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# EXPERIMENTAL SEARCH FOR EVAPORATING PRIMORDIAL BLACK HOLES

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Primordial black holes (PBHs) are black holes, which may form in the early Universe through the gravitational collapse of primordial cosmological density fluctuations. Due to the Hawking radiation these PBHs are supposed to evaporate by emitting particles. Recent developments in the experimental searching for evaporating PBHs in the local Universe are reviewed. The technique of searching for the gamma-ray bursts (GRBs) from evaporating PBHs on shower arrays is discussed.

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## INTRODUCTION

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 (galaxies and clusters of galaxies) 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; significantly, the power spectrum of these fluctuations is entirely determined by the parameters of the theoretical inflation model used and primarily by the form of the inflation potential. There exist quite a few models (see, e.g., [1] and references therein), in which a fluctuation spectrum that ensures the formation of a considerable number of PBHs is predicted.

The regularities of the black-hole formation are determined not only by the cosmology and physics of the early Universe. Theoretical predictions of the PBH-formation probability depend strongly on the theory of gravitation and the model of gravitational collapse used.

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Direct search for the PBHs is based on the Hawking radiation [2], which leads to their evaporation on the characteristic time scale

$$t_{\rm ev} \simeq 10^{10}\ {\rm y}\ (M_{\rm PBH}/10^{15}\ {\rm g})^3.$$

It should be noted that the evaporation of black holes has not been completely studied to date. There are many theoretical models of the evaporation process [3–7].

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.

PBHs might arguably be the most natural candidates to solve the dark-matter problem: they are cold, weakly-interacting, and do not require extensions of the Standard Model of particle physics.

Therefore, experimental detection of PBHs could provide a unique probe of the early Universe, gravitational collapse, high-energy physics and quantum gravity. The nondetection of PBHs at the current level of the experimental technique also carries useful information and allows further progress to be made in understanding of the early Universe.

The technique of searching for the photon signal from evaporating PBHs depends on temporal and energy characteristics of their gamma-ray emission. As these characteristics differ for different evaporation models, the upper limit obtained for the number density of evaporating PBHs in a local region of space depends strongly on the specific evaporation model. Three evaporation models have been used in the analysis: in the first (best-known) model [3], the photons produced by the fragmentation of evaporated quarks are assumed to make a large contribution to the total photon spectrum from evaporating PBHs; in the other two models [4, 5], the photons produced by the interaction of evaporated quarks (and leptons) with one another are also taken into account. The interactions of evaporated particles are important if something like a photo- or chromosphere is formed around the PBH during its evaporation (as is assumed in [4, 5]).

## 1. THE GAMMA-RAY EMISSION FROM EVAPORATING PBHs

In the model of MacGibbon and Webber [3] (hereafter MW90), 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 nonthermal. In the chromospheric models of Heckler [4] (hereafter H97) and Daghigh and Kapusta [5] (hereafter DK02), 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. The emitted gamma-ray photon spectra from PBHs depend on the time left until the end of black holes (BH) evaporation $t_l$, which, in turn, is related to the Hawking temperature:

$$t_l = 4.7 \cdot 10^{11} \left( \frac{T_H}{1\ \text{GeV}} \right)^{-3}\ \text{s}. \tag{1}$$

The time-integrated spectra for the three evaporation models [9] are partially shown in Fig. 1. For approximation formulas for the spectra see [10], Sec. 3.3. The duration of a burst for a given gamma-ray photon-energy threshold $E_{\text{th}}$ is defined as the time left until the end of PBH evaporation, during which 99% of the gamma-ray photons with $E_\gamma \geqslant E_{\text{th}}$ are emitted. The burst duration is plotted versus the threshold energy in Fig. 2 for the three evaporation models. One can see that the search for evaporating PBHs 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 can be carried out only within the framework of

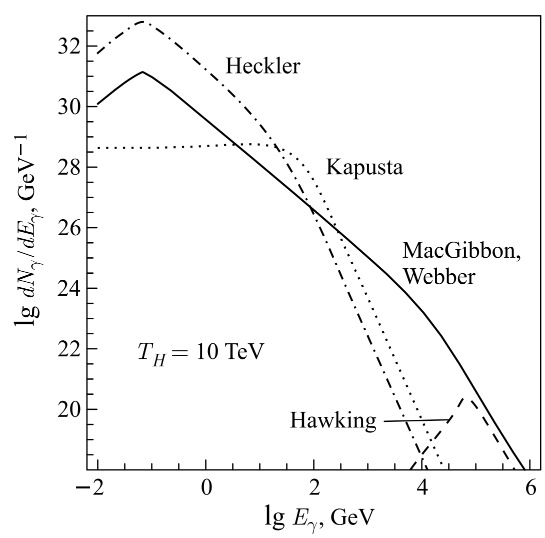


Fig. 1. Time-integrated photon spectrum from an evaporating BH for the initial Hawking temperature $T_H = 10$ TeV (the BH lifetime in this case is approximately 0.5 s): the MW90 model without a chromosphere (solid line), the H97 model with a chromosphere (dash-dotted line), the DK02 model with a chromosphere (dotted line), and the spectrum of direct photons calculated using the Hawking formula (dashed line)

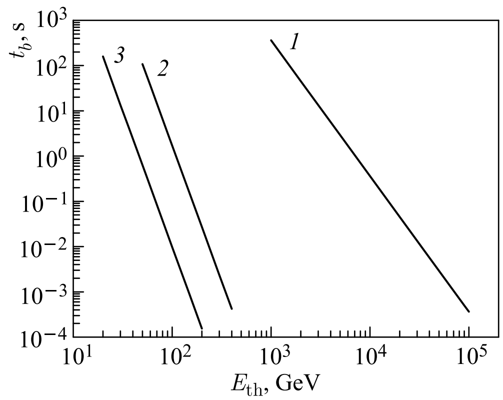


Fig. 2. Burst duration $t_b$ versus threshold gamma-ray photon energy for various evaporation models: MW90 without a chromosphere (*1*), DK02 with a chromosphere (*2*), and H97 (*3*)

the evaporation model without a chromosphere. 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.

By way of example, the technique of searching for very-high-energy GRBs from evaporating PBHs is described for the Andyrchy EAS array [11].

## 2. SEARCHING FOR VERY-HIGH-ENERGY GRBs FROM EVAPORATING PBHs AT THE ANDYRCHY EAS ARRAY

Following [12], the effective energy of the gamma-ray photons detected by the EAS array is defined as 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. For the EASs detected by the Andyrchy array, this energy is 60 TeV.

As was mentioned above, the spectrum of the gamma-ray photons emitted by PBHs, $dN_\gamma/dE_\gamma$, depends on the time $t_l$ left until the end of the black-hole evaporation. Since the array detects the EASs generated by primary gamma-ray photons with energy $E_\gamma$ incident at zenith angle $\theta$ with probability $P(E_\gamma, \theta)$ and since the spectrum of the gamma-ray photons emitted by PBHs $dN_\gamma/dE_\gamma$ depends on $t_l$, the spectrum recorded by the array (its response function) $P(E_\gamma, \theta)dN_\gamma/dE_\gamma$

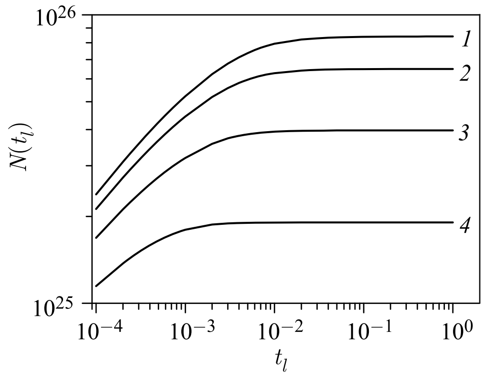


Fig. 3. Total number of gamma-ray photons emitted by PBH that can be detected by the Andyrchy array versus the time $t_l$ left until the end of black-hole evaporation (MW90 evaporation model): *1* — $\theta = 0\,^\circ$; *2* — $\theta = 10\,^\circ$; *3* — $\theta = 20\,^\circ$; *4* — $\theta = 30\,^\circ$

also depends on $t_l$. The total number of gamma-ray photons emitted by PBHs that can be detected by the array,

$$N_\gamma(\theta, t_l) = \int\limits_0^\infty dE P(E_\gamma, \theta) \frac{dN_\gamma}{dE_\gamma}, \tag{2}$$

also depends on $t_l$. Here, $\theta$ is the zenith angle at which the PBH is seen from the array. Figure 3 shows the dependences of $N_\gamma(\theta, t_l)$ (integrated burst profile) for several zenith angles $\theta$. It should be noted that the burst profile mainly determines the technique of searching for GRBs from PBHs on a specific array, in particular, the choice of a time interval $\Delta t$ for the search for EAS clusters.

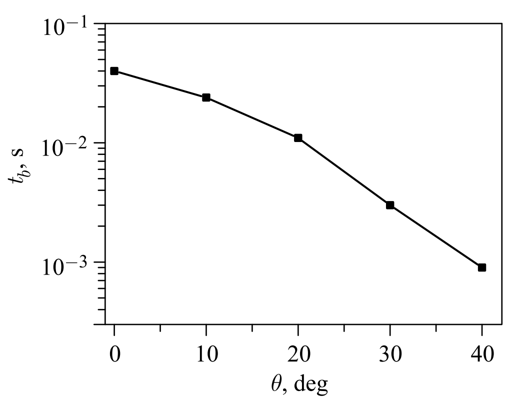


Fig. 4. Burst duration versus zenith angle for the Andyrchy EAS array (MW90 evaporation model)

The burst duration $t_b$ is plotted in Fig. 4 versus the zenith angle for the Andyrchy array. One can see that the array can record the events from evaporating PBHs in a limited range of zenith angles, because the expected GRB duration at large zenith angles is shorter than the array dead time per event $t_d = 1$ ms.

At EAS arrays the searching for bursts over the celestial sphere is, in fact, the searching for temporal and directional concentrations of events (clusters). Since we take fairly short time intervals, spatial concentrations of events are searched for in the horizontal coordinate system. Each cluster is characterized by multiplicity $n$, duration $\Delta t$, absolute time $T$, and arrival direction $(\theta, \phi)$. We searched for the groups of EASs arrived from one angular bin for time intervals of a given duration, $\Delta t = t_b(\theta)$. Because of the short time intervals (accordingly, the reduced background of chance coincidences), we used a large angular bin with radius $\alpha_r = 7.0\,^{\circ}$; such a bin contains 90% of the events from a point source. The experimentally-measured detection rates of such clusters are in agreement with those expected from the background of chance coincidences.

Let a PBH be located at distance $r$ from the array and be seen from it at zenith angle $\theta$. The mean number of gamma-ray photons detected by the array over the burst time $t_b$ is then

$$\bar{n}(\theta) = \frac{\epsilon N(t_b(\theta)) S(\theta)}{4\pi r^2}, \tag{3}$$

where $S(\theta)$ is the array area and $\epsilon = 0.9$ is the fraction of the events from a point source that fell into the taken angular bin, $N(t_b(\theta))$ is the total number of gamma-ray photons emitted by PBHs that can be detected by the array during $t_b$. The number of bursts detected over the total observation time $T$ can be represented as

$$N = \rho_{pbh} T V_{\text{eff}}, \tag{4}$$

where

$$V_{\text{eff}} = \int d\Omega \int_0^{\infty} dr\, r^2 F(n(\theta), \bar{n}(\theta), t_b(\theta)) \tag{5}$$

is the effective volume of the space surveyed by the array, $\rho_{pbh}$ is the number density of evaporating PBHs, and $F(n, \bar{n}, t_b)$ is the detection probability of a cluster of $n$ EASs with the mean value of $\bar{n}$ over the burst time $t_b$. In turn, the total detection probability can be expressed as a product of the Poisson probability of $n$ EASs falling on the array with the mean value of $\bar{n}$ and the probability to detect all $n$ EASs over the burst time $t_b$ with the array dead time per event $t_d$:

$$F(n, \bar{n}, t_b) = f(n, t_b, t_d) \frac{\mathrm{e}^{-\bar{n}}\, \bar{n}^n}{n!}. \tag{6}$$

In calculating the effective volume, we take $n(\theta) = n'(\theta) + 1$ (this means that the distributions of the detected clusters in multiplicity can be explained by the background of chance coincidences). The probabilities $f(n, t_b, t_d)$ of detecting $n(\theta)$ EASs over the burst time $t_b(\theta)$ with the array dead time per event $t_d$ were calculated by the Monte Carlo method by taking into account the burst time profile for a given zenith angle. The effective volume of the space surveyed by the array, $V_{\text{eff}}$, is $1.88 \cdot 10^{-9}$ pc$^3$. 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

$$\rho_{\text{lim}} = \frac{4.6}{V_{\text{eff}} \cdot T}, \qquad (7)$$

in our case, $\rho_{\text{lim}} = 8.2 \cdot 10^8$ pc$^{-3} \cdot$ y$^{-1}$.

To improve the constraint on the number density of evaporating PBHs, the multidimensional analysis has been used [13]. The constraints are usually obtained from a condition of absence of clusters with a given multiplicity and duration. Thus, a one-dimensional problem is solved — each cluster (not depending on multiplicity) corresponds to the point with coordinate $\Delta t$ on the time axis, and cluster duration distribution is analyzed then. However, for the cluster with $n$ showers, the number of independent parameters (time intervals) is $n-1$, and such a cluster can be represented as a point in space with $n-1$ dimensions. In those cases when the time characteristics of the PBH produced clusters are different from the ones arising due to chance coincidences, the increase of the number of parameters can help to separate the PBH events from the background ones. As an example, Fig. 5 shows three-dimensional distributions of clusters expected from PBHs (*a*) and experimentally registered clusters (*b*) for the case of $n = 4$ and $\theta = 30°$. It is seen that the measured clusters and the ones expected from PBHs occupy different regions in three-dimensional space.

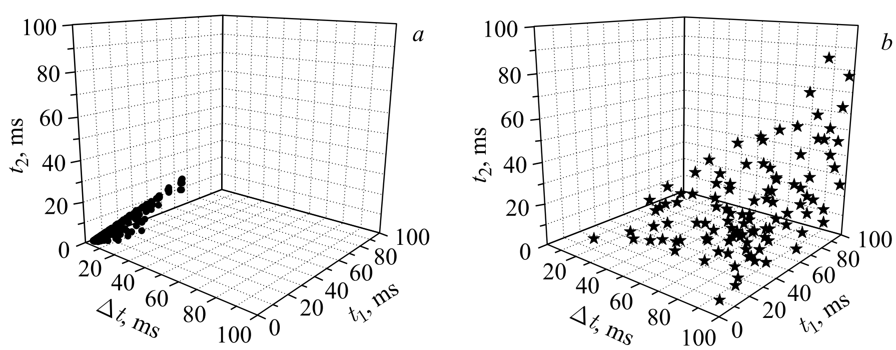


Fig. 5. Three-dimensional distributions for clusters with $n = 4$, zenith angle is $\theta = 30\,°$. *a*) Events expected from the evaporating PBH; *b*) events registered by the Andyrchy array

Thus, due to background reduction, the constraint on the PBH number density obtained on a given array has been improved. In this case, the effective volume of the space surveyed by the Andyrchy array is $V_{\text{eff}} = 2.8 \cdot 10^{-9}$ pc$^3$. The upper limit on the number density of evaporating PBHs at the 99% confidence level is slightly better comparing with the one-dimensional analysis: $\rho_{\text{lim}} = 5.4 \cdot 10^8$ pc$^{-3} \cdot$ y$^{-1}$.

## 3. COMPARISON WITH THE RESULTS OF OTHER EXPERIMENTS

Until now, high-energy gamma-ray bursts (GRBs) from the last PBH evaporation stage have been searched for in experiments at EAS arrays [11, 12, 14–16] and the Cherenkov telescopes [17–20]. The authors of all these papers used the MW90 theoretical model to interpret the experimental results and to obtain their constraints on the PBH number density.

Effects of the array dead time and the burst time profile on the burst detection probability for EAS arrays with high threshold energy (CYGNUS [12], HEGRA [15] and Tibet [14]) have been discussed in [11]. It was argued that disregarding these effects leads to a significant overestimation of this probability (i.e., the factor $F$ in Eq. (5) for the effective volume $V_{\rm eff}$) and, as a result, to an underestimation of the upper limit on the PBH number density. In the limiting case, the array can be insensitive to the high-energy GRBs from PBHs altogether, since for $t_d \geqslant t_b$ no more than one gamma-ray photon can be detected over the burst time, and a burst of $n$ gamma-ray photons can be detected if $nt_d < t_b$. It should be noted that taking into account the dead time is unimportant at relatively low gamma-ray photon energies ($\sim 1$ TeV), when the burst time is large enough (see Fig. 2).

The upper limits on the number density of evaporating PBHs for the MW90 evaporation model versus effective energy of the detected gamma-ray photons are shown in Fig. 6. One can see that more strict constraints were obtained in the experiments on the Cherenkov telescopes, owing to the larger effective volume

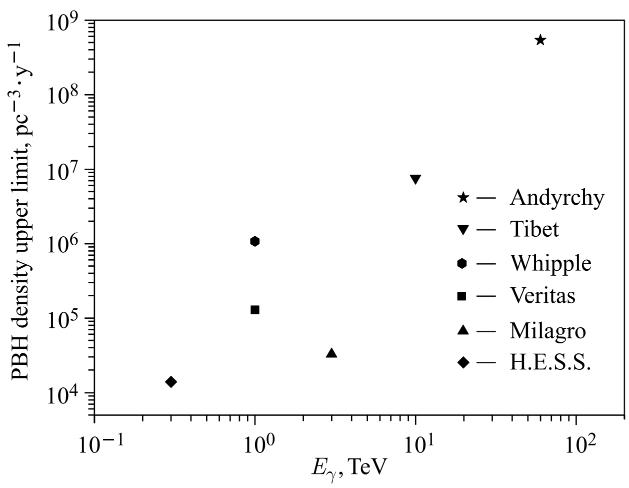


Fig. 6. Upper limits on the number density of evaporating PBHs for the evaporation model without a chromosphere, MW90, versus effective energy of the detected gamma-ray photons

of the space surveyed by the telescopes (due to their lower energy threshold).

However, it should be noted that the effective gamma-ray photon energy in EAS experiments is about two orders of magnitude higher than that in the Cherenkov telescopes. Thus, EAS experiments upper limits pertain not to black holes in general, but to black holes with certain properties (emitting $\sim$ 100-TeV gamma-ray photons at the end of their evaporation during bursts lasting $\sim$ 10 ms).

## 4. SEARCH FOR EVAPORATING PBHs WITH CHROMOSPHERIC MODELS

To date, the search for evaporating PBHs using the chromospheric models predictions has been carried out only on the Andyrchy and Carpet-2 shower arrays of the Baksan Neutrino Observatory [10, 21]. The total lifetime of this experiment is 8.6 y. The technique of searching for spikes in the total count rate when the arrays operate in the mode of detection of a single cosmic-ray component has been used to directly search for GRBs from evaporating PBHs in the context of chromospheric H97 and DK02 models. The particle arrival direction cannot be determined when operating in this mode; the effective energy of the primary gamma-ray photons depends mainly on the array altitude above the sea level. The effective energy of the gamma-ray photons registered by the arrays is 8 GeV. The low effective energy of primary photons is an advantage of this technique. But the search for GRBs based on this technique is conducted against a high cosmic-ray background. This circumstance leads to a smaller effective volume of space surveyed by the arrays. As a consequence, less strict constraints (at the 99% confidence level) for the PBH number density were obtained for the chromospheric models [10]: $\rho_{\rm lim} = 5 \cdot 10^9$ pc$^{-3} \cdot$ y$^{-1}$ for the H97 model and $\rho_{\rm lim} = 10^9$ pc$^{-3} \cdot$ y$^{-1}$ for the DK02 model.

## CONCLUSION

The upper limits on the number density of evaporating PBHs in local region of the Galaxy were obtained in wide-range energies (from $\sim$ 100 GeV to $\sim$ 100 TeV) in the framework of the MW90 evaporation model without a chromosphere.

Until now, the search for evaporating PBHs using the chromospheric evaporation models (DK02 and H97) predictions has been carried out only on the Andyrchy and Carpet-2 shower arrays. The upper limits on the number density of evaporating PBHs were obtained at $E_\gamma \sim 8$ GeV. It should be noted that one can expect a significant improvement of the upper limit for the chromospheric models within a few years, due to the lowering of the energy threshold below 50 GeV in the second phase of H.E.S.S, H.E.S.S-2, experiment [20].

As there are many theoretical models of the BH evaporation process, it is necessary to carry out the search for evaporating PBHs in the framework of the different evaporation models.

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