Experimental search of bursts of gamma rays from primordial black holes evaporating through the chromosphere's formation

E.V. Bugaev[*], **V.B. Petkov**[*†], **A.N. Gaponenko**[*], **P.A. Klimai**[*], **M.V. Andreev**[*†‡], **A.B. Chernyaev**[*], **I.M. Dzaparova**[*†], **D.D. Dzhappuev**[*], **Zh.Sh. Guliev**[*], **N.S. Khaerdinov**[*], **N.F. Klimenko**[*], **A.U. Kudzhaev**[*], **A.V. Sergeev**[*†‡], **V.I. Volchenko**[*], **G.V. Volchenko**[*] **and A.F. Yanin**[*]

[*] *Institute for Nuclear Research, Russian Academy of Sciences, 60th October Anniversary Prospect 7a, 117312 Moscow, Russia*

[†] *Terskol Branch of the Institute of Astronomy of the Russian Academy of Sciences*

[‡] *International Center for Astronomical, Medical and Ecological Research, National Academy of Sciences of Ukraine*

***Abstract*. Experimental data of arrays "Andyrchy" and "Carpet-2" of Baksan Neutrino Observatory (Institute for Nuclear Research), obtained in the regime of a detection of the single cosmic-ray component, are used for a search of the bursts of cosmic gamma rays from evaporating primordial black holes. The chromospheric theoretical model of the evaporation process is used for the analysis. Distributions of the counting rate fluctuations on both arrays agree with the expectations from the cosmic ray background. The new constraints on the concentration of evaporating primordial black holes in the local region of Galaxy are obtained. The comparison of the results of different experiments is given.**

***Keywords*: primordial black holes, gamma rays, extensive air showers**

I. INTRODUCTION

It has been argued recently [1] that the photon flux calculation from an evaporating black hole (BH) given in [2] is the most reliable, and that the photospheric and chromospheric effects considered in [3], [4] are negligibly small. It is clear, however (and we try to show it in this section), that scenarios of BH evolution, in which interactions between emitted particles (and even some kind of the thermal atmosphere around the BH) exist, cannot, in general, be discarded.

In Secs. II and III we study the detection of BH evaporation using three models (considering them on an equal footing), just to demonstrate the sensitivity of the method to the BH photon spectrum.

According to Hawking [5] the fundamental information about the quantum state of matter undergoing gravitational collapse will be lost behind the event horizon of the resulting BH. It means that the thermal Hawking radiation carries no information about the initial quantum state of the system, and, after the complete evaporation of the BH, information is lost, in violation of the rules of quantum theory. It is known, however, that there are ways of reconciling of the BH evolution with quantum theory (see [6] and references therein). In particular, a phenomenological description of BH evolution based on the idea of a stretched horizon (SH), or "membrane", is, in our opinion, quite interesting. It is postulated in this approach that the process of formation and evaporation of a BH, as viewed by a distant observer, can be described entirely within the context of standard quantum theory. From the point of view of an outside observer, the SH is a boundary surface equipped (by assumption) with some microphysical degrees of freedom that appear in the quantum Hamiltonian. The SH can receive and emit signals. To distant observers, clocks at the event horizon appear infinitely slowed while they appear to run at a finite rate at the SH. The thermal radiation from the BH is interpreted in this approach as originating on the SH. The infalling matter leads to a thermal excitation of the SH. The local proper temperature at the SH, T_s, is related to the asymptotically measured Hawking temperature by

$$T_s \sim \frac{M}{M_P} T_H, \quad (1)$$

where M_P/M is the time dilation factor (M_P is the Planck mass), $d\tau/dt$, connecting the time intervals at the SH with the intervals of coordinate time t (by definition [6], the SH of a four-dimensional Schwarzschild BH has an area about one Planck unit greater than the global event horizon). Using $T_H \sim M_P^2/M$, one obtains from (1) that $T_s \sim M_P$, independently of the size or mass of the BH.

It is very important that the SH is assumed to be in thermal equilibrium during most of the evaporation. A distant observer would estimate the number of particles emitted per unit time which is proportional to a product of the BH area and the time dilation factor [6],

$$\frac{dN}{dt} \sim M^2 \frac{d\tau}{dt} \sim M \quad (2)$$

(if all these particles go to infinity). On the other hand, the number per unit time of particles that actually emerged to infinity is

$$\frac{dN}{dt} \sim \frac{L}{E_{\rm typ}} \sim \frac{1}{M} \quad (3)$$

($E_{\rm typ}$ is the typical energy of the emitted particles, $E_{\rm typ} \sim T_H \sim M_P^2/M$). It follows from (2) and (3) that most of the particles emitted from the SH do not go to infinity. This gives rise to a thermal atmosphere above the SH (due to repeated interactions of emitted particles with the SH and with each other).

In string models such a scenario is modified in the following way. The SH is placed at a distance $\sim l_s$ from the event horizon. Here, l_s is the string scale. The local proper temperature at the SH is equal to [7] $T_s = 1/2\pi l_s$. We suppose, that the string coupling, $g^2 = Gl_s^2$, is extremely small, so that the Planck and string scales are well separated. When, in the course of the evaporation, the Hawking temperature T_H approaches T_s (which is the Hagedorn temperature of string theory), the radius of the BH becomes equal to l_s. In this point the BH can transform into a higher-entropy string state. The possibility of such transformation was discussed in many works (see [8] and references therein). It is essential that the ideas of the string-BH correspondence [9] and of identifying the states of a BH with the highly excited states of a fundamental string [7], [10] help us to understand the physical nature of the BH entropy (by other words, the nature of the "internal states of a BH", or, "the degrees of freedom of the horizon").

The most important conclusion from this scenario is that the resulting, weakly coupled, string decays at the Hagedorn temperature, and the momenta of the emitted particles never exceed T_s (which can be as small as 0.1 TeV).

It follows from these arguments that, in principle, an existence of the thermal atmosphere and interactions inside of the evaporating BH is conceivable. Moreover, the final BH temperature can be much smaller than T_P.

II. The experiment

Up to now, the search for the bursts of high-energy gamma rays which are generated at the final stages of PBH evaporation was carried out in ground-based experiments detecting the EASs on several shower arrays [11], [12], [13], [14], [15] and on the Whipple Cherenkov telescope [16]. Because of high energy detection threshold, the interpretation of the results of these experiments can be performed only within the framework of the evaporation model without a chromosphere [2] (hereafter, MW90). The duration of the high-energy burst predicted by chromospheric evaporation models is too short, much shorter than the detection dead time in these experiments (the duration of burst t_b is, by definition, the time interval during which 99% of photons that can be detected by the array evaporate).

For the direct search of PBH gamma ray bursts within the framework of the chromospheric models of BH evaporation, another technique has to be applied, which is sensitive to photons with rather small energies, namely of order of few GeV. Shower particles generated in atmosphere by photons with energy $\sim 10 - 100$ GeV are strongly absorbed before reaching the detector level,

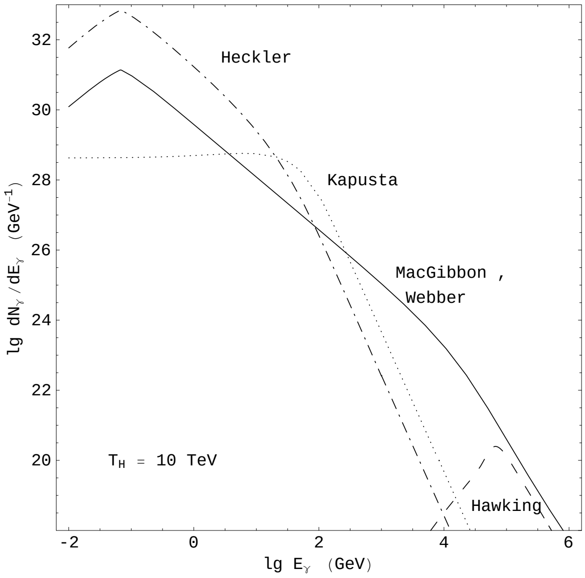

Fig. 1: Time-integrated photon spectra from a BH with initial Hawking temperature $T_H = 10$ TeV. Such a BH has about 0.5 s until the full evaporation.

so, the average number of signals in the detector module is smaller than 1. Therefore, in this energy range PBH bursts can be sought for by operating with the modules in single particle mode, that is, by measuring the single particle counting rate of the individual modules. The primary arrival directions of photons are not measured, and bursts can be detected only as spikes (short-time increases) of the cosmic ray counting rate. The effective energy of the primary gamma-ray photons detected by this method depends mainly on the altitude of the array above sea level. This technique was employed earlier to seek for cosmic gamma-ray bursts with energies exceeding several GeV [17], [18], [19], [20]. First constraints on the number density of evaporating PBHs within chomospheric framework were obtained in work [21] for the evaporation models by Heckler [3] (hereafter, H97) and Daghigh and Kapusta [4] (hereafter, DK02). It should be noted that for the PBH search within the framework of model MW90, the same technique still can be applied. The comparison of three evaporation models considered can be found in [22], and time-integrated photon spectra for particular value of Hawking temperature are shown in Fig. 1.

The present experiment was performed on Andyrchy and Carpet-2 arrays of Baksan neutrino observatory of INR RAS. Both arrays are situated close to each other (horizontal distance between them is about 1 km), but their altitudes above sea level are different: Andyrchy - 2060 m (atmospheric depth - 800 g cm^{-2}), Carpet - 1700 m (atmospheric depth - 840 g cm^{-2}).

Andyrchy consists of 37 scintillation detectors. The area of each detector is 1 m^2. To detect a single cosmic-ray component, the total counting rate of all of the detectors is measured each second. The search for gamma-ray bursts using this technique is carried out against the high cosmic-ray background ($\bar{\omega} = 11440$ s^{-1}), which requires the highly stable and reliable performance of all equipment. The monitoring is realized through simultaneous measurements (with 1-s acquisition rate) of the counting rates in the four parts of the array comprising 10, 9, 9, and 9 detectors, respectively. An use of such information allows to exclude 1-second intervals with unreasonably large deviations of counting rate between the parts of the array which could come from faultiness of individual detectors or registration channels, faultiness of counting rate measurement channels of separate parts of the array or non-synchronous impulsive electromagnetic disturbance in detectors or signal cables. A detailed description of the array and its operating parameters is given in [23].

Carpet-2 array [24], [25] consists of the actual Carpet facility (400 liquid scintillation detectors covering area of 196 m^2), six remote points (RP; 108 detectors of the same kind with total area 54 m^2), and the muon detector (175 detectors of the type used in Andyrchy array placed in the underground tunnel).

The detection probabilities $P(E_\gamma, \theta)$ of the secondary particles produced by the primary photons with energy E_γ falling on the arrays at zenith angle θ were determined by simulating electromagnetic cascades in the atmosphere and the detectors. The effective energy of gamma rays registered by Andyrchy and RP is 8 GeV, for Carpet and muon detector this energy is, correspondingly, 200 GeV and 2 TeV. Because of this, only data from Andyrchy and RP was actually used in this work.

The total number of gamma rays which can be detected by the array is given by

$$N_\gamma(\theta, t_l) = \int_0^\infty dE_\gamma P(E_\gamma, \theta) dN_\gamma/dE_\gamma. \quad (4)$$

It depends on the time t_l left until the end of PBH evaporation. Here, dN_γ/dE_γ is the spectrum of photons emitted by the PBH during the same time interval t_l. Let a PBH be located at distance r from the array with area S and be seen from it at zenith angle θ. The mean number of gamma-rays detected by the array is then

$$\bar{n}(\theta, r) = \frac{N_\gamma(\theta, t_l) S(\theta)}{4\pi r^2}, \quad (5)$$

which will give an excess over the average counting rate $\bar{\omega}$ in units of root mean square deviation:

$$f(\theta) = \frac{\bar{n}(\theta, r)}{\sqrt{\bar{\omega}}} = \frac{N_\gamma(\theta, t_l) S(\theta)}{4\pi r^2 \sqrt{\bar{\omega}}}. \quad (6)$$

The time interval Δt which should be used to search for bursts of gamma rays from evaporating PBHs in the particular experiment depends both on the burst duration and on its time profile. Burst duration for Andyrchy and RP ($E_{th} \sim 8$ GeV) exceeds 10^4 s for all considered evaporation models. It should be noted that the search of long bursts (tens of seconds and more) in ground-based experiment, especially when working in single-particle mode, is difficult because of short-time variations of cosmic ray intensity [18], [20]. Fig. 2 shows, for considered models, the dependencies of total number of gamma rays that can be detected by Andyrchy array on the time t_l. It is seen that even for a rather strong increase of t_l (from 1 s to 20 s) the number of gamma particles increases only by a factor of 2 to 4 (depending on the model). At the same time, the number of background events increases proportional to the time interval. The consequence of this consideration is that in our experiment, the search is most effective for 1-second time intervals.

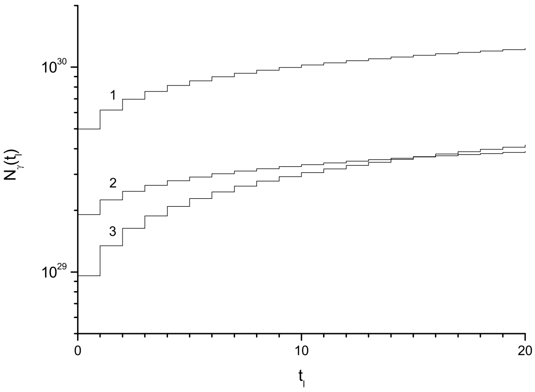

Fig. 2: Full number of gamma particles that can be detected by the Andyrchy array for $\theta = 0°$, as a function of time until the end of PBH evaporation, for different evaporation models: 1 - DK02, 2 - H97, 3 - MW90.

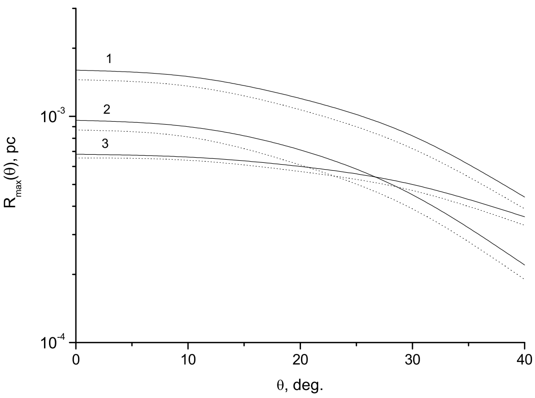

Fig. 3: Maximum distance from which the evaporating PBH can be detected. Solid lines are for Andyrchy (number of particles in this case is $n = 640$), dotted lines are for RP ($n = 918$); models used are: 1 - DK02, 2 - H97, 3 - MW90.

Deviations in the array counting rate lasting $\Delta t \leq 1$ s are sought using the parameter F_i that is equal to the deviation (measured in units of the Poisson sigma) of the number of counts k_i during the i-th second of a 15-min interval from the average number of counts during this interval: $F_i = (k_i - \bar{k})/\sqrt{\bar{k}}$. Since variations in the cosmic-ray intensity over a time of 15 min are negligible in the first approximation and the average counting rate is fairly high, one can expect that the parameter F_i has a Gaussian distribution with the zero mean value $V = 0$ and unit standard deviation $\sigma = 1.0$.

The actual experimental data mostly confirms this assumption. For the RP data, no excesses were found larger than 7 standard deviations. For Andyrchy, the only event with a large (7.9σ) deviation was detected on April 17, 2002 at 17:31:29 UT , all other data is well fitted by a Gaussian distribution with maximum deviations of 6σ. If we assume that the 7.9σ Andyrchy event is caused by evaporating PBH, then, taking into account that RP is examining the same region in the sky, the excess in RP counting rate should be in the region $(6.6 - 7.7)\sigma$ for chromospheric models, or in the region $(8.2-8.5)\sigma$ for MW90 model. However, for this 15-min interval, no excess larger than 3.2σ was detected by RP, so this single Andyrchy event cannot be explained by the evaporating PBH.

One can estimate the maximum distance from which a PBH can be seen using the formula [see Fig. 3]

$$R_{\max} = \sqrt{\frac{N_\gamma(\theta, t_l = 1\ \mathrm{s}) S(\theta)}{4\pi n}} \ . \tag{7}$$

III. Results and conclusions

Generally, the effective volume surveyed by the array is calculated using the formula

$$V_{\text{eff}} = \int d\Omega \int\limits_0^\infty dr r^2 F(n, \bar{n}(\theta, r)). \tag{8}$$

Here, $F(n, \bar{n}(\theta, r))$ is the Poisson probability to register n or more events having the average $\bar{n}(\theta, r)$ determined by Eq. (5). Taking into account that no excesses above 6σ were detected on Andyrchy, we put $n = 6\sqrt{\bar{\omega}} = 640$, and the effective volume for this array is, depending on the model: 1.2×10^{-10} pc^3, 5.6×10^{-10} pc^3, 8.1×10^{-11} pc^3 for H97, DK02 and MW90, correspondingly. For RP, no excesses above 7σ are discovered (in this case $\bar{\omega} = 17200$, so, $n = 7\sqrt{\bar{\omega}} = 918$), and the effective volume is: 7.6×10^{-11} pc^3, 4.1×10^{-10} pc^3, 7.1×10^{-11} pc^3 for H97, DK02 and MW90, correspondingly.

The number of bursts detected over the total observation time T can be represented as

$$N = \rho_{\text{pbh}} T V_{\text{eff}} \ , \tag{9}$$

where ρ_{pbh} is the number density of evaporating PBHs. Assuming that evaporating PBHs are distributed uniformly in the local region of the Galaxy and taking into account that both arrays survey the same sky region at different time, one can calculate the upper limit ρ_{lim} on the number density of evaporating PBHs at the 99% confidence level using the formula

$$\rho_{\text{lim}} = 4.6/(V_A T_A + V_{RP} T_{RP}), \tag{10}$$

with full observation time $T_A = 6.27$ yr for Andyrchy and $T_{RP} = 2.34$ yr for RP. Substituting the effective volumes with values calculated above, we finally obtain for ρ_{lim}: 10^9 pc^{-3} yr^{-1}, 5×10^9 pc^{-3} yr^{-1}, 6.8×10^9 pc^{-3} yr^{-1} for evaporation models DK02, H97 and MW90, respectively.

One can note, that in the case of a non-chromospheric model MW90, the limit obtained in this work is worse than the limit from the Andyrchy array obtained using method of EAS detection [15]. However because the effective energies of detected photons differ by several orders of magnitude, these limits should be regarded as complementary. For the case of DK02 and H97 models, the limit has been significantly improved compared to our previous work [21].

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