the source or from pair production on the thermal X rays (Grenier, Hermsen, & Henriksen 1993). In fact, the Vela and Geminga magnetospheres may be quite thin to MeV-GeV γ rays that may therefore leave the magnetosphere without generating profuse photon-pair showers. Their magnetospheres may thus be deprived of the extensive cascades which produce the strong X-ray pulsed emission that is observed from the Crab pulsar, and also generate the copious particle wind that powers the Crab synchrotron nebula.

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