Searching for Very-High-Energy Gamma-Ray Bursts from Evaporating Primordial Black Holes

V. B. Petkov¹, E. V. Bugaev¹, P. A. Klimai¹*, M. V. Andreev², V. I. Volchenko¹, G. V. Volchenko¹, A. N. Gaponenko¹, Zh. Sh. Guliev¹, I. M. Dzaparova¹, D. V. Smirnov¹, A. V. Sergeev², A. B. Chernyaev¹, and A. F. Yanin¹

¹Institute for Nuclear Research, Russian Academy of Sciences, ul. 60-letiya Oktyabrya 7a, Moscow, 117312 Russia
²International Center for Astronomical and Medicoecological Research, National Academy of Sciences of Ukraine, Ukraine

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Abstract—Temporal and energy characteristics of the very-high-energy gamma-ray bursts from evaporating primordial black holes have been calculated by assuming that the photospheric and chromospheric effects are negligible. The technique of searching for such bursts on shower arrays is described. We show that the burst time profile and the array dead time should be taken into account to interpret experimental data. Based on data from the Andyrchhy array of the Baksan Neutrino Observatory (Institute for Nuclear Research, Russian Academy of Sciences), we have obtained an upper limit on the number density of evaporating primordial black holes in a local region of space with a scale size of $\sim 10^{-3}$ pc. Comparison with the results of previous experiments is made.

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INTRODUCTION

Primordial black holes (PBHs) can be formed in the early Universe through the gravitational collapse of primordial cosmological density fluctuations. Therefore, the formation probability of PBHs and their observational manifestations depend significantly on how the primordial density fluctuations emerged and developed. The pattern of black hole formation is determined not only by the cosmology and physics of the early Universe. Theoretical predictions of the PBH formation probability depend strongly on the adopted theory of gravitation and, which is also important, on the adopted model of gravitational collapse. The evaporation of black holes on which their experimental search is based has not been completely studied either. Thus, PBH detection will provide valuable information about the early Universe and can be a unique test of the general theory of relativity, cosmology, and quantum gravity (Carr 2003). Knowledge of the spatial distribution of PBHs is important for their direct search. As was shown by Chisholm (2006), the local PBH number density in our Galaxy could be many orders of magnitude higher than the mean PBH number density in the Universe (the density ratio could reach $\sim 10^{22}$, which is much larger than the previously predicted value of $\sim 10^{7}$). Therefore, the constraints on the PBH number density imposed by direct searches can be more stringent than those imposed by diffuse extragalactic gamma-ray background measurements.

The high-energy gamma-ray bursts (GRBs), i.e., significant and time-localized excesses of gamma radiation above the background, are generated at the final PBH evaporation stage. Since the calculated temporal and energy characteristics of such bursts depend on the theoretical evaporation model (Bugaev et al. 2007), the technique of an experimental search and, accordingly, the constraints imposed on the PBH number density in the local Universe are model-dependent. PBHs can be searched for in experiments on arrays designed to detect extensive air showers (EASs) from cosmic rays with effective primary gamma-ray energies of 10 TeV or higher only within the framework of the evaporation model without a chromosphere (MacGibbon and Webber 1990). The duration of the high-energy GRBs predicted by
chromospheric evaporation models is too short, much shorter than the dead time of EAS arrays.

It should be noted that the duration of the high-energy GRBs is fairly short in the evaporation model without a chromosphere as well. Therefore, the effect of the array dead time on the burst detection probability should be taken into account when interpreting the experimental data from EAS arrays with a high threshold energy of the primary gamma-ray photons.

THE EXPERIMENT

The Andyrchy array to detect EASs from cosmic rays is located on the flank of Mount Andyrchy at an altitude of ~2060 m above sea level; its geographical coordinates are 43.28° N and 42.69° E. The array consists of 37 scintillation detectors based on plastic scintillator, each with an area of 1 m². The separation between the detectors in the horizontal plane is ~40 m and the total area of the array is 5 × 10⁴ m². The EAS trigger becomes active when ≥4 array detectors are triggered simultaneously; the trigger rate is ~9 s⁻¹. The effective angular resolution of the array for such events is 3.8°. The array dead time per EAS event does not depend on the EAS power and is 1 ms. The array and its operating parameters were described in detail previously (Petkov et al. 2006).

The detection probabilities \( P(E_\gamma, \theta) \) of the EASs generated by primary gamma-ray photons with energy \( E_\gamma \) incident on the array at zenith angle \( \theta \) were determined by simulating electromagnetic cascades in the atmosphere. The characteristics of the secondary particles that reached the array level were used as input parameters in the code for calculating the detector response, in which the energy release and the triggering time of each array detector were calculated. For the event simulated in this way, the arrival direction of the simulated EAS was reconstructed on the basis of a standard technique used in processing the recorded events. In Fig. 1, the EAS detection probability is plotted against the primary gamma-ray photon energy for several zenith angles. Since the detection probability of primary gamma-ray photons is a relatively smooth function of the photon energy, the median energy of the primary gamma-ray photons detected by the array depends on their energy spectrum. Following Alexandreas et al. (1993), we will take the median energy of the primary gamma-ray photons when the source is located at zenith and the gamma-ray spectrum is a power law with an index of −2.7 as the effective energy of the gamma-ray photons detected by the array. For the EASs detected by the Andyrchy array, this energy is 60 TeV.

For each of the events selected by the EAS trigger, we reconstructed the EAS arrival direction, i.e., the zenith and azimuth angles \((\theta, \phi)\) in the array coordinate system. Based on our processing, we created an archive of preprocessed information for the period 1996–2001 (the net accumulation time is ~1100 days and the total number of events is ~6.22 × 10⁶), which contains the absolute event time (with an accuracy of 1 ms) and the EAS arrival direction. Searching for GRBs over the celestial sphere (without referencing to the already detected bursts) is, in fact, searching for spatiotemporal concentrations of events (clusters). Since we take fairly short time intervals, spatial concentrations of events are searched for in the horizontal coordinate system. For each event \(i\) with an absolute time \(t_i\) and arrival angles \((\theta, \phi)_i\), we search for a cluster of such events \(i, i + 1, \ldots, i + n - 1\) that the EAS arrival directions differ by less than \(\alpha_r\) from the weighted mean direction. Thus, each cluster is characterized by multiplicity \(n\), duration \(\Delta t\), absolute time \(T\), and arrival direction \((\theta, \phi)\).

Previously, data from the Andyrchy array (Smirnov et al. 2005; Smirnov 2005) were used to search for cosmic GRBs over the celestial sphere. Groups of EASs arrived from one angular cell \(\alpha_r = 4.0\) in radius were selected; the minimum and maximum time differences in the cluster were taken to be 10 ms and 10 s, respectively. For each multiplicity \((n \geq 2)\), the dependences of the number of clusters with a given multiplicity \(n\) were derived. The background of chance coincidences (the formation of clusters with a given multiplicity \(n\)) was calculated using a similar processing of the simulated events. The EAS arrival angles \((\theta, \phi)\) and the time between