Search for TeV gamma-rays from evaporating primordial black holes [1]

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(HEGRA[3])

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Abstract

Data taken with the HEGRA extensive air shower array are used to search for satellite independent TeV γ-ray bursts. In this study we focus on a search for bursts lasting only a few seconds (1 - 10 sec) and consider the implications for the phenomenon of evaporating PBH ("primordial black holes").

1 Introduction

Primordial density fluctuations may have led to the creation of black holes of arbitarily small masses in the early universe. Due to Hawking radiation these primordial black holes are supposed to evaporate by emitting particles with Compton wavelength less than their Schwarzschild radius. The theory predicts that in the final stage (lasting only a few seconds) a PBH should explode and radiate particles with energies well above 1 TeV. Following this aspect we have carried out a TeV burst search with the HEGRA ("High Energy Gamma Ray Astronomy") extensive air shower array [1] on the Canary Island La Palma (Spain).

2 Burst search and γ/hadron-separation

A crucial aspect in TeV-γ-astronomy is to develop methods for reducing the dominating hadron background. Given the γ-efficiency $\epsilon_\gamma(\alpha)$ and the hadron efficiency $\epsilon_\mathrm{h}(\alpha)$ for a given method, where α is a continous parameter to adjust the separation properties, one has to determine $\alpha^{\mathrm{PS}}_{\mathrm{max}}$ which maximizes the ratio $\epsilon_\gamma/\sqrt{\epsilon_\mathrm{h}}$ in order to achieve the highest significance for a steady point source detection. In the case of the burst search the situation is different and determing the optimal cut value $\alpha^{\mathrm{BS}}_{\mathrm{max}}$ is more complicated.

We argue that an excess at small $\mathrm{P_{obs}}$, meaning the Poisson probability to observe a given number of events in a search bin as described below, would indicate a TeV burst, where small means $\mathrm{P_{obs}} \ll \mathrm{N_{tot}^{-1}}$, $\mathrm{N_{tot}}$ is the total number of analysed events. Hence, the zero hypothesis of detecting no burst can be written as

$$\frac{1}{\mathrm{N_{tot}}} = \mathrm{P_{obs}} = 1 - \sum_{\mathrm{k=0}}^{\tilde{\mathrm{n}}_{\mathrm{max}}} \frac{\lambda_{\mathrm{exp}}^{\mathrm{k}}}{\mathrm{k!}} \mathrm{e}^{-\lambda_{\mathrm{exp}}} \quad (1)$$

[1] This work was supported by the BMBF, FRG, under contract 05 2WT164

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where $\tilde{n}_{max}$ is the maximum number of observed and λ_{exp} the expected number of events in a bin as defined above. The last term for a hadron reduced data set (where λ_{exp} has to be substituted by $\lambda_{exp}\epsilon_h$ and N_{tot} by $N_{tot}\epsilon_h$) is given by

$$\sum_{k=0}^{n_{max}} \frac{(\lambda_{exp}\epsilon_h)^k}{k!} = e^{\lambda_{exp}\epsilon_h}\left(1 - \frac{1}{\epsilon_h N_{tot}}\right) \tag{2}$$

Obviously $\tilde{n}_{max}$ and n_{max} in equation (1) and (2) are integer values. However, it is possible to define both $\tilde{n}_{max}$ and n_{max} as real numbers by using their expectation values, calculated by means of MC from a large number of repetions of the corresponding simulation. The analytical way of computing $\langle n_{max}\rangle$ uses the fact that there always exists an integer value n' so that

$$\sum_{k=0}^{n'} \frac{(\lambda_{exp}\epsilon_h)^k}{k!} \leq e^{\lambda_{exp}\epsilon_h}\left(1 - \frac{1}{\epsilon_h N_{tot}}\right) < \sum_{k=0}^{n'+1} \frac{(\lambda_{exp}\epsilon_h)^k}{k!} \tag{3}$$

holds while $n' \leq \langle n_{max}\rangle < n' + 1$. In order to determine $\langle n_{max}\rangle$ we define:

$$D(n) \equiv \log\left(e^{\lambda_{exp}\epsilon_h} - \sum_{k=0}^{n} \frac{(\lambda_{exp}\epsilon_h)^k}{k!}\right) = \log\left(\sum_{k=n+1}^{\infty} \frac{(\lambda_{exp}\epsilon_h)^k}{k!}\right) \tag{4}$$

$D(n)$ is a decreasing function of the integer n and can be locally approximated by a linear fit. Using this property one can estimate the continous parameter

$$\langle n_{max}\rangle = n' + \frac{D(n') - \log(e^{\lambda_{exp}\epsilon_h}/(N_{tot}\epsilon_h))}{D(n') - D(n'+1)} \tag{5}$$

where we have used n' from equation (3). The calculated $\langle n_{max}\rangle$ is the expectation value for an analysis of N_{tot} air showers with a hadron efficiency ϵ_h. To define a burst sensitivity S_{burst} it is neccessary to anticipate equation (6) which directly leads to the volume probed by the detector. As described below the maximum distance of a detectable evaporating PBH is proportional to $(\epsilon_\gamma/(\langle n_{max}\rangle + 1))^{1/2}$. Comparing this with the case of the full data set and taking into account that one wants to maximize the probed volume, the burst sensitivity can be defined as $S_{burst} \equiv (\epsilon_\gamma(\langle\tilde{n}_{max}\rangle + 1)/(\langle n_{max}\rangle + 1))^{3/2}$, where $\langle\tilde{n}_{max}\rangle$ is taken from the full data set. It is now straightforward to adjust the separation parameter α so that the burst sensitivity is optimized. We have used a γ/hadron-separation based on a neural net analysis of the HEGRA Geigertowers [2]. So far this method has been applied to roughly 30% of the full data set used in this study. Figure 1 indicates that the optimal cut value α, set to 0.55 in the analysis, depends slightly on N_{tot} and that the burst sensitivity is a decreasing function of N_{tot}. That means that due to a decreasing ratio of $\langle\tilde{n}_{max}\rangle/\langle n_{max}\rangle$ a γ/hadron-separation becomes less effective for an increasing number of analysed events.

3 Method of search

Several techniques have been developed to search for burst phenomena in air shower data. A very efficient way to maximize the detection sensitivity for short bursts is

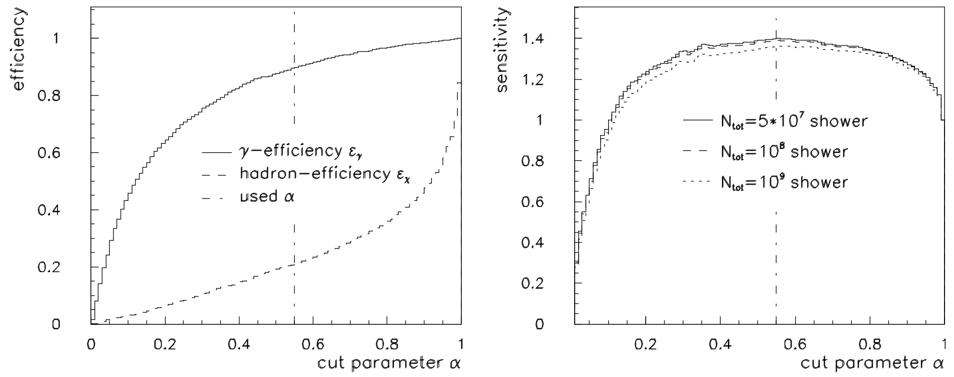

Figure 1: The left figure shows the γ- and hadron-efficiency as a function of the cut parameter α (taken from [3]). The right figure describes the behaviour of the burst sensitivity for different N_{tot}. Accounting for experimental uncerntainties an optimal (and stable) cut value is 0.55.

to let every single air shower define its own temporal and angular bin, which is then checked to contain additional "burst" events. Employing this method we present the analysis of 6×10^7 air showers taken with the HEGRA array between September 1994 and December 1994. The technique can be summarized as follows:

1. For each run containing approximately 500 000 events a background skymap of the full and a hadron reduced data set is computed in the horizontal coordinate system.

2. Each reconstructed event defines the beginning of a temporal bin (1,2,5 and 10 sec) and the position of a circular bin. The optimal bin radius which maximizes the significance for a point source is $r = 1.58 \times \sigma_{res}$. In the case with no a priori source location [3], using single events to determine the center of the search bin, the optimal bin radius is $\sqrt{2}$ times larger ($\simeq 2°$ for the SM ("scintillator matrix") and $\simeq 1.2°$ for AIROBICC [4]).

3. After determing the expected number of additional events in such a bin (typically around 0.04 for the SM and a temporal bin of 1sec) the Poisson probability P_{obs} is calculated that the detected number is consistent with the background. An excess of unlikely observations would therefore indicate a TeV burst.

4 Results

We have neither found a significant excess at small P_{obs} in the full nor in the reduced data set for any of the 4 time intervalls (fig. 2). The smallest P_{obs} is 1.8×10^{-7} for the full and 4×10^{-6} for the reduced data set corresponding to 4 and 2 additional events, respectively (in the following paragraph values for the hadron reduced data set are stated in brackets - keep in mind that it contains only 30% of the full data set). This is

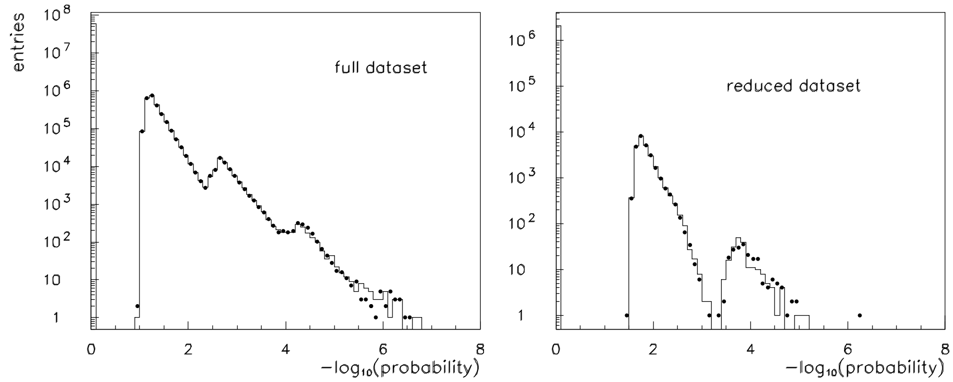

Figure 2: In the left (right) figure the probability distribution for the full (hadron reduced) data set is shown. While the solid line corresponds to the experimental data the dots represent the MC expectation.

consistent with the hypothesis of no burst. Given a differential spectrum of a special burst mechanism it is straightforward to convert this result into a corresponding upper limit. This was done for the evaporation of PBH [3] with a differential spectrum of the last 1sec-evaporation phase. Convolving dN/dE with the effective area A(E,θ) of the array yields the expected number of events seen by HEGRA

$$\mu(\mathrm{r},\theta) = \frac{\beta}{4\pi \mathrm{r}^2} \int_{30\mathrm{TeV}}^{\infty} \epsilon_\gamma \frac{\mathrm{dN}}{\mathrm{dE}} \mathrm{A}(\mathrm{E},\theta)\mathrm{dE} \tag{6}$$

where β is the fraction of PBH-photons falling into the optimal search bin. Since not more than 4(2) additional events in a bin were observed, setting $\mu(\mathrm{E},\theta)$ to 5(3) and reversing equation (6), gives a measure of how distant a PBH can evaporate and still be detectable under a certain zenith angle. From this maximum distance the volume can be determined to $3.9(7.2) \times 10^{-6}\mathrm{pc}^3$. Combining the probed volume and the overall time of the data set produces an upper limit of $\dot\rho_{\mathrm{PBH}} = 4.7(8.4) \times 10^6 \mathrm{y}^{-1}\mathrm{pc}^{-1}$ at 99% C.L. The statistical independence of the data set (1989-1993) used by the CYGNUS group for computing $\dot\rho_{\mathrm{PBH}}$ (which had to be corrected by introducing the factor β) leads to a common upper limit of $\dot\rho_{\mathrm{PBH}} = 8.9(9.7) \times 10^5 \mathrm{y}^{-1}\mathrm{pc}^{-3}$.

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