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Search for 10 TeV Gamma-Ray Bursts with the Tibet Air Shower Array

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A search for gamma-ray bursts at the 10 TeV energy region was made using data of the Yangbajing air shower experiment in Tibet. About 4×10^8 events were analyzed to search for shower clusters appearing in a given time interval and a given small sky bin. An equal-zenith angle method is used to estimate the background. Some clusters show the excess to the background but with less significance as the evidence of gamma-ray bursts. The much-higher sensitivity of the Yangbajing Phase II array to the detection of the 10 TeV gamma-ray bursts is discussed.

Key words: cosmic rays, air showers, gamma-ray bursts.

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1. INTRODUCTION

Since the first discovery of gamma-ray bursts (GRBs) more than twenty years ago, their origin has been a problem still unresolved. In recent years the burst and transient source experiment (BATSE) on board the Compton GRO has been detecting GRBs at 20 keV to 2 MeV at a rate of about one event per day [1]. At higher energies (0.1-10 GeV), COMPTEL and EGRET [2] have also observed some

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GRBs with arrival time almost the same or somewhat delayed to BATSEs. To date, the observations show that GRBs are distributed isotropically in the sky and they are unlikely to have corresponding objects [3]. Some detailed measured spectra of GRBs show a harder power law distribution with a differential index between 2.0 and 2.6, and has a flux value of about 1 photon per cm^2 per MeV per second at 1 MeV [3], implying that if the spectra of GRBs could extend to higher energy region, e.g., 1-100 TeV, it should be observable with highly sensitive ground-based apparatus.

The detection of the 1-100 TeV GRBs is very interesting and important. Since these gamma-rays are strongly attenuated by the photon-photon interactions with the infrared and microwave photon fields when traveling cosmological distances, the positive detection of such GRBs will be a strong support to the origin of GRBs in the Galaxy. If, on the other hand, GRBs are not detected information will be on the production mechanism of GRBs or distance of GRB sources. In addition, the difference of the arrival time between higher energy GRBs and lower energy ones will provide information on the gamma-ray production mechanism at a source.

There have been several works devoted to the search for GRBs at the 1-100 TeV energy region using ground-based cosmic ray observational apparatuses [4]. To date, however, all the reported results are not positive. It is obvious that a GRB search at about 1 TeV is strongly limited by the narrow aperture and short observation time of the atmospheric Cherenkov telescopes. Though the extensive air shower experiments have advantages in these two aspects, its main demerit is that it cannot identify gamma-ray-induced showers from proton-induced ones, and the latter makes a very heavy background. The increase of the signal-to-noise rate relies mainly on the high counting rate. However, many GRB searches at the 100 TeV region are limited by a low counting rate of high-energy showers.

The Tibet extensive air shower array has the lowest observation threshold (about 10 TeV) and the highest counting rate [5] among the existing arrays in the world. Its counting rate for showers had been 20-30 Hz in the past few years, and reached recently to about 250 Hz. It is important to explore the 10 TeV GRB phenomena using the Tibet array data.

2. YANGBAJING EXPERIMENT

The Tibet air shower array is located in Yangbajing at an altitude of 4300 m a.s.l. (90.53°E and 30.11°N), corresponding to an atmospheric depth of 606 g/cm^2. The array whose data are used in this work is a part of the whole array that is now running, and is called the Phase I array. It consists of 49 scintillation detectors of 0.5 m^2 each, which are distributed on a grid of 15 m spacing. Among them, 45 detectors (FT detectors) are equipped with a fast response photomultiplier (PMT) to measure the arrival direction of air showers with a good accuracy. Data used in this work were taken from June 1990 to September 1992. During this period the system has operated at a trigger rate of about 20 Hz under any 4-fold coincidence in the FT detectors and recorded about 9×10^8 shower events. The effective running time for this period is 598.6 days.

A database was made by imposing the following event selection criteria: (1) Each of any four FT detectors produces a signal corresponding to more than 1.25 particles traversed. (2) Among the four detectors recording the highest particle densities, two or more are in the innermost 5×5 detectors. (3) The mean lateral spread of each shower is less than 25 meters. We call the three satisfactory conditions above the "contained" events, and in total about 4×10^8 contained events are obtained.

The Monte Carlo simulations were done to examine the performance of the array [6]. It is found that for contained events: (1) The mode energy of primary particles detected by this array is about 7 TeV for protons and 8 TeV for γ-rays. (2) Detection efficiencies of the contained events at 10 TeV are about 26% for proton-induced showers and 42% for gamma-induced ones, respectively. (3) Furthermore, the observation of the moon shadow, with a sufficient significance, has confirmed well the angular resolution of the array being better than 1° for all the contained events [6].

3. METHOD

There will be two possible approaches to search for 10 TeV GRBs. One is to examine shower data for finding evidence of high-energy emissions coincident, in arrival time and directions, with the GRBs detected by BATSE. Since at a given time the sky regions observed by BATSE and by ground-based detectors are often different and also that the sensitive fields of view of these two kinds of detectors are different, it is estimated that only about one-fourth of the BATSE GRBs should be examined.

Another approach is based on the following assumption: Observation of GRBs at TeV energies does not always relate to that at the MeV-GeV energy region. Hence TeV energy GRBs can be searched for independently. Since these two kinds of experiments survey different sky regions in half the observation time this approach is indispensable.

This work mainly follows the second approach, focusing on the search of shower clusters which appear in a small sky region as well as a short-time interval with sufficient significances. The procedure of searching for such shower clusters is:

(1) Every contained shower is examined as a starting shower of a possible shower cluster, and the possibility of the shower being a starting event of a GRB is evaluated.

(2) The number of following showers is then counted within a cone with the axis being the direction of the first shower and the radius of 1.5° (corresponding to the solid angle $\Delta\Omega = 2.15 \times 10^{-3}$ sr) and in the time interval $\Delta t = 17.28$ sec (0.002 day) starting from the arrival time of the first shower, and all showers satisfying the above conditions are defined as a shower cluster. The size of the cone with the radius 1.5° is known to include about 70% of signals coming from a source direction, since the angular resolution of the array is about 1°. A time interval of 17.28 sec is conveniently set because a typical duration time of the BATSE GRBs is about 10 sec. Obviously this value may be changed.

(3) The number of showers in a cluster, m (we call it the multiplicity of the cluster hereafter) will take one of the values: 1, 2, 3, ···. We may then obtain the multiplicity distribution of shower clusters and estimate the significance of those clusters with higher multiplicities.

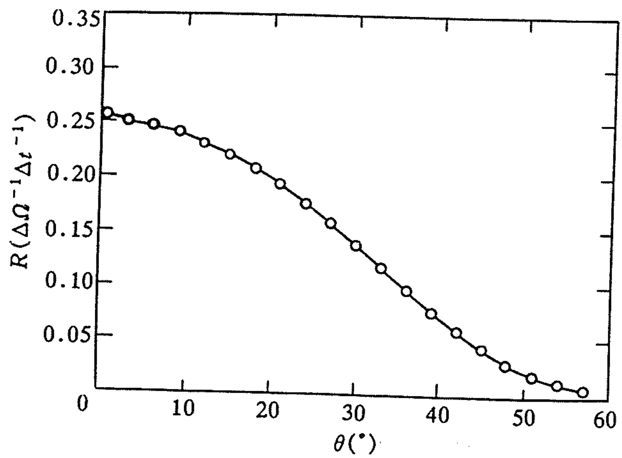

Fig. 1
The average number of showers in a sky bin (defined in the text) versus the zenith angle.

4. EQUAL-ZENITH ANGLE ESTIMATION OF THE BACKGROUND

In order to search for the possibly existing GRB events, one needs to estimate the background. It is well known that the background event rate strongly depends on the zenith angles of the arriving showers due to different atmospheric thickness caused by showers having different incident angles. The analysis of the data shows that, within $\Delta\Omega$ and Δt mentioned above, the average number of showers at a zenith angle $\theta = 0°$ is 0.25; this value decreases with θ; it is 0.01 at $\theta = 55°$ (see Fig. 1). One has to consider this factor when estimating the significance of a shower cluster. We adopted the "equal-zenith-angle method," i.e., for a shower cluster observed in a certain sky region, any sky region with the zenith angle same as this cluster is taken as the background region. A non-uniformity of the shower trigger rate in the azimuth angle distribution, mainly due to the square shape of the Yangbajing array, is seen to be so small (less than 2-3%) that it may be disregarded. Also, it is observed that in a certain sky region with a given zenith angle the average rate of shower events changes somewhat over time, mostly due to the atmospheric temperature and pressure effects. The maximum amplitude of this change seen in the data is about $\pm 11\%$. To minimize these effects we take 10 to 20 days as a time interval, and evaluate the average background rate in every time period.

Now the problem: according to the procedure of searching for shower clusters as introduced in last section (for convenience this procedure is called Method A hereafter), what distribution does the multiplicity, m, of the background clusters follow?

Let us first consider another procedure, and call it Method B. To search for shower clusters for a certain zenith angle θ_0 and with a small sky region $\Delta\Omega$, the starting time t_0 is taken randomly and the time interval Δt is taken one by one. It is obvious that in this case the multiplicity n of a shower cluster takes values 0, 1, 2, ···, and obeys a Poisson distribution:

$$f(n) = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}, \qquad (n = 0, 1, 2, \cdots), \tag{1}$$

where the expectation $\langle n \rangle$ depends on the zenith angle θ_0. However, in Method A, we always fix the starting point of a time interval at the arrival time of a shower. In this case it is expected that the multiplicity, m, of a shower cluster will no longer follow a Poissonian. Nevertheless, if ignoring the first shower of a shower cluster one may expect that the random variable $m - 1$, which takes values of 0, 1, 2, ···, will obey a Poisson distribution. This is because that for a series of randomly arriving showers, the time difference between two neighboring showers is known to follow an exponential distribution, and an exponential distribution does not depend on the choice of the starting point of the random variable. Therefore, the variable $m - 1$ obtained by Method A should follow the same distribution as the variable n obtained by Method B, i.e.,

$$f(m-1) = \frac{\langle n \rangle^{m-1}}{(m-1)!} e^{-\langle n \rangle}, \quad (m = 1, 2, 3, \cdots), \tag{2}$$

Obviously, taking $n = m - 1$, Eq.(2) is identical to Eq.(1).

For a further confirmation, an event sample with a fully random arrival time is produced by a Monte Carlo procedure, and then event clusters are searched by Methods A and B, separately. 50 million events were created. The distributions of $m - 1$ obtained by Method A and n by Method B are obtained and a χ^2 test is made using the same Poissonian. The χ^2 values and their degrees of freedom are listed in Table 1 which show that $m - 1$ and n follow a same Poisson distribution with similar significance. Thus, in the following, we will use Eq.(2) to calculate the background probability of clusters obtained by Method A.

Table 1
χ-square test of Monte Carlo data using a Poisson distribution.

$\langle n \rangle$	(A)		(B)	
	Degrees of freedom	χ^2	Degrees of freedom	χ^2
0.30	5	2.397	6	2.752
0.20	4	2.316	5	1.636
0.10	3	1.412	4	0.611
0.05	3	0.299	3	1.324

(A) time interval always started from a shower; (B) time interval started randomly and one following another.

5. RESULTS

We analyzed 3.993×10^8 contained air shower events with zenith angles less than 60° that were taken from 18 June 1990 to 29 September 1992. First, the distribution of the multiplicity, m, of shower clusters in a given zenith angle interval and in $\Delta\Omega$ and Δt was made. For all the zenith angle bins the $m - 1$ distributions are seen to follow essentially a Poissonian of the corresponding background. Some deviations from the background in some time intervals and some zenith angle bins are seen in the larger multiplicity region.

For a further analysis we selected some outstanding shower clusters by the following conditions:

$$\begin{aligned} &m \geq 7 \text{ for all } \theta; \\ &m = 6 \text{ for } \theta > 31°; \\ &m = 5 \text{ for } \theta > 43.5°; \\ &m = 4 \text{ for } \theta > 53°. \end{aligned} \tag{3}$$

In the data set analyzed, one cluster with $m = 8$, 28 clusters with $m = 7$, 19 with $m = 6$, and 3 with $m = 5$ were observed.

The cluster having the largest multiplicity ($m = 8$) in $\Delta\Omega$ and Δt appeared at $MJD = 48198.15993196643$ with the zenith angle 12.7° ($r.a. = 185.87°$, $dec = 18.02°$). For the observation period of this cluster at this zenith angle, the average number of showers within $\Delta\Omega$ and Δt is obtained to be $\langle n \rangle = 0.22$. The background probability is then calculated to be 3.95×10^{-9} using a Poissonian with $n = 7$. In Fig. 2 the circles are the m distribution of 2040144 shower clusters recorded between $\theta = 10.5°$ and 13.5° within about 60 days from September to November, 1990, and the line is the distribution of the background. It is seen that the event with $m = 8$ significantly exceeds the background.

In the whole data set analyzed the fraction of the events appeared in a small sky region with the zenith angle bin $\theta = 10.5°$ and 13.5° is 1.8×10^{-3} and the number of trials should be 7.35×10^5. Taking this as the number of trials, the probability of the cluster as an accident event is 2.90×10^{-3}, about 3 standard deviations of a Gaussian probability.

For 28 clusters with $m = 7$, their $\langle n \rangle$ are different due to different zenith angles. Calculating the probability p_i and the number of trials N_i of the cluster i ($i = 1, 2, \cdots, 28$) and taking N_i as the weight the average probability of this group of clusters as an accident event is estimated as

$$P_{bk} = \sum_{i=1}^{28} P_i N_i \Big/ \sum_{i=1}^{28} N_i = 6.93 \times 10^{-2}. \tag{4}$$

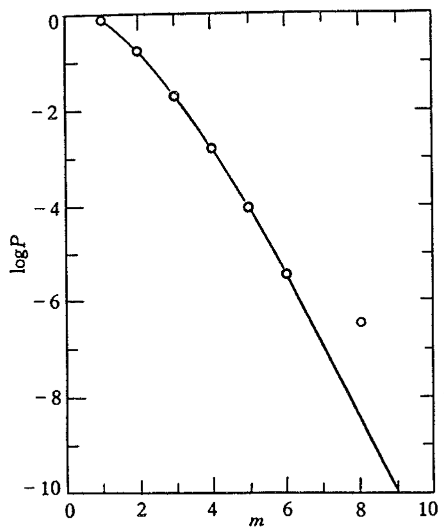

Fig. 2

The circles show the m distribution of shower cluster recorded between $\theta = 10.5°$ and $13.5°$ within about 60 days from September to November, 1990, and the line is the distribution of the background.

Using the same method to calculate the average probabilities of 19 clusters of $m = 6$ and 3 clusters of $m = 5$ the resultant values are 5.68×10^{-2} and 7.74×10^{-2}, respectively.

The above analysis tells us that in the data set of 10 TeV showers recorded by the Yangbajing experiment Phase I, some shower clusters that arrived in $\Delta\Omega$ and Δt with higher multiplicity show probabilities higher than that of the background. However, all their significances are within 2 to 3 standard deviations, and are therefore not high enough to serve as evidences of 10 TeV GRBs.

6. DISCUSSIONS

Taking the standard normally used in the gamma-ray astronomy, a source candidate with a significance of 3-5 standard deviations could only be treated as a marginal one, and could not be confirmed as a source. For convenience we assume that more than six standard deviations is a necessary condition to confirm a source. For the zenith angle region the $m = 8$ cluster appeared, if a cluster with $m = 12$ would be observed, the probability of the background will be 1.17×10^{-15}. In this case, timing the number of trials, the accidental probability is still lower than 9×10^{-10}, already having a significance higher than 6 standard deviations. So, we may set whether an array is able to detect the shower cluster with a probability of 10^{-15} in $\Delta\Omega$ and Δt as the criterion of its sensitivity to detect 10 TeV GRBs. According to this criterion the sensitivity of the Yangbajing Phase I array is a little lower.

The main barrier of the detection of 10 TeV GRBs is the large background formed by very large amount of proton showers which could not be identified. If there exist 10 TeV GRBs appearing as clusters with $m = 4$, 5, and 6 in the Yangbajing Phase I array, they will be completely covered by background events. However, as could be seen in the above analysis, because GRB is a phenomenon of many gamma-rays arrived at a short-time interval, the enlargement of the detection area is very important to increase the ratio of signal to noise and the detection sensitivity.

The Yangbajing Phase II array has been collecting data with an effective area increased by a factor of 8. As an example we consider the cluster with $m = 4$ observed in the Phase I array. There

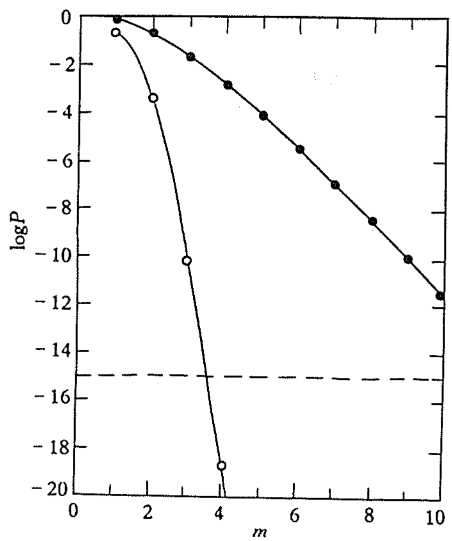

Fig. 3
The probability of the background clusters of the Phase I array, the sensitivity of the array to detect 10 TeV GRBs, and the possibility of the separation of 10 TeV GRBs from the backgrounds in the Phase II array (see the text).

are about 8 million of such clusters in the data set analyzed. Assuming that there is only one cluster with $m = 4$ which is a true GRB, it will appear as a cluster of $m \sim 25$ in the Phase II array. In this case the average event rate of the background is $\langle n \rangle = 1.76$, and the probability of an $m = 25$ cluster is 2.2×10^{-19}. On the other hand, those background clusters with $m = 4$ in the Phase I array will become ones with $m \sim 7$ in the Phase II array. Therefore the cluster with $m = 25$ has a significance high enough to be recognized as a GRB.

In Fig. 3, the background probabilities of clusters with multiplicity m in the Phase I array are shown as dots, while the background probabilities of those GRBs, if any, with m in the Phase I array are shown as circles when they appear in the Phase II array. In this figure, the probabilities of $m =$ 1, 2, 3, and 4 are calculated by using $m = 1, 9, 17$, and 25, and $\langle n \rangle = 1.76$ as the case of the Phase II. The dotted line in Fig. 3 shows the sensitivity of an apparatus detecting 10 TeV GRBs. It is seen from the figure that the Phase II array will be sensitive enough to detect all GRBs, if any, appearing as clusters with $m \geq 4$ in the Phase I array.

In addition to this work, the results of the search for 10 TeV GRBs coincident with BATSE GRBs were published elsewhere [7].

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