Experimental search of bursts of gamma rays from primordial black holes using different evaporation models

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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. Different theoretical models of the evaporation process are 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 the photospheric and chromospheric effects considered in [3, 4] are negligibly small. It is clear, however (and we try to show this 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). We do not insist on the validity of concrete chromospheric models; our aim is to demonstrate the sensitivity of the experimental method used in the present paper (which is based on the registration of evaporated photons with energies $\sim 10$ GeV) to a form of the BH photon spectrum, having in mind that its right shape may be different from the "canonical" one.

The famous Hawking’s result [5] according to which a BH will emit black body radiation, precisely corresponding to the temperature $T_{H} = \frac{\hbar c}{8\pi G M}$ (where $T_{R}$ is the dimensionless Rindler temperature, $T_{R} = \frac{1}{2\pi}$) had been obtained in a semiclassical approximation. It has been assumed, in particular, that back-reaction effects are effectively small and do not influence the classical collapse geometry. It is well known that Hawking’s derivation of the evaporation spectrum is based on information loss phenomenon [6] and, correspondingly, on the possibility of a nonunitary evolution of the BH.

This is a direct consequence of the strict locality of quantum field theory which leads to an independence of the external and internal Hilbert states (i.e., states located outside and inside horizon, respectively) and, as a result, to an appearing of the density matrix for the BH decay rather than a pure state.

It had been argued in many works, however (see, e.g., [7], [8], [9]), that the semiclassical approximation used in [5] is too crude; generically, one cannot regard outgoing particle as a Hawking particle that was not affected by the ingoing matter. Moreover, the gravitational interactions of the Hawking radiation (when it already separates from the horizon) with infalling particles can be strong enough for deforming the metric and for a breakdown of locality. It is known that the dynamics of strong gravitational physics is inherently nonlocal, and it is natural to assume that just this nonlocality may be the resolution of the above-mentioned paradox of information loss [9].

An approximate (effective) accounting of the back-reaction effects is realized in the approach in which the boundary condition for all fields on a surface a few Planck distances away from horizon is postulated. The examples are the “brick wall” model [10], the “stretched horizon” model [11] and the “bounce” model [12]. These models are based on an assumption that strong gravitational interactions among the field quanta effectively form this barrier between the horizon and the wall.

It is argued in these works 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, with unitary $S$-matrix and pure quantum states.

An idea of the stretched horizon (SH) was proposed
many years ago [14] but at that times it was considered as a useful mathematical construction rather than a physical object equipped with some microphysical degrees of freedom. One should stress, however, that the approach using a concept of the SH is appropriate only for an external observer, not for a free falling one. The main point of the approach is that the SH can, through its degrees of freedom, absorb, thermalize and emit any quantum mechanical information falling into the BH, without any information loss [11].

The local proper temperature at the SH, $T_s$, is related to the temperature measured by distant observers (which is, by definition, the Hawking temperature $T_H$), by the connection

$$ T_s = \frac{dt}{d\tau} T_H, $$

where $d\tau/dt$ is the time dilation factor, connecting the time intervals at the SH with the intervals of coordinate time $t$, which is given by

$$ \frac{d\tau}{dt} = \frac{\rho_h}{4MG \sim \frac{\rho_h}{r_h}}. $$

Here, $\rho_h$ is the distance of SH from the horizon, $r_h$ is the gravitational radius. In the "standard" case, when $\rho_h \sim GM_P \equiv l_P$ ($M_P$ is the Planck mass), one has

$$ \frac{d\tau}{dt} \sim \frac{M_P}{M}, $$

and, if $T_s \sim M_P$ (independently of the size or mass of the BH), one obtains

$$ T_H \sim \frac{M_P^2}{M}. $$

It is very important that the SH is assumed to be in a thermal equilibrium with the surrounding material 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 [11].

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

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

$$ \frac{dN}{dt} \sim \frac{L}{E_{\text{typ}}} \sim \frac{1}{M} $$

($E_{\text{typ}}$ is the typical energy of the emitted particles, $E_{\text{typ}} \sim T_H \sim M_P^2/M$, $L$ is the BH luminosity, $L \sim 1/M^2$). It follows from (5) and (6) 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).

One should stress that, in these models, BH decays as a pure quantum mechanical state, so, a spectrum of the emitted radiation does not need to have a precise thermal form predicted in [5], at least at final stages of the evaporation, when BH mass is small.

In general case, the temperature of the SH, $T_s$, as well as the distance $\rho_h$, depend on microphysics. Correspondingly, the maximum value of the Hawking temperature $T_H$, and a form of the spectrum of evaporated particles are model dependent. Evidently, this model dependence is especially large at final stages of the evaporation when a radius of the BH, $r_h$, is comparable with $\rho_h$. In this case the centrifugal barrier becomes inefficient and the thermal atmosphere around the SH gradually becomes open for a space surrounding the BH. The experimental signature may be similar with those predicted in chromospheric models if the maximum Hawking temperature $T_H$ is much smaller than $M_P$, as is predicted in some scenarios. For example, such a situation is possible in string models. In these models, the SH is placed at a distance $\sim l_s$ from the event horizon ($l_s$ is the string scale). The local proper temperature at the SH is equal to $T_s = 1/2\pi l_s$. We suppose, that the string coupling, $g^2 = G_{10}^2$, is extremely small, so that the Planck and string scales are well separated. When, in a 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 [15] and references therein).

It is essential also that the ideas of the string-BH correspondence [16] and of identifying the states of a BH with the highly excited states of a fundamental string ([14], [17]) 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 stretched horizon").

It is important to note that strings are ideally suited for interactions with the SH due to a spread in the transverse space (during approaching the SH) and due to Regge behavior of string scattering amplitudes and their growing cross sections [18].

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).

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 [19], [20], [21], [22], [23] and on the Whipple Cherenkov telescope [24]. 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 (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, 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 [25], [26], [27], [28]. First constraints on the number density of evaporating PBHs within chromospheric framework were obtained in work [29] 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 [30], and time-integrated photon spectra for particular value of Hawking temperature are shown in Fig. 1.

![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.](image)

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 [31].

Carpet-2 array [32], [33] 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 $E_\gamma$ falling on the arrays at zenith angle $\theta$ 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

$$N_\gamma(\theta, t_\ell) = \int_0^\infty dE_\gamma P(E_\gamma, \theta) dN_\gamma/dE_\gamma. \quad (7)$$

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

$$\bar{n}(\theta, r) = \frac{N_\gamma(\theta, t_\ell) S(\theta)}{4\pi r^2}, \quad (8)$$

which will give an excess over the average counting rate.
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 $\bar{V} = 0$ 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 (7.9$\sigma$) 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 6$\sigma$. If we assume that the 7.9$\sigma$ 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 3.2$\sigma$ 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]

$$R_{\text{max}} = \sqrt{\frac{N_r(\theta, \bar{t} = 1\text{ s})S(\theta)}{4\pi n}}. \quad (10)$$

III. RESULTS AND CONCLUSIONS

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

$$V_{\text{eff}} = \int d\Omega \int dr r^2 F(n, \bar{n}(\theta, r)). \quad (11)$$

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. (8). Taking into account that no excesses above 6$\sigma$ were detected on Andyrchy, we put $n = 6\sqrt{\bar{\omega}} = 640$, and the effective volume for this array is, depending on the model: $1.2 \times 10^{-10}$ pc$^3$, $5.6 \times 10^{-10}$ pc$^3$, $8.1 \times 10^{-11}$ pc$^3$ for H97, DK02 and MW90, respectively. For RP, no excesses above 7$\sigma$ were observed (in this case $\bar{\omega} = 17200$, so, $n = 7\sqrt{\bar{\omega}} = 918$), and the effective volume is: $7.6 \times 10^{-11}$ pc$^3$, $4.1 \times 10^{-10}$ pc$^3$, $7.1 \times 10^{-11}$ pc$^3$ for H97, DK02 and MW90, respectively.
The number of bursts detected over the total observation time $T$ can be represented as

$$N = \rho_{pbh}TV_{\text{eff}}, \quad (12)$$

where $\rho_{pbh}$ 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 $\rho_{\text{lim}}$ on the number density of evaporating PBHs at the 99% confidence level using the formula

$$\rho_{\text{lim}} = 4.6/(V_AT_A + V_{RP}T_{RP}), \quad (13)$$

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 $\rho_{\text{lim}}$: $10^3$ pc$^{-3}$ yr$^{-1}$, $5 \times 10^3$ pc$^{-3}$ yr$^{-1}$, $6.8 \times 10^3$ pc$^{-3}$ yr$^{-1}$ for evaporation models DK02, H97 and MW90, respectively.

One can note, that in a case of the 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 [23]. 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 [29].

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REFERENCES

[1] J. H. MacGibbon, B. J. Carr and D. N. Page, Phys. Rev. D 78, 064043 (2008) [arXiv:0709.2380 [astro-ph]].
[2] J. H. MacGibbon and B. R. Webber, Phys. Rev. D 41, 3052 (1990).
[3] A. F. Hecker, Phys.Rev. Lett. 78, 3430 (1997).
[4] R. G. Daghigh and J. I. Kapusta, Phys.Rev. D 65, 064028 (2002).
[5] S. W. Hawking, Commun. Math. Phys. 43, 199 (1975) [Erratum-ibid. 46, 206 (1976)].
[6] S. W. Hawking, Phys. Rev. D 14 (1976) 2460.
[7] G. ’t Hooft, Int. J. Mod. Phys. A 11, 4623 (1996) [arXiv:gr-qc/9607022].
[8] S. B. Giddings and M. LipPERT, Phys. Rev. D 69, 124019 (2004) [arXiv:hep-th/0402073].
[9] S. B. Giddings, Phys. Rev. D 74, 106005 (2006) [arXiv:hep-th/0605196].
[10] G. ’t Hooft, Nucl. Phys. B 256, 727 (1985).
[11] L. Susskind, L. Thorlacius and J. Uglum, Phys. Rev. D 48, 3743 (1993) [arXiv:hep-th/9306069].
[12] C. R. Stephens, G. ’t Hooft and B. F. Whiting, Class. Quant. Grav. 11, 621 (1994) [arXiv:gr-qc/9310006].
[13] K. S. Thorne, R. H. Price and D. A. Macdonald, “BLACK HOLES: THE MEMBRANE PARADIGM,” NEW HAVEN, USA: YALE UNIV. PR. (1986) 367p.
[14] L. Susskind, [arXiv:hep-th/9309145].
[15] T. Damour and G. Veneziano, Nucl. Phys. B 568, 93 (2000) [arXiv:hep-th/9907030].
[16] G. T. Horowitz and J. Polchinski, Phys. Rev. D 55, 6189 (1997) [arXiv:hep-th/9612146].
[17] E. Halyo, B. Kol, A. Rajaraman and L. Susskind, Phys. Lett. B 401, 15 (1997) [arXiv:hep-th/9609075].
[18] L. Susskind, Phys. Rev. D 49, 6606 (1994) [arXiv:hep-th/9308139].
[19] V. Connaughton et al., Astropart. Phys. 8, 179 (1998).
[20] D. E. Alexandreas et al., Phys. Rev. Lett. 71, 2524 (1993).
[21] M. Amenomori et al., Proc. 24th International Cosmic Ray Conference, Rome (Italy), v.2, 112 (1995).
[22] B. Funk et al., Proc. 24th International Cosmic Ray Conference, Rome (Italy), v.2, 104 (1995).
[23] V. B. Petkov et al., Astron. Lett. 34, 509 (2008) [Pisma Astron. Zh. 34, 563 (2008)] [arXiv:0808.3093 [astro-ph]].
[24] E. T. Linton et al., JCAP 0601, 013 (2006).
[25] M. Aglietta et al., Astrophys. J. 469, 305-310 (1996).
[26] S. Vernetto, Astropart. Phys. 13, 75 (2000) [arXiv:astro-ph/0003254].
[27] V. V. Alexeenko et al., Nucl. Phys. (Proc. Suppl.) B 110, 472 (2002).
[28] V. B. Petkov et al., Kinematics and physics of celestial bodies 3, 234 (2003).
[29] V. B. Petkov, E. V. Bugaev, P. A. Klimai and D. V. Smirnov, JETP Lett. 87, 1 (2008) [Pisma Zh. Eksp. Teor. Fiz. 87, 3 (2008)] [arXiv:0803.2313 [astro-ph]].
[30] E. Bugaev, P. Klimai and V. Petkov, Proc. 30th ICRC, Mexico , v.3, 1123 (2007), [arXiv:0706.3778 [astro-ph]].
[31] V. B. Petkov et al., Instrum. Exp. Tech. 49, 785 (2006).
[32] E. N. Alekseev et al., Izv. Akad. Nauk Ser. Fiz. 40, 994 (1976).
[33] D. D. Dzhappuev et al., Bull. Rus. Acad. Sci.: Physics 71 N4, 525 (2007).