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Investigation of EGRET gamma-ray sources By an Extensive Air Shower Experiment

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Ultra-high-energy ($E > 100$ TeV) Extensive Air Showers (EASs) have been monitored for a period of five years ($1997 - 2003$), using a small array of scintillator detectors in Tehran, Iran. The data have been analyzed to take in to account of the dependence of source counts on zenith angle. During a calendar year different sources come in the field of view of the detector at varying zenith angles. Because of varying thickness of the overlaying atmosphere, the shower count rate is extremely dependent on zenith angle which have been carefully analyzed over time. High energy gamma-ray sources from the EGRET third catalogue where observed and the data were analyzed using an excess method. Upper limits were obtained for 10 EGRET sources [1]. Next we investigated the EAS event rates for the 10 sources and obtained a flux for each of them with related parameters of our experiment and some simulations. Then we investigated the gamma-ray spectrum in the Ultra-high-energy range with comparison of these fluxes with reported fluxes of and EGRET.

1. Introduction

The EGRET instrument on-board $Compton\ Gamma\ Ray\ Observatory$ ($CGRO$) has detected both diffuse and discrete gamma-ray emission. The diffuse emission is both Galactic and extra galactic in nature. EGRET has detected about 271 high energy ($>$ 100 MeV) gamma-ray sources [2]. But the effective sensitivity of EGRET is from 100 MeV to 30 GeV.

Whether the EGRET sources emit at still higher energies, is an interesting question. Gamma-rays with energies of about 100 TeV and more, entering the earth atmosphere, produce Extensive Air Showers (EASs) [3] which could be observed by the detection of the secondary particles of the showers on the ground level [4].

We report the results of a small particle detector array located at the Sharif University of Technology in Tehran. This small array is a prototype for a larger EAS array to be built at an altitude of 2600 m ($\equiv$ 756 g cm^{-2}) at ALBORZ Observatory (AstrophysicaL oBservatory for cOsmic Radiation on alborZ) (http://sina.sharif.edu/~observatory/) near Tehran. The prototype was installed on the roof of the physics department of Sharif University of Technology in Tehran. In this work we present the observational results for 10 EGRET third catalogue sources. Then we investigated the effective area and effective time of observation of each source. Next we compared the obtained fluxes and spectral indices with the presented fluxes and spectral indices of the EGRET third catalogue sources.

2. Experimental arrangement

The array is constructed of 4 slab plastic scintillators ($100 \times 100 \times 2$ cm^3) arranged in a square; at $51^\circ\ 20^{'}$E and $35^\circ\ 43^{'}$N, elevation 1200 m (890 g cm^{-2}). If at least one particle hits a detector its PMT creates a signal with a pulse height which is related to the direction, number of particles, and location of the particle tracks in the scintillator. The output signals from the PMTs are amplified ($\times$10) and then transferred one by one to discriminators with threshold 20 mV (The separation point between the signal and background noise levels). Each discriminator has two outputs, one of them connected to a coincidence logic unit which acts as a trigger

condition. The trigger condition is satisfied when at least one charged particle passes through each of the four detectors within a time window of 150ns. The other discriminator output is connected to one of three Time to Amplitude Converters (TAC) which are set to a full scale of 200ns (maximum acceptable time difference between two scintillators). Then the outputs of the three TACs are fed into a multi-parameter Multi Channel Analyzer (MCA) via an Analogue to Digital Converter (ADC) unit. When all of the scintillators have coincidence pulses, the TACs are trigged by the logic unit and the 3 time lags between the output signals of PMTs (4,1), (2,3) and (2,1) are read out as parameters 1 to 3. So by this procedure an EAS event is logged.
Two different experimental configurations were used in the experimental set up. The first ($E1$) and the second ($E2$) experimental configurations were identical except for the size of the array. In $E1$ the size is 8.75 m $\times$ 8.75 m and in $E2$ the size is 11.30 m $\times$ 11.30 m.

3. Data analysis

The logged time lags between the scintillators and Greenwich Mean Time (GMT) of each EAS event were recorded as raw data. We synchronized our computer to GMT (http://www.timeanddate.com). Our electronic system has a recording capability of 18.2 times per second. If an EAS event occurs, its three time lags will be recorded and if it does not occur 'zero' will be recorded. Therefore the starting time of each experiment and the count of records gives us the GMT of each EAS event. Our detected EAS events are a mixture of cosmic-ray events and gamma-ray events. In $E1$ the total number of EAS events was 53,907 and the duration of the experiment was 501,460 seconds. So the mean event rate of the first experiment was 0.1075 events per second. The distribution of the time between successive events is in good agreement with an exponential function, indicating that the event sampling is completely random. In $E2$ the total number of events was 173,765 and the duration of the second experiment was 2,902,857 seconds, so its mean event rate was 0.05986 events per seconds.
We refined the data to separate out acceptable events. Events are acceptable if there is good coincidence between the four scintillator pulses. We omitted the events with zenith angles more than $60°$. Therefore after the separation we obtained smaller data sets of 46,334 and 120,331 for $E1$ and $E2$ respectively. Since we cannot determine the energy of the showers on an event by event basis, we estimate our lower energy threshold by comparing our event rate to a cosmic-ray integral spectrum [5]

$$J(E) = 2.78 \times 10^{-5} E^{-2.22} + 9.66 \times 10^{-6} E^{-1.62} - 1.94 \times 10^{-12} \quad 40 \leq E \leq 5000 \text{ TeV} \tag{1}$$

The obtained lower energy limits were 39 TeV in $E1$ and 54 TeV in $E2$. The calculated mean energies were 94 and 132 TeV in $E1$ and $E2$ respectively. Since the distribution of cosmic-ray events within the array in these energy ranges is homogeneous and isotropic, we used an excess method to find signatures of EGRET third catalogue gamma-ray sources. This method was used for both $E1$ and $E2$.
The complete analysis procedure is as follows [1]:

- The local coordinates: zenith and azimuth angles of each EAS event (z, φ) were calculated using a least-square method based on the logged time lags and coordinates of the scintillators. A zenith angle $60°$ is implemented to increase the significance.
- The distributions of the local angles of the EAS events were investigated to understand the general behavior of these events. We fitted these distributions with the two functions as follows [6]:

$$f(\phi) = A_\phi + B_\phi \cos(\phi - \varphi_1) + C_\phi \cos(2\phi - \varphi_2) \tag{2}$$

$$dN = A_z \sin z \cos^n z dz \tag{3}$$

which in the second equation $A_z = 95358$ and $n = 5.85$.

- Equatorial coordinates (RA,Dec) of each EAS event were calculated using its local coordinates, the GMT of the event and geographical latitude of the array. Then we calculated galactic coordinates (l,b) of each EAS event from its equatorial coordinates for epoch J2000. Fig. 1 shows the EAS events distribution in the galactic coordinates.
- We estimated the errors in (l,b) of the investigated EGRET sources from the error factors in the array. In this stage we obtained $\bar{r_e} = 4.35° \pm 0.82°$ as the mean angular error of our experiment.
- We investigated cosmic-ray EAS events by simulations based on a homogeneous distribution. This simulation incorporated all known parameters of the experiment.
- We investigated the statistical significance of random sources and of sources from the third EGRET catalogue using the method of Li & Ma [7] and derived the best-known location for the EGRET sources in the TeV range.

4. Calculation of effective area and time

Number of secondary particles in the growth profile of EAS events increases in atmosphere until the shower maximum and then decrease after it. About 100 TeV the shower maximum is about 500 g cm^{-2} and a fraction of these secondary particles arrive to the ground level particle detectors like our array.
For calculating the effective surface of each experiment we used Greisen lateral distribution function [3] and CORSIKA code [8] for simulation of the two types of the showers (94 TeV and 132 TeV) at Tehran level (1200 m$\equiv$ 890 g cm^{-2}). Of course from our data we obtained a distribution function for zenith angle of EAS events. The mean zenith angle is $26°$ in both $E1$ and $E2$. Also we calculated the $\bar{z}$ with the extracted weight function $dN/dz = \cos^n z \sin z dz$ from the zenith distribution and obtained the $26°$ too. So in the first approximation we used the effective thickness of the passed atmosphere as $890\mathrm{g\ cm}^{-2}/\cos(26°) = 980\mathrm{g\ cm}^{-2}$. In the thickness, the number of the secondary particles are $N_{E1} = 5265$ and $N_{E2} = 8571$, these two numbers obtained from 1000 simulation for each energy. So based on the Greisen function the mean effective surfaces of EAS events at Tehran level are $965\ \mathrm{m}^2$ and $2173\ \mathrm{m}^2$ respectively. With these results we could obtain the mean effective surface of the array in the upper level of the atmosphere (The surface that if a primary particle pass through it, the array could detect its EAS event) $718\ \mathrm{m}^2$ and $1751\ \mathrm{m}^2$ for $E1$ and $E2$ respectively.
for calculation of the effective time of observation of each source every 24 hours, we used spherical trigonometry and mean zenith angle of the related EAS events of each source. Therefore we obtained the time for each source with consideration of the weight function dN/dz. So mean effective time of observation of our array every 24 hours is $4h$,$40^{'}$. With this order for each source we obtained a flux (events/cm^2 s) for $E1$ and $E2$ which is shown in Table 1.

5. Results and Conclusions

These results have been compared with the EGRET results. For each source we have 3 fluxes and 3 energies from EGRET, $E1$ and $E2$, so we could extract a spectral index for each source. Our results show that our spectral indices are in agreement with 4 spectral indices of EGRET sources and 2 are near. But mean flux for all 10 sources are in an approximate agreement with EGRET (Figure 1). With more attention to the table 1 is seen that our results are in agreement with lower indices of EGRET sources.
In the calculation of effective surface of EAS events we used an approximation about the energy and number of secondary particles, and we used from Greisen lateral distribution. In the future with more accurate logged events in ALBORZ observatory we could calculate these results more accurately.

Name(3EG)	l	b	$\log E$	$\log F$	$\gamma \pm \Delta\gamma_{EGT}$	$\log F_{E1}$	$\log F_{E2}$	$\gamma \pm \Delta\gamma_{OUR}$	
0237+1635	156.46	-39.28	8.89	-6.19	1.85±0.12	-10.83	-11.10	2.00±0.07	$\surd$
0407+1710	175.63	-25.06	8.31	-6.49	2.93±0.37	-10.20	-11.02	1.77±0.12	
0426+1333	181.98	-23.82	8.63	-6.85	2.17±0.25	-10.67	-10.84	1.77±0.10	$\sim\surd$
0808+5114	167.51	32.66	8.36	-7.00	2.76±0.34	-10.40	-10.97	1.70±0.08	
1104+3809	179.97	65.04	9.17	-6.86	1.57±0.15	-10.46	-11.24	1.86±0.13	$\surd$
1308+8744	122.74	29.38	8.27	-6.62	2.17±0.66	-10.48	-11.06	1.77±0.08	$\surd$
1608+1055	23.51	41.05	8.40	-6.46	2.63±0.24	-10.46	-11.26	1.84±0.11	
1824+3441	62.49	20.14	8.73	-6.54	2.03±0.50	-10.16	-10.76	1.80±0.09	$\surd$
2036+1132	56.12	-17.18	8.34	-6.88	2.83±0.26	-10.50	-11.34	1.76±0.12	
2209+2401	81.83	-25.65	8.46	-6.84	2.48±0.50	-10.46	-10.86	1.74±0.05	$\sim\surd$

Table 1. Comparison of our spectral indices of the 10 sources with the spectral indices of them which is introduced by the 3rd EGRET catalogue, log E and log F are log E_{EGRET} and log F_{EGRET}.

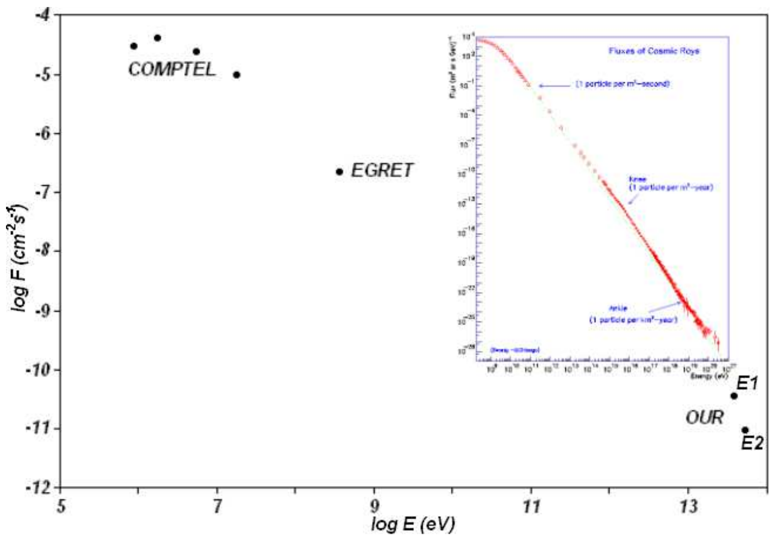

Figure 1. Comparison of the mean flux of $E1$ and $E2$ for the 10 sources with cosmic-ray spectrum.

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