Search for very short gamma-ray bursts at the Andyrchy EAS array on millisecond timescale

A.N. GAPONENKO, V.B. PETKOV, V.YU. GRISHKAN, I.M. DZAPAROVA, A.F. YANIN, A.N. KURENYA, E.A. GORBACHEVA.

Abstract: We have developed a novel data acquisition system for the Andyrchy EAS array. This system allows to measure the count rate on millisecond timescales and thus to explore very short bursts of the cosmic ray intensity such as gamma ray bursts, evaporating primordial black holes etc. We used the “single particle” technique. New upper limits for the number density of evaporating black holes in a local region of space with a characteristic size of $\sim 10^{-3}$ pc for various evaporation models have been obtained.

Keywords: cosmic ray, gamma-ray burst, primordial black hole.

1 Introduction

Emission of gamma ray bursts (GRBs) and evaporating primordial black holes (PBHs) with photon energy more than a few GeV can be registered by ground based air shower arrays operating in the “single particle” operation mode [1]. In such experiments the total count rate of all detectors of the array is measured. With single particle technique, the energy and arrival direction of the primary gamma-rays cannot be measured. The GRBs and evaporating PBHs can be detected only, if the secondary particles generated by the primary gamma-rays give a statistical significant excess of event over all-sky background due to cosmic rays. In this case the study of the temporal behaviour of the high energy emission can be possible. A search for high energy GRBs and evaporating PBHs has been performed by “Andyrchy” air shower array [2][3].

2 Experiment

The Andyrchy EAS array is located at altitude 2060 m above sea level (the atmospheric depth is 800 g/cm$^2$) and consists of 37 scintillation detectors [4]. A plastic scintillator 1 m² in area and 5 cm in thickness is viewed by one photomultiplier tube. The most probable energy release in a detector from single particles is $\sim 10$ MeV , the detector triggering threshold is 5 MeV. The new DAQ of the array allows us to measure a flux of the single cosmic ray component every millisecond (fig. 2).

Signal from each detector is going to the “input unit” and then split in the “control unit”. The output signals from the “control unit” are then going to two DAQ subsystems: the EAS registration subsystem and the counting rate measurements subsystem (fig. 2). The Fastwel UNIO 6-5 device allows us to measure the count rate of each detector individually. External clock source has been used (with ISA clock device) with millisecond time accuracy. The continuous flow of information is read in a timely manner. For this the real-time operating system linux (with PREEMPT_RT patch) is used. As a result we have a count rate in millisecond for the each detector and total array (fig. 2). Every 15 minutes the data are written to the file server.

3 Evaporating PBH

Primordial black holes can be formed in the early Universe through the gravitational collapse of primordial cosmological density fluctuations those that give rise to the observed structure of the Universe during its subsequent evolution. For an appreciable number of PBHs to be formed, it is important that significant density fluctuations on small mass scales existed in the early Universe. The curvature fluctuations and the related density fluctuations are currently believed to result from an inflationary expansion of the Universe. There exist quite a few models (see, e.g., [5]) in which a fluctuation spectrum that ensures the formation of a considerable number of PBHs is predicted.

Theoretical predictions of the PBH formation probability depend strongly on the theory of gravitation and the model of gravitational collapse. The evaporation of black holes (BHs) [6] on which many methods of their experimental search are based has not been completely studied either. Therefore, experimental detection of PBHs can become a unique test for the general theory of relativity, cosmology, and quantum gravity [7].

The distribution of PBHs in space is important for their direct search. Because of the local increase in the density of PBHs in our Galaxy [8], the constraints on their number density imposed by a direct search can be more stringent than those imposed by diffuse extragalactic gamma-ray background measurements, which are sensitive only to the mean PBH density in the Universe.

In the model of MacGibbon and Webber (MW90) [9], it is assumed that the emitted particles (quarks and leptons) do not interact with one another and that all of the emitted quarks propagate freely and decay independently. The photon spectrum is formed through the fragmentation of quarks and the decay of unstable hadrons, causing this spectrum to be non thermal. In the chromospheric models of Heckler (H97) [10] and Daghigh and Kapusta (DK02) [11], the interacting emitted particles form a (nearly) thermal chromosphere, which leads to a steeper photon spectrum at high energies as a result of energy fragmentation.

In this paper the three models mentioned above were analyzed. The corresponding photon spectra were taken from [12].
4 Results

Let a PBH be located at distance \( r \) from the array and observed by this array in the direction specified by the zenith angle \( \theta \). Then, the mean number of \( \gamma \)-ray photons detected by the array is equal to

\[
\bar{n}(\theta, r) = \frac{S(\theta)}{4\pi r^2} N(\Delta t, \theta),
\]

where \( N(\Delta t, \theta) \) is the total number of the gamma-ray photons emitter by the PBH that can be detected by the array:

\[
N(\Delta t, \theta) = \int_0^\infty dE_\gamma P(E_\gamma, \theta) \frac{dN_{\gamma}}{dE_\gamma}(\Delta t).
\]

Here, \( (dN_{\gamma}/dE_\gamma)(\Delta t) \) is the spectrum of gamma-ray photons emitted by the PBH during the time interval \( \Delta t=1 \) ms until the end of the PBH evaporation and \( S(\theta) \) is the area of the array. The detection probabilities \( P(E_\gamma, \theta) \) of the secondary particles produced by primary gamma-ray photons with energy \( E_\gamma \) incident on infinite-area arrays at zenith angle \( \theta \) were determined by simulating electromagnetic cascades in the atmosphere and on the array detectors. The CORSIKA code [13] was used to simulate electromagnetic cascades in the atmosphere. The number of bursts detection during the entire observation time \( T \) can be written as

\[
N = \rho_{\text{pbh}} T V_{\text{eff}}
\]

where

\[
V_{\text{eff}} = \int_0^\infty d\Omega \int_0^\infty drr^2 F(n, \bar{n}(\theta, r))
\]

is the effective volume of the space surveyed by the array, \( \rho_{\text{pbh}} \) is the number density of the evaporation PBHs and \( F(n, \bar{n}) = e^{-\bar{n}\bar{n}}/n! \) is the Poisson probability of the detection on \( n \) events for the mean value \( \bar{n} \).

If the evaporating PBHs are distributed uniformly in the local region of the Galaxy, then the upper limit \( \rho_{\text{lim}} \) on the number density of evaporating PBHs at the 99% confidence level can be calculated from the formula

\[
\rho_{\text{lim}} = \frac{4.6 \cdot 10^{-8}}{V_{\text{eff}} \cdot T}.
\]

Preliminary results obtained during the observation period \( T = 70.75 \) hours are shown in table 1.

<table>
<thead>
<tr>
<th>models</th>
<th>( V_{\text{eff}} \cdot \text{pc}^3 )</th>
<th>( \rho_{\text{lim}} \cdot \text{pc}^{-3} \cdot \text{year}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW90</td>
<td>1.84 \cdot 10^{-9}</td>
<td>3.1 \cdot 10^{10}</td>
</tr>
<tr>
<td>H97</td>
<td>7.23 \cdot 10^{-9}</td>
<td>7.87 \cdot 10^{10}</td>
</tr>
<tr>
<td>DK02</td>
<td>1.78 \cdot 10^{-8}</td>
<td>3.2 \cdot 10^{10}</td>
</tr>
</tbody>
</table>

Table 1: Effective volume \( V_{\text{eff}} \) we can observe and upper limit \( \rho_{\text{lim}} \) on the number density of evaporating PBHs.
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Fig. 2: Counting rate per millisecond. $a$ - individual detector, $b$ - all array. full line - experiment, dashed line - calculate Poisson distribution.

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References