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An episode of ultrahigh energy radiation from the γ-ray source Geminga: GRAPES I observations at Ooty during 1984–1987

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A study of showers arriving from the direction of the γ-ray source Geminga (1E0630+178) has shown evidence for emission of ultrahigh energy radiation during the one week interval October 10–16, 1986. 83 showers were observed in the source bin as against an expected background of 44.1. The probability of observing this excess based on Monte Carlo simulations is less than 10^{-4}. The flux observed during this period $(1.00\pm0.24)\times10^{-11}$ cm^{-2} s^{-1} at energies $\geq 10^{14}$ eV corresponds to a time-averaged luminosity of 6×10^{32} erg s^{-1}.

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Geminga remained for over a decade an unidentified strong source of high-energy (≥ 50 MeV) γ rays since its discovery in 1972 by the Small Astronomy Satellite II (SAS II) [1]. Unlike the other two strong sources of high-energy γ rays that were unambiguously identified with the Crab and Vela pulsars, Geminga continued to be a puzzle for the astrophysics community. COS-B [2] launched in 1975 studied Geminga in greater detail and a more precise location of this source was obtained. Searches for a counterpart at other wavelengths resulted in identification of a soft x-ray source 1E0630+178 with Geminga. However, the recent discovery of pulsations at a period of 237 ms in x rays [3] from 1E0630+178 based on Roentgen satellite (ROSAT) data provided a unique opportunity to identify Geminga with a neutron star. Employing the pulsar parameters from x-ray data pulsations [4] have been detected at γ-ray energies ≥ 50 MeV from the Energetic Gamma Ray Experiment Telescope (EGRET). A search of the earlier COS-B [5] database covering the period 1975–1982 has also shown pulsations at the 237-ms period. The rotational energy-loss rate of the pulsar in Geminga is $\sim 4\times10^{34}$ erg s^{-1} which implies a distance [4] of ≤ 38 pc assuming an efficiency for conversion of rotational energy into γ rays to be $\leq 1\%$.

A nearby source at a distance of ≤ 38 pc, Geminga, would be detected at ultrahigh energies (UHE's) with existing extensive air shower (EAS) arrays even if its luminosity at UHE is a fraction of that observed at energies ≥ 50 MeV. However, several recent detections of sources of UHE radiation have largely been episodic in nature [6–9]. Therefore, any search should look for both steady and episodic emissions. Emission of UHE radiation from compact sources implies acceleration of particles to PeV (10^{15} eV) energies and beyond which may be difficult to sustain over long intervals of time. It, therefore, is to be expected that such emissions may frequently be sporadic in nature.

We have been operating an EAS array at Ooty (11.4° N latitude, 2200 m altitude) in southern India since 1984. This array is suitably located to detect sources in the equatorial region such as Geminga (1E0630+178). The Ooty EAS array called GRAPES I for gamma-ray astronomy at PeV energies, phase I has collected data with 24 scintillation detectors from 1984 to 1987. The array has since then been upgraded to GRAPES II with 100 density/timing scintillation detectors and 200-m^2 area muon detector. During the GRAPES I phase showers were selected with a fourfold coincidence between detectors located near the center of the array. For each shower, data on relative arrival time and particle density in each detector along with the real time (absolute time known to 0.5 ms) were recorded. All showers recorded during phase I have been analyzed [10,11] for arrival direction (zenith angle θ, azimuth ϕ, right ascension α, and declination δ), core location (x and y), lateral distribution parameter (shower age s), and shower size (Ne). A total of 6.9×10^6 showers constitute the final database for studies on cosmic sources. The effective energy threshold is $\sim 10^{14}$ eV for showers arriving at $\theta=6.4°$, the angle for Geminga at meridian transit. The angular resolution of the array has been estimated [12] to be 1.6°. Consequently a 4°×4° bin in α and δ, centered on Geminga ($\alpha=98.3°$, $\delta=17.8°$), has been designated as the source bin.

Using the entire database we have looked for directional excess in the source bin relative to the mean of eight surrounding 4°×4° bins. The use of these eight bins ensures concurrent estimate of the background which is essential in view of the fact that several UHE sources have shown time variable fluxes. In addition there can be slight variations in the shower rate due to changes in atmospheric pressure or due to drift of the effective threshold for the triggering detectors. Cuts on core distance ($r_c \leq 30$ m) and zenith angle ($\theta \leq 40°$) are imposed on the data to ensure better accuracy for various shower parameters. The core distance cut of 30 m does not introduce any bias in the selection of showers because for GRAPES I array the four triggering detectors are located near the center of the array and placed on a horizontal plane. Consequently, the array has a uniform response in the azimuthal (ϕ) direction. The zenith angle cut of 40° also does not introduce any bias in the selection of showers because the fraction of showers rejected by this cut are only 0.14% of the total number of showers recorded. A

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total of 3723 showers were observed in the source bin as compared to a mean of (3651±21.5) for the eight background bins. Here a correction has been applied for the zenith angle dependence of shower rate on declination because six out of eight background bins have declination different from that of the source bin. For estimating this correction we have used the entire database of 6.9×10^6 events. First the number of showers in three declination bands ranging from 11.8° to 15.8°, from 15.8° to 19.8°, and from 19.8° to 23.8° are computed because these three bands have same declination coverage as the eight background bins. In a day Geminga is observable for 326 min when it lies within 40° from vertical direction. When a $4°\times4°$ source bin is observed for a full day (326 min) it traces a unique path in the local spherical coordinates (zenith angle θ and the azimuthal angle ϕ). The trajectory of this path depends only on the latitude of the site and on the declination of the source. On the other hand, when a 4° wide band in declination is selected for observation at any given time then the entire path in the local spherical coordinates (θ,ϕ) for that declination is observed at that very instant. When separate declination bands are observed simultaneously, the number of showers in each band reflect the effect of declination only. Various possible systematic effects such as atmospheric pressure changes, breaks in the data taking, etc., are eliminated when taking ratios of shower counts in different bands. The number of showers in the three declination bands were 588 423, 554 164, and 501 262. A weighted mean of these three numbers in the ratio of 3:2:3 (which corresponds to the declinations of the eight bins in the same ratio) yields 547 173. The weighted mean, 547 173 which corresponds to the eight background bins, when it divides the observed number 554 164 (corresponding to the source bin) yields a ratio of 1.0128. The counts in the background region have been scaled up by the factor of 1.0128 to take care of this small (1.3%) systematic effect.

Since there is a systematic variation in the observed shower rate as a function of zenith angle of the source we have restricted our analysis to the data of "good" days. Eight $4°\times4°$ bins surrounding the source bin provide an estimate of the concurrent background. A "good" day is defined as a day when the observations on the source and the background region lasted 326 min as the source moved from 40.8° E to 40.8° W ($\theta\leq40°$). During nearly 3 yrs of observations, there were a total of 652 "good" days for the source bin with a mean shower rate of $(5.71\pm0.09)\ \mathrm{d}^{-1}$. The mean shower rate for the background bins was $(5.60\pm0.03)\ \mathrm{d}^{-1}$. The net excess $(0.11\pm0.10)\ \mathrm{d}^{-1}$ is statistically insignificant. A 90% C.L. upper limit of $2.3\times10^{-13}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ is obtained for steady flux from Geminga at energies $\geq10^{14}$ eV. This may be compared with an upper limit of $4.1\times10^{-13}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at 90% C.L. at energies $\geq4\times10^{13}$ eV [13] reported by the CYGNUS Collaboration.

We have detected episodic emission from several binary x-ray sources such as Cyg X-3, Her X-1, Sco X-1 and binary pulsar PSR 1957+20 [6–9]. It therefore is of interest to search for episodic emission from Geminga as well. Since the daily shower rate was small $(5.71\pm0.09)\ \mathrm{d}^{-1}$, a meaningful study of day-to-day shower rate variation is not possible; therefore, we have studied variations in the weakly shower rate. It is to be noted that a period of one week does not necessarily consist of seven consecutive calendar days, since runs occasionally were interrupted on some days due to breakdown in either electrical power or instrumentation. In Fig. 1, the difference in the weakly shower rate between the source and the mean of the eight background bins is shown for the entire duration of 93 weeks. An unusually large excess of 39 showers is seen for the 70th week. The start of this week is on 1986 October 10 and it ends on 1986 October 16. There are no breaks for the entire duration of this week.

In Fig. 2, we show the frequency distribution of the number of excess showers in the source bin as compared to the mean of background bins for weakly data. Also shown is a Gaussian fit using a standard deviation equal to the root-mean-square (rms) spread derived from the 93 data points and normalized to the area of the histogram in Fig. 2. Clearly, except for one data point (70th week),

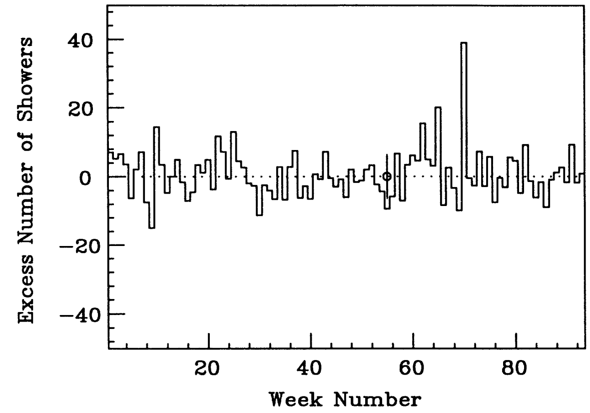

FIG. 1. Variation in the excess number of showers observed in the source bin relative to the mean number observed in the background region as a function of time for the data of 93 weeks in intervals of 1 week.

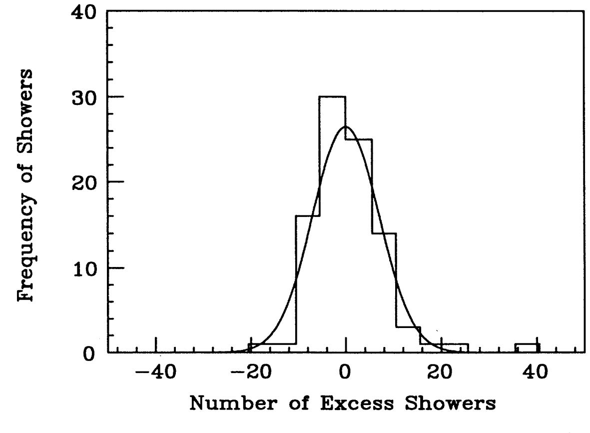

FIG. 2. A histogram of the frequency of excess number of showers in the source bin relative to the mean number in the background region. The Gaussian fit has the same area as the histogram and a σ equal to the rms deviation of the 93 data points.

the rest of the data are well described by the Gaussian. To accurately determine the background counts during this week we have used 32 bins in a band of 44°(α)×12°(δ) centered on Geminga but excluding the 4°×4° source bin. Appropriate correction is applied for the background counts to account for the declination effect on the background rate measured in this fashion. This correction factor is estimated to be 1.0117 using a method which has been described earlier. A total of 1394 showers were observed which increases to 1410 after applying the correction thus implying an expected mean background rate of (44.06 ± 1.17) week.$^{-1}$ A total of 83 showers were observed in the source bin during the 70th week. The Poisson probability of observing 83 showers for a mean of 44.06 is 1.1×10^{-7}. However, a more appropriate method is the one which allows for fluctuations in the background [14] as well. Using this method for a count of 1410 showers for 32 background bins and 83 on-source showers implies a Gaussian excess of 5.12σ which corresponds to a probability of 1.5×10^{-7}.

Monte Carlo simulations have to be performed to estimate the significance of observing an excess $\geq 5.12\sigma$ for intervals ranging anywhere from 1 to 93 weeks. This is necessary to correctly estimate the significance of the observed excess in view of the weekly search made. Consequently, we have carried out simulations to determine the probability of observing an equivalent $\geq 5.12\sigma$ excess in any combination of data of contiguous weeks. Using the mean weekly shower rate of 44.06, the number of showers expected in each of the 93 weeks are generated from the Poisson distribution which then forms one simulated "GRAPES I" observation. Using this data set, 93 1-week, 92 2-week, etc., and one 93-week combinations are formed by adding successive weeks of data. All of these (4371) combinations are then scanned to detect any occurrence of an excess equivalent to $\geq 5.12\sigma$ relative to the mean of the corresponding combination. A total of 958 out of 10^7 simulated "GRAPES I" observations showed an excess $\geq 5.12\sigma$. Therefore, the probability for observing an excess $\geq 5.12\sigma$ in any combination of data from one or more successive weeks out of 93 weeks is estimated as $(9.6 \pm 0.3) \times 10^{-5}$. These simulations demonstrate that the number of degrees of freedom are severely constrained when considering all the possible combinations within a single data set of 93 weeks. The effective number of degrees of freedom is only $9.58 \times 10^{-5}/1.53 \times 10^{-7} = 626$, although the total number of combinations is 4371.

The number of showers observed on each of the 7 days forming the 70th week are shown in Fig. 3. For comparison number of showers observed in the source bin during 7 days preceding the hot week (69th week) and for 7 days after the hot week (71st week) are also shown in Fig. 3. Also shown in the same figure as a dashed line are the daily mean number of showers from the 32 background bins for the 3-week interval centered on the hot week. Here it needs to be emphasized that there was no break in data taking for the entire interval of 3 weeks. The two arrows in Fig. 3 indicate the interval 1986 October 10–16, which is the duration of the 70th week. As can be clearly seen most of the excess seems to have occurred on 1986 October 10, 12, 14, and 16. On the remaining 3 days there seems to be no significant activity. No activity is seen for each of the 7 days preceding and following the hot (70th) week. This suggests that the UHE flux from Geminga may have been variable over time scales ≤24 h. In order to further investigate the variation of UHE flux at shorter time scales (<24 h) we have studied the distribution of "double" events [8,9]. A "double" is *a priori* defined as a shower in a given bin followed by a second shower in the same bin within 15 min. The interval of 15 min is chosen because of several observations of bursts in the UHE flux over similar time scales. This interval is also considered suitable for study of time clustering in GRAPES I data since the mean time separation between showers in any bin is ≥60 min. The probability of occurrence of a "double" cannot be evaluated directly by using the mean shower rate, because the shower rate varies significantly over the 326 min of observation during a day due to its dependence on the zenith angle. Therefore, we have carried out Monte Carlo simulations [8,9] to estimate the frequency of "doubles" using the observed shower rate and the observed variation of shower rate with zenith angle, simulating exactly the zenith angle sweep by the source region centered on the declination of Geminga.

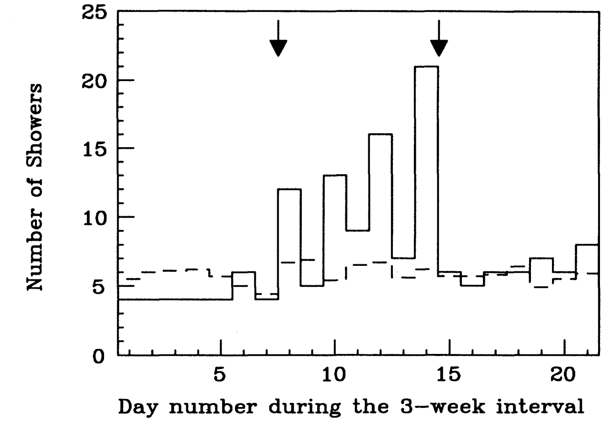

FIG. 3. Number of showers observed daily in the source bin during the 70th week and during the preceding and following 1 week are shown by the solid line. The dashed line indicates the mean number of showers from the 32 background bins. The arrows indicate the start and end of the 70th week.

The mean number of "doubles" observed in the source bin was 1.58 d^{-1}, to be compared with the simulated rates of (1.50 ± 0.06) d^{-1}. If, however, the data from the 70th week are excluded then the observed rate dropped to 1.54 d^{-1} in excellent agreement with the expected rate of (1.50 ± 0.06) d^{-1}. Here it is to be noted that the uncertainty on the simulated data reflects the rms spread for a single simulated "GRAPES I" observation. These simulations have been carried out by using a daily shower rate of 5.71 d^{-1}. Specifically for the 70th week a total of 40 "doubles" were observed while 38.5 ± 8.0 are expected from simulations if a shower rate of 11.9 d^{-1} (which was the actual rate observed during 70th week) is used in place of 5.71 d^{-1}. Consequently, the rate of "doubles" is entirely consistent with an expectation based on the observed rate of showers. The increase in the rate of "doubles" during the hot week is completely accounted for by the increased shower rate. We therefore do not find any evidence for short-term (~15 min) activity during the entire 93 weeks of observations on Geminga.

In view of the recent detection of 237-ms pulsations in x ray and ≥ 50 MeV γ rays we have searched for pulsations in the showers in the source bin during the 70th week. Shower arrival times were folded using the pulsar period [5] after transforming them from the observatory to the solar system barycenter. The resulting phasogram showed a flat distribution. Therefore, there is no evidence for 237-ms pulsations in the episodic flux.

To conclude we do not see any evidence for a steady flux of UHE radiation from Geminga. However, compelling statistical evidence has been presented to show that an enhanced flux of UHE radiation was observed over the interval 1986 October 10–16. The observed excess of 39 showers during this week corresponds to a mean flux of $(1.00\pm0.24)\times10^{-11}$ cm^{-2}s^{-1} at an energy $\geq 10^{14}$ eV. This implies a luminosity of 6×10^{32} erg s^{-1} assuming isotropic emission. This value of the luminosity, although episodic, is nearly 1.5% of the rotational energy-loss rate of the pulsar. There is no evidence for pulsations at the characteristic 237-ms period of the pulsar during the episode. The flux, although seemingly variable over the 7 days of the episode, showed no evidence for any activity at much shorter (~15 min) time scales through the study of "double" events.

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