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Ultrahigh-Energy Gamma-Ray Emission from the Geminga Pulsar

Yu. I. Neshpor, A. A. Stepanyan*, Yu. L. Zyskin, O. R. Kalekin,
V. P. Fomin, N. N. Chalenko, and V. G. Shitov
Crimean Astrophysical Observatory, National Academy of Sciences of Ukraine, p/o Nauchnyĭ, Crimea, 334413 Ukraine

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Abstract—In 1996–1997, the Geminga pulsar was observed at the Crimean Astrophysical Observatory with a ground-based gamma-ray telescope. An analysis of the observational data suggests that this object is a source of ultrahigh-energy gamma rays. An analysis of the temporal distribution of gamma-ray photons by an epoch-folding technique reveals a periodicity in the gamma-ray emission with a period of 0.237 s. © *2001 MAIK "Nauka/Interperiodica".*

Key words: *pulsars, ground-based gamma-ray astronomy, gamma-ray photons*

INTRODUCTION

As a source of ultrahigh-energy gamma-ray emission, the Geminga pulsar was first discovered more than twenty years ago by the SAS-2 satellite (Kniffen *et al.* 1975) and, two years later, by the COS-B satellite (Masnou *et al.* 1977). Using the instrumentation onboard the *Einstein* X-ray satellite, Bignami *et al.* (1983) managed to identify Geminga with a weak X-ray source. As a result, Geminga was also detected at an optical wavelengths (Bignami *et al.* 1987). It is one of the most puzzling objects in modern astrophysics. It is of interest primarily because its gamma-ray flux (at energies > 50 MeV) is a thousand and two hundred thousand times higher than that in the X-ray and optical bands, respectively. Thompson *et al.* (1977) detected a periodicity with a period of 59 s in the SAS-2 observational data for 1972–1973 at energy 35 MeV. Subsequently, from 1972 until 1983, the Geminga flux was found to be also variable with the same period in other energy bands (Bignami *et al.* 1984) up to ultrahigh energies (Zyskin and Mukanov 1983). However, Buccheri *et al.* (1985) questioned the validity of the estimates for the significance of the above results.

Geminga observations continued and produced results. Based on ROSAT data, Halpern and Holt (1992) found pulsations with a period of 0.237 s in the X-ray emission from Geminga. The reduction of EGRET (Bertsch *et al.* 1992), COS-B (Bignami and Caraveo 1992; Hermsen *et al.* 1992), and SAS-2 (Mattox *et al.* 1992) observational data confirmed the presence of a periodicity with a period of 0.237 s. The ground-based observations of Geminga in 1983 (Bowden *et al.* 1993) and in 1984–1985 (Vishwanath *et al.* 1993) through the detection of Cherenkov flashes in the atmosphere also revealed a pulsating component with a period of 0.237 s in the ultrahigh-energy gamma-ray emission. According to *Gamma-1* observations, the total pulsating flux is $(1.1 \pm 0.3) \times 10^{-6}$ cm^{-2} s^{-1} at energies 300–5000 MeV (Akimov *et al.* 1993). It should be noted, however, that the Whipple Observatory group detected no ultrahigh-energy gamma rays from Geminga during their 1989–1991 observations (Akerlof *et al.* 1993). Radio observations of Geminga at the radio-astronomical station of the Astrospace Center (Lebedev Physical Institute, Russian Academy of Sciences) in 1992, 1993, and 1996 revealed radio pulses with a period of 0.237 s (Shitov and Pugachev 1997). Mattox *et al.* (1998) analyzed the long-term (24.2 years) SAS-2, COS-B, and EGRET data on gamma-ray emission. The ephemeris of the Geminga pulsar was computed with a high accuracy. In 1996 and 1997, the Geminga gamma-ray source was observed at the Crimean Astrophysical Observatory with the GT-48 gamma-ray telescope at ultrahigh energies. Below, we analyze the observational data.

DESCRIPTION OF THE GT-48 GAMMA-RAY TELESCOPE

The GT-48 gamma-ray telescope records photons with energies $>10^{12}$ eV by detecting Cherenkov flashes produced by the interaction of ultrahigh-energy gamma-ray photons with the nuclei of atoms in the Earth's atmosphere. The area illuminated by a Cherenkov flash is rather large, tens of thousands of square meters, which makes it possible to record low ($\sim 10^{-11}$ cm^{-2} s^{-1}) gamma-ray fluxes. The main obstacle to detecting and analyzing ultrahigh-energy gamma-ray sources is a substan-

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* E-mail address for contacts: arnold@crao.crimea.ua

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tial background of cosmic rays. The latter produce Cherenkov flashes in the Earth's atmosphere that are difficult to distinguish from those generated by gamma-ray photons.

New detectors, multi-element cameras, are used to cut off most of the Cherenkov flashes produced by charged cosmic-ray particles. Multi-element cameras form discretized images of Cherenkov flashes. The first telescope of this type came into operation in 1982 at the Whipple Observatory (USA) (Cawley *et al.* 1983).

Our observations with the GT-48 gamma-ray telescope at the Crimean Astrophysical Observatory were started in 1989. The facility consists of two identical altazimuth mountings (sections), northern and southern, separated by a distance of 20 m in the north–south direction and located at an altitude of 600 m above sea level. We have repeatedly described GT-48 in various papers (Vladimirskiĭ *et al.* 1994; Neshpor *et al.* 1998). The GT-48 gamma-ray telescope differs from other operating telescopes in that it also records Cherenkov flashes in the ultraviolet (200–300 nm). The total area of the GT-48 mirrors is 54 m^2. The control system moves the facility with a tracking accuracy of $\pm 1'$. Observations can be carried out both in the mode of coincidence between the two sections and independently with each section. The flash detection time is recorded to within one microsecond. A crystal oscillator is used as the clock. The relative accuracy of the clock rate was 5×10^{-9} over the observing period.

DATA REDUCTION

We observed the Geminga object ($\alpha = 6^{h}33^{m}37^{s}$ and $\delta = 17°46'25''$ for the epoch 1996) with two aligned sections in coincidence mode with a time resolution of 100 ns. The advantages of this detection technique were detailed by Chalenko *et al.* (1997). We tracked the object by comparing observations of the gamma-ray source with cosmic-ray background observations shifted in time from each other by 40 min. The off-source observations preceded the on-source observations, and they were performed at the same azimuth and zenith angles. Five and eight 35-min-long observing sessions were conducted in 1996 and 1997, respectively; the total duration of the source's observations was 175 and 280 min in 1996 and 1997, respectively.

The data were subjected to preliminary reduction, which is required to correctly calculate the first and second moments of the light distribution. The latter were used to determine the following Cherenkov-flash parameters: effective length A, effective width B, orientation angle φ characterizing the direction of maximum elongation of the flash image, and centroid coordinates of the light distribution X_c and Y_c. All the other possible Cherenkov-flash parameters can be inferred from these quantities (Vladimirskiĭ *et al.* 1994). After the preliminary data reduction, 3867 on-source and 3826 off-source events and 5725 on-source and 5690 off-source events observed in 1996 and 1997 were left for the subsequent analysis.

For the possible flux of gamma-ray photons to be determined, they must be selected by excluding flashes produced by charged cosmic-ray particles.

As we have already noted above, the parameters of the Cherenkov flashes from ultrahigh-energy gamma-ray photons differ little from the parameters of the flashes generated by charged cosmic-ray particles (*p*-showers). Nevertheless, most of the flashes generated by *p*-showers can be excluded, thereby significantly increasing the ratio of the number of selected gamma-ray photons to the number of background ones. In this case, we must correctly choose the boundary values for the selection parameters to obtain an optimal signal-to-noise ratio $Q = (N0_s - N0_b)/\sqrt{N0_s + N0_b}$, where $N0_s$ and $N0_b$ are the numbers of selected gamma-ray-like flashes in the on- and off-source observations, respectively. The difference $N0_s - N0_b = N_\gamma$ is the number of selected gamma-ray photons detected over the observing period, and $\sqrt{N0_s + N0_b}$ is the statistical error in the number of gamma-ray photons after selection. If the selection is made by using several parameters, then up to 99% or more flashes from the charged component can be excluded.

Since the parameters of each flash (event) recorded simultaneously with each section were determined independently, they had two values denoted for the northern and southern sections by numbers 1 and 2, respectively. We used several selection criteria with Cherenkov-flash parameters to reduce the background of the flashes generated by charged cosmic-rays particles.

When selecting events, we primarily considered the flash amplitude V, which is proportional to the total "energy" of the recorded radiation (integrated flux from the flash). The amplitude was determined for the same area as the second moment of the flashes. Showers with amplitudes $V(1) < 100$ discretization units (500 photons) of the analog-to-digital converter or $V(2) < 100$ were excluded from the subsequent analysis, because the parameters of these flashes were determined with a large error.

The effective length A and effective width B of the flash image were used as the selection parameters. Events were excluded from the subsequent analysis, if at least one of the following conditions was satisfied: $A(1) > 0\overset{\circ}{.}30$; $A(2) > 0\overset{\circ}{.}32$; $B(1) > 0\overset{\circ}{.}17$; and $B(2) > 0\overset{\circ}{.}17$.

As has already been noted above, we recorded the ultraviolet emission from flashes. The electrons from *p*-showers of a given energy are known to penetrate appreciably deeper into the Earth's atmosphere than those from gamma-ray showers of the same energy. As a result, the Cherenkov flashes from *p*-showers have considerably higher fluxes in the wavelength range 200–300 nm (ultraviolet) than those from gamma-ray showers (Stepanyan *et al.* 1983). Below, the ratio of the

Table 1. The number of detected and selected events

Selection method	Number of on-source events	Number of off-source events	Difference	Difference-to-error ratio	Year
Without selection	3867	3826	41	0.43	1996
Selection by coordinate-independent parameters	176	103	73	4.37	
Without selection	5725	5690	35	0.33	1997
Selection by coordinate-independent parameters	109	86	23	1.65	

flash amplitude in this spectral range (*U*) to the total amplitude in the visible range (*V*) is called the *UV* parameter for simplicity. This parameter was first successfully used by us when analyzing observations of the Crab nebula (Kalekin *et al.* 1995) and, subsequently, of other objects.

Selection with the *UV* parameter averaged over all the years of observations increased the confidence level of the results to 4.4 standard deviations. The *A*, *B*, *V*, and *UV* parameters do not depend on the flash position relative to the source and are called coordinate-independent parameters.

The data obtained by selection using the above parameters are given in Table 1.

Thus, the observational data for Geminga on the coordinate-independent parameters of flashes can be considered to point to the presence of an ultrahigh-energy gamma-ray flux from this object. An analysis of the periodic pattern of ultrahigh-energy gamma-ray radiation further confirms this result.

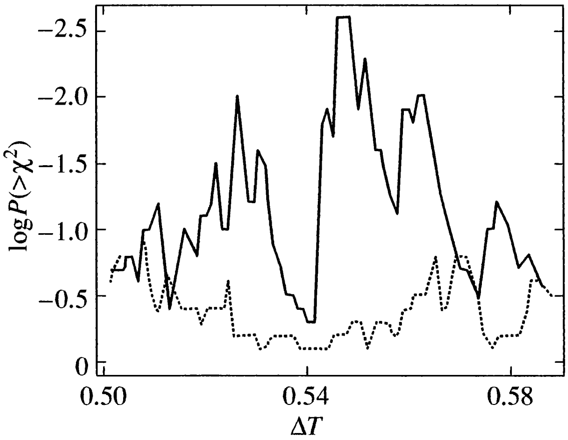

Fig. 1. A fragment of the periodogram as constructed from the 1996 data. The logarithm of the statistical probability of a random deviation ($>\chi^2$) is plotted along the vertical axis; $\Delta T = (T - 0.237099300) \times 10^7$, where T is the period in seconds, is plotted along the horizontal axis. The solid and dotted lines refer to on- and off-source observations, respectively.

PULSATING GAMMA-RAY RADIATION

The above observations were analyzed in an effort to detect a pulsating component with a period of 0.237 s in the ultrahigh-energy gamma-ray radiation. We do not pose the problem of searching for a period but only want to test the hypothesis that there is a periodicity in our observations based on the highly accurate ephemeris inferred from published long-term data (Shitov and Pugachev 1997; Mattox *et al.* 1998). Using SAS-2, COS-B, and EGRET data, Mattox *et al.* (1998) obtained the following ephemeris for the epoch t = JD 2446600 (June 18, 1986): $f = 4.217705363081(13)$ Hz, $\dot{f} = -1.9521712(12) \times 10^{-13}$ Hz s^{-1}, and $\ddot{f} = 1.49(3) \times 10^{-25}$ Hz s^{-2}. Shitov and Pugachev (1997) derived the following period from the radio observations of Geminga from 1992 until 1996: $T = 0.23709745295(12)$ s and $T = 10.9765(15) \times 10^{-15}$ s s^{-1} for the epoch JD = 2448400. Although the error in the period inferred from radio data is larger, the epoch of these observations is closer to that of our observations (JD 2450401, November 13, 1996).

We used the above results to compute the period and its derivative for the epoch of our observations. For November 13, 1996, $T = 0.2370993496$ s and $\dot{T} = -1.09715948 \times 10^{-14}$ s s^{-1} (Mattox *et al.* 1998) and $T = 0.2370993506$ s and $\dot{T} = -1.09765 \times 10^{-14}$ s s^{-1} (Shitov and Pugachev 1997) (the second derivative was not determined). For November 1, 1997, $T = 0.2370996833$ s and $\dot{T} = -1.09713706 \times 10^{-14}$ s s^{-1} (Mattox *et al.* 1998) and $T = 0.2370996845$ s and its derivative is the same (Shitov and Pugachev 1997). We analyzed the observational data for periodicity in a narrow frequency range within ±5 steps of independence of the computed periods. For our data, the independence step is 5×10^{-9} s and 4×10^{-9} s for 1996 and 1997, respectively, which is much larger than the difference between the frequencies predicted by Shitov and Pugachev (1997) and Mattox *et al.* (1998) (10^{-9} s). The analysis was performed by the epoch-folding technique for the events selected by coordinate-independent parameters from on-source observations (176 and 109 events for 1996 and 1997, respectively). For checking purposes, we also analyzed

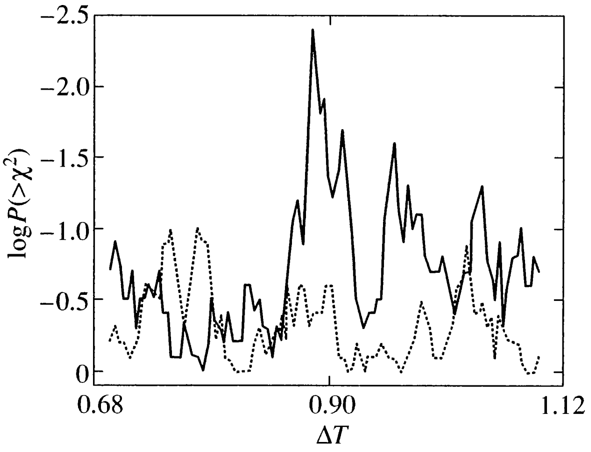

Fig. 2. A fragment of the periodogram as constructed from the 1997 data (the notation is the same as in Fig. 1). $\Delta T = (T - 0.237099600) \times 10^7$.

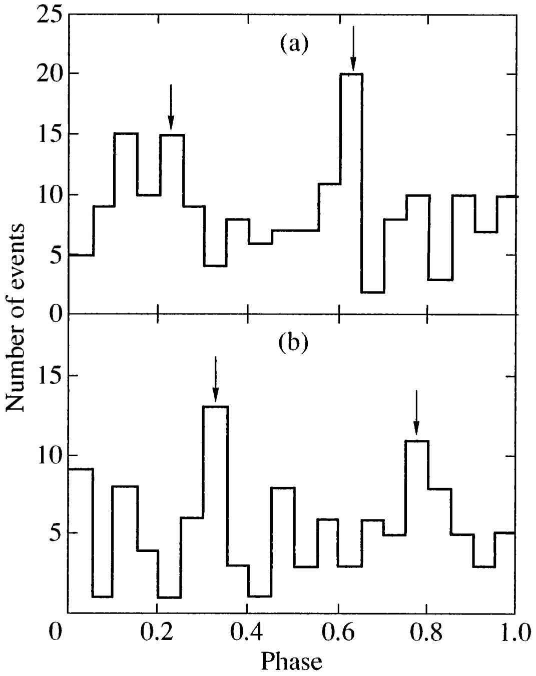

Fig. 3. Phase histograms for (a) $T = 0.237099354$ s (1996) and (b) $T = 0.237099688$ s (1997).

the events selected by coordinate-independent parameters from off-source observations (103 and 86 events for 1996 and 1997, respectively). For each event, we determined its phase from the specified period and its derivative. The period was taken at the start of our observations. Variations in the period derivative during our observations (less than one month) were disregarded because they were small. We broke down the entire period into twenty phase bins and constructed the phase histogram (light curve) of events. The light curves were constructed for each trial period and analyzed by the χ^2 test. For each χ^2, we determined the $(>\chi^2)$ probability of a random distribution for the phase histogram.

Table 2. Gamma-ray flux measurements for Geminga

Observatory	Epoch of observations	Energy range, TeV	Flux, 10^{12} cm^{-2} s^{-1}
HEGRA	1996	>1	<2.3
Whipple	1989–1991	>0.5	<8.8
Durham team	1983	>1	30
Ootakamund	1984–1985	>0.8	21 ± 8
Crimean Astrophysical Observatory	1996, 1997	>1	24 ± 8

We then analyzed the periodograms obtained in this way. Figures 1 and 2 show their fragments based on the 1996 and 1997 data, respectively. In Figs. 1 and 2, the trial period and the logarithm of probability $P(>\chi^2)$ are plotted along the horizontal and vertical axes. The solid and dotted lines refer to the on- and off-source observations, respectively.

The logarithm of probability in the periodograms obtained from off-source observations does not exceed unity (in absolute value). This fact and the pattern of the periodograms constructed from on-source observations suggest that there is a periodicity in the ultrahigh-energy gamma-ray radiation with period T = 0.237099354(5) for 1996 and T = 0.237099688(4) s for 1997. The independence step is given in parentheses. We consider this value to be the error with which the period can be determined. In addition, recall that the relative error in the detection time over the period of GT-48 observations was 5×10^{-9}.

The probabilities of a random phase distribution of events are $P = 2.3 \times 10^{-3}$ for 1996 and $P = 3.4 \times 10^{-3}$ for 1997. Given the derivative, the period inferred by Malofeev and Malov (1997) for an epoch (MJD = 50434.4) close to that of our observations yields P = 0.237099351 s, which closely matches our period for MJD = 50401. It is of interest to examine the phase histograms (light curves) for these two periods (see Fig. 3). Note the presence of two peaks in the light curves (marked by arrows) separated by $\Delta\varphi$ = 0.40–0.45. The 1996 and 1997 light curves cannot be phased because of the uncertainty (error) in the period. The light curve reported from Mattox *et al.* (1998) also exhibits two peaks separated by $\Delta\varphi$ = 0.48.

CONCLUSION

Having analyzed our observations of the Geminga pulsar, we obtained the following results:

(1) An ultrahigh-energy gamma-ray flux is observed from the pulsar at a confidence level of 4.4 standard deviations.

(2) A periodicity analysis by the epoch-folding technique in a narrow interval near the period inferred in other energy bands [radio and high-energy (~100 MeV) gamma-ray photons] revealed a periodicity in the gamma-ray flux. The probability of a random phase distribution of the flux is 0.3%.

These two results collectively suggest that Geminga is an ultrahigh-energy gamma-ray source.

As we already pointed out in the Introduction, the results of Geminga observations by different groups of researchers differ markedly. The measured fluxes and the epochs of observations are given in Table 2.

The negative results obtained at the Whipple and HERGA observatories (Aharonian *et al.* 1999) may be attributable to variability of the source. As we noted in the Introduction, positive results were obtained in the observations of the Durham (Bowden *et al.* 1993) and Indian (Vishwanath *et al.* 1993) teams of researchers.

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