TERRESTRIAL BLACK HOLES AS SOURCES OF SUPER-HIGH ENERGY RADIATION

A. P. TROFIMENKO and V. S. GURIN

Astronomical Section of Minsk Department of Astronomical-Geodesical Society, Minsk, Byelorussia

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Abstract. Small black holes which can be located in the Earth interior are proposed as sources of superhigh energy radiation and their origin is not constrained to the Big Bang. We estimate the intensity and spectrum of massless and massive particles radiation due to the Hawking effect for black holes with masses of 10^8–10^{16} g and consider possibility of their registration according to the following peculiarities: high particle energies, thermal energetic spectrum, transientness or an explicit trend to the intensity and energy increase, and some expressed direction of emission connected with the source localization.

1. Introduction

The problem of quantum black hole (BH) evaporation is known to attract the significant attention, and in cosmology the concept of primordial BH was proposed which assume their origin due to the Big Bang (Zeldovich and Novikov, 1971; Hawking, 1971; Blanford and Thorne, 1979). This hypothesis is not removable completely, however it collides with many troubles since such BHs could provide observable effects due to electromagnetic radiation in the range from radio to γ-rays (Vainer, 1978; Jelley *et al.*, 1977; Porter and Weekes, 1977) and estimations in these works gave only the values of upper limits for the concentration of small BHs in Galaxy. These calculations have indicated the very small contribution of small BHs in the cosmic background, and determination of the observable limit in optics, for radiowaves, and gamma rays have given no footings to justify this hypothesis.

Although black holes are considered conventionally as objects of study in astrophysics of stars, galaxies, and their clusters, where theoretical constructions of models connected with them are realized, but equations of general relativity do not give themselves explicit restrictions on mass of BH them. Ideas on possible occurrence of small BHs within interior of cosmic objects in stars, in planets of the Solar system were proposed by Trofimenko (1989, 1990a), Clayton *et al.* (1975), Fogg (1989) (see also Gribbin, 1990), and particularly in the Earth by Trofimenko (1990a,b, 1991). In spite of non-triviality such propositions do not contradict to observable facts and even can help to explain some puzzling phenomena associated with different bodies of the Solar system. The most specific manifestation of small BHs should be expected at small distances, that is possible for cosmic BHs only in the case of their nearest location. In this respect BHs in the Earth are essentially more discoverable. It should be pointed out that the proposi-

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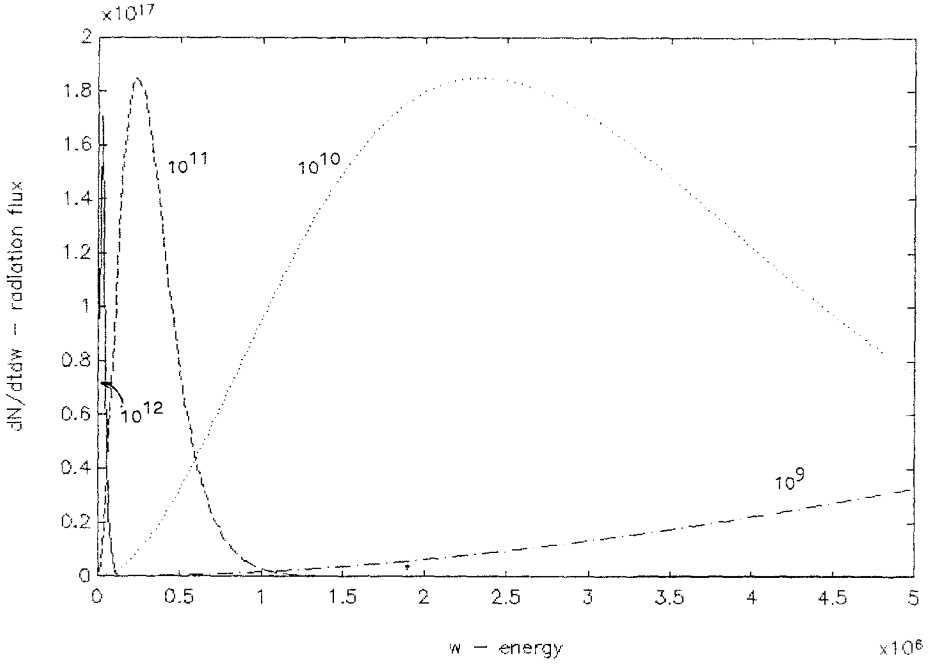

Fig. 1(a).

tion on BHs in planets does not exclude cosmological ones, a part of them can enter planets and other cosmic bodies. The expectation of BHs in bodies of condensed matter is even more probable than their single isolated existence in space due to gravitational trapping.

It is a very essential fact in this topic that BHs of small mass (10^8–10^{15} g) have less-than-atom sizes, and, likely, interact very weakly with matter of the bodies in which they occur (Greenstein and Burns, 1984). Therefore their long existence within dense bodies appears quite feasible with no explicit manifestations.

The one of specific features of small BHs, which is distinctive as compared with BH of star mass, is the Hawking radiation. The Hawking effect is noticeable for BH with mass not more 10^{20}–10^{25} g. It consists in emission of the set of elementary particles, and the less the BH mass the more probability to emit massive particles and particles of high spin (Thorne, 1986). But, the main part of emitted quanta are massless ones, and the radiation flux is falling down sharply for photons and gravitons. As far as massless scalar particles are not discovered, neutrino is to be the expected main part in the the small BH radiation with masses 10^{12}–10^{18} g. With decreasing BH mass during the radiation process another particles will be radiated: electrons and positrons, muons, pions, etc. Such radiation due to the Hawking effect can become one of observational manifestations of micro-BHs in the Earth, and a useful mean of search for small BHs. Taking into account the

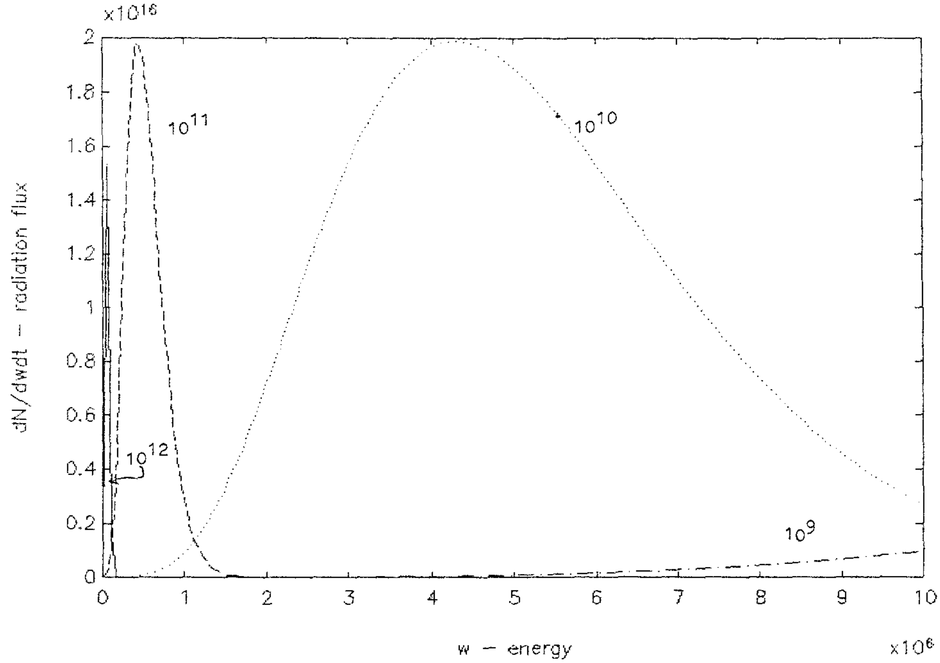

Fig. 1(b).

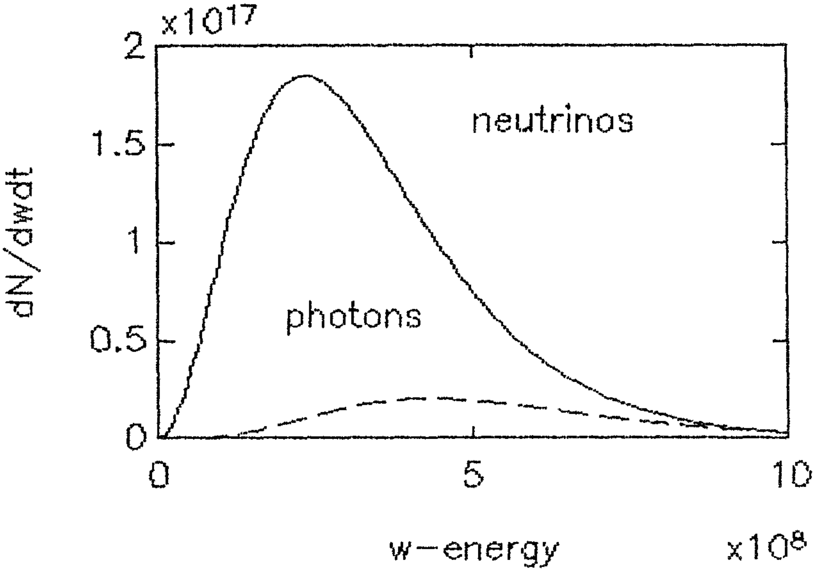

Fig. 1(c).

Fig. 1. Rate of radiation of massless particles with spin-1/2 (neutrino); (a) and with spin-1 (photons), (b) from BHs of different M_{BH} (numbers near curves, $dN/dt\,d\omega$, $s^{-1}\,\mathrm{MeV}^{-1}$), (c) shows rates neutrino and photons radiation from BH with $M = 10^8$ g.

high penetrativeness of neutrino and extensively investigated cosmic neutrino radiation a discovery of the higher neutrino flux from the Earth interior could be ponderably evidenced in support of occurrence of a BH within our planet. In contrast to neutrino another particles although easier detectable but have worse penetrativeness in matter. The latter can be suitable only for particles of superhigh energy, which together with excess of neutrino flux above the background within present propositions are expectable, e.g., near the active volcanos and as 'hot points' which are conditioned or stimulated the seismic activity. The origin of these small BHs in the Universe of complicated topology (Trofimenko, 1991) can be considered as the generalized cosmological one, but in contrast with the standard Friedmannian model it has no restrictions for time of evolution and for immediate connections of parameters of early Universe with those measured now.

2. Spectrum and Rates of Particles Emission from BH

We shall carry out calculations of particle emission features and deal with the emission from non-rotating BHs, since integral characteristics of radiation depend on the fact of rotation rather weakly. Moreover, a fast rotating BH and in a more degree a charged one in interiors of dense bodies will speedly dump its rotating momentum and charge due to environmental interaction.

General formulae for massless particles emission with certain quantum numbers from a BH for decrease of BH mass due to emission of particles with quantum numers l, m, p are (cf. Page, 1976)

$$(\mathrm{d}M/\mathrm{d}t) = -(1/2\pi) \sum_{l,m,p} \int \Gamma_{\omega lmp}\{\exp(8\pi M\omega) \pm 1\}^{-1} \omega \, \mathrm{d}\omega \,, \tag{1}$$

where M is BH mass at the given time, ω is energy of particles (we use the geometrized units: $G = c = \hbar = 1$), and ± correspond for fermions or bosons emitted, respectively. We shall compare contributions from leading modes for different kinds of particles at small energies and from all modes in the case of high energies.

Taking into account the dominating contribution of modes with $l = s = 1/2$ for massless quanta (e.g., neutrinos)

$$\Gamma_{\omega lmp} = M^2\omega^2 \,, \tag{2}$$

for spin-1 quanta (e.g., photons)

$$\Gamma_{\omega lmp} = (64/9)\mathrm{M}^4\omega^4 \,, \tag{3}$$

and for massive spin-1/2 particles (e.g. electrons, muons)

$$\Gamma_{\omega lmp} = \frac{2\pi(\omega + \mu)M^3\omega^3[1 + (1 - \mu^2/\omega^2)]}{1 - \exp\{-2\pi M\omega(1 + (1 - \mu^2/\omega^2)][1 - \mu^2/\omega^2)^{-(1/2)}\}} \,. \tag{4}$$

At high energies of emitted quanta $\Gamma_{\omega lmp}$ shall have the value of the geometric optical cross-section same for all kinds of particles (McGibbon and Webber, 1990)

$$\Gamma_{\omega lmp} = 27M^2\omega^2 . \tag{5}$$

In our case this high energy limit is valid for BH with $M < 10^{12}$ g.

The radiation spectrum $\mathrm{d}N/\mathrm{d}t\,\mathrm{d}\omega$ is determined by the integrand (1) with the corresponding substitution of (2–5)

$$\mathrm{d}N/\mathrm{d}t\,\mathrm{d}\omega = \Gamma_{\omega lmp}/(\exp(8\pi M\omega) \pm 1) .$$

Furthermore we give the results of calculations for parameters of BHs which could occur presumably in the Earth's interior.

The massless neutrino radiation spectrum of the Schwarzschild black hole is the almost symmetric bell-like curve, and location of its maximum determined by mass of BH (Figure 1).

Energetics of emitted particles depends on the single parameter very essentially, and BHs with $M > 10^{10}$ g radiate neutrinos with energies > 1 TeV. That is very contrasting with solar neutrino when energies are not more than 15 MeV, for BHs of the given mass range a more energetic (by a factor of 10^3–10^4) particles are expectable. The full flux of the particles radiated due to this process in the form of neutrino around the whole spectrum or some spectral range is obtained by integrating the expressions $\mathrm{d}N/\mathrm{d}\omega\,\mathrm{d}t$, and in the case of six kinds of massless (or with negligible mass) neutrinos,

$$\mathrm{d}N/\mathrm{d}t = 4.365 \times 10^{34}/M\,s^{-1} . \tag{6}$$

For each kind of fermionic pairs with the rest mass 10 MeV

$$\mathrm{d}N/\mathrm{d}t = 2.266 \times 10^{34}/\mathrm{M\,s}^{-1} . \tag{7}$$

For photons the total flux for the leading radiation mode (both polarizations)

$$\mathrm{d}N/\mathrm{d}t = 3.5822 \times 10^{34}/\mathrm{M\,s}^{-1} . \tag{8}$$

Evidently, for high energy limit the full flux for each kind of massless particles will be determined by the similar correlation with other factors: i.e.,

$$\mathrm{d}N/\mathrm{d}t = 1.964 \times 10^{35}/\mathrm{M\,s}^{-1} ,$$

and at last the multiplication by the number of possible particles will give the value of total flux from BH.

It should be pointed out that the total neutrino spectrum from a small BH will be rather specific as compared with other known neutrino sources in the connection with existence of ν_μ (Lederman, 1982) and ν_τ (Perl, 1975), which will give practically equal parts into the full flux. In other words, the neutrino flux consists of six parts corresponding to the three $\nu - \bar{\nu}$ pairs with equal energies and power.

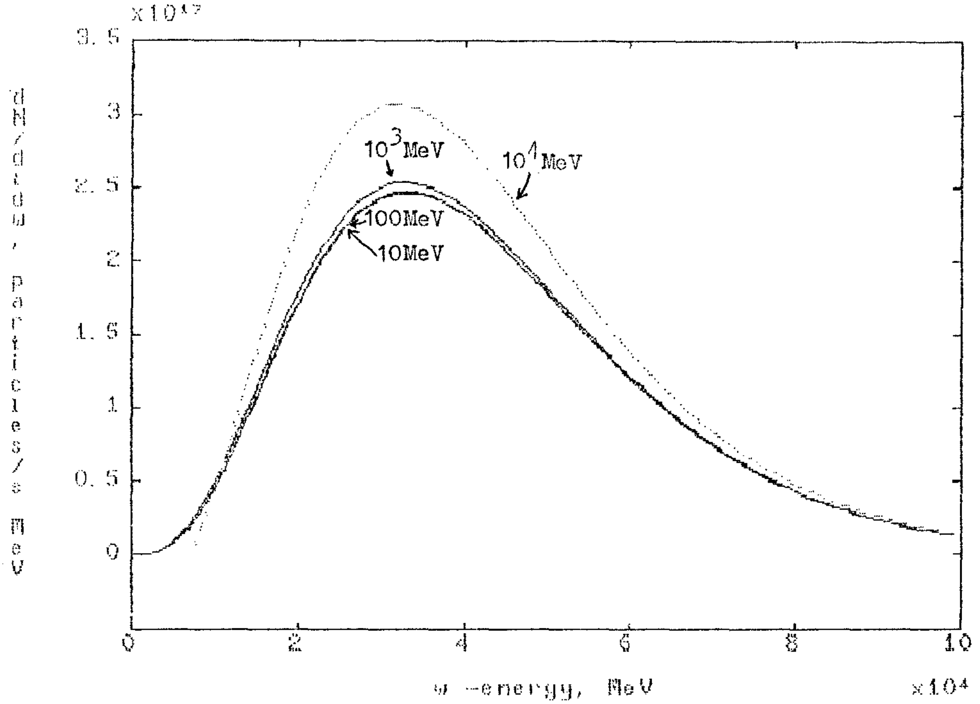

Fig. 2. Rates of radiation from BH with $M = 10^{12}$ g for spin-1/2 particles with different rest masses: $1 \div 10\,000$ MeV.

From the formula (4) and Figure 2 one can see that rest masses supposed for ν_e and ν_μ, and even for ν_τ ($\leqslant$45 MeV) (Boehm and Vogel, 1987) do not have practical effect on the spectrum and integral flux in the range of $M_{\mathrm{BH}} < 10^{14}$–$10^{15}$ g when particles with energy higher than 10^3–10^4 MeV are emitted, since the term $1 - \mu^2/\omega^2 \approx 1$ and the contribution in $\omega + \mu$ is also can be neglected. The outlook of the spectrum in $\omega + \mu$ is also can be neglected. The outlook of the spectrum as the whole is similar with that of massless particles, and the total flux and the location of maximum of $\mathrm{d}N/\mathrm{d}t\,\mathrm{d}\omega$ are not distinct essentially. Moreover, by increase of particles energy the effect of their rest mass upon the features of emission becomes less, and for energies above 10 GeV these differences can be neglected for all known particles. However, the flux due to presupposed fourth type of neutrino mass of which ~45 GeV appear only at last steps of BH evaporation after protons and neutrons (quarks).

3. High Energy Particles Due to Explosions of Micro-BHs

The above formulas reflect the contribution of one kind of spin-1/2 particles, and to calculate exactly radiation of different generations particles it should be considered the spectrum of each kind.

In order to consider the dynamics of particles flux, which is seen to be not constant since mass of evaporation BH decreases, we assume firstly the model including 104 particles (Olensis and Hill, 1984) of the electroweak scheme (Weinberg, 1980; Salam, 1980; Glaschow, 1980). It includes 90 of spin-1/2 fermions, and because of the effect of rest mass in the range of these particles upon the rate of neutrino emission is rather small, we may multiply the values for emission of one kind of particles by the factor of 100 for the rough estimation of the total flux. Quasistationary approximation used by derivation of the Hawking radiation from BH remains true in this range of energies, since the specific time scale of quantum gravitational effects, $t_{pl} \approx 10^{-44}$ s and time scale for BH, r_g/c, is much less than time of BH existence in the above range of masses. Then time of BH existence will be of the order $\tau = M^3/3\alpha$, where $\alpha \approx 10^{-3}$. Effects of grand unification, likely, will contribute in the range of energies above 10^{15} GeV. For $M_{\mathrm{BH}} \leq 10^8$ g, α must have the more value.

Unstable particles will be created by BHs under consideration and transformed into stable ones (γ, e, ν, p, etc.), i.e. as the result the total flux will include quanta from decay of lower-spin mesons and hyperons (η, Λ, Σ, Ξ, etc.).

BHs with mass of 10^8–10^9 g emit particles with energy more than 1 TeV for BHs and live only 0.001–0.1 s. Their last instant will be manifested as a considerable transient burst of diversity kinds of decaying particles rather than a stationary flux. It can produce in principle all known particles and resonanses and also give new kinds of particles at energies not attainable by means accelerators and colliders. This feature can help to pick out a 'signal' from BH as compared with the background cosmic one and claims the special requirements to the detecting equipment and experimental conditions.

As the most probable range of BH masses from the point of view of their registration by means of quasistationary neutrino emission we can propose 10^{11}–10^{12} g (from time of the order days up to several years) (Figure 3). Their life time is suitable for experiment during which the rising of neutrino flux should be expected with the outmost burst at the end. And this final explosion, probably, will appear as the single event, since the effect of BH mass upon the radiation spectrum will be the more and more expressed by approximating to the final step of BH evaporation. Even if the number of BHs in the Earth is 10^8–10^9, restricted by the mass of the planet and their energetics a simultaneous explosion of two BHs is hardly probable, but mass distribution of BHs can be rather wide: 10^{13}–10^{27} g. In other words, it should be expected non-correlated bursts of particles from deep-located BHs up to the centre of the Earth and from near-surface BHs another particles of high energy are detectable. The same direction of these fluxes will be evidence in support of their BH origin.

Energy of particles from BHs exploding at the final step ($M_{\mathrm{BH}} \sim 10^8$–$10^{10}$ g) can attain values higher 100–1000 TeV and are expectable as transient bursts from micro-BH located or moving under the Earth's surface.

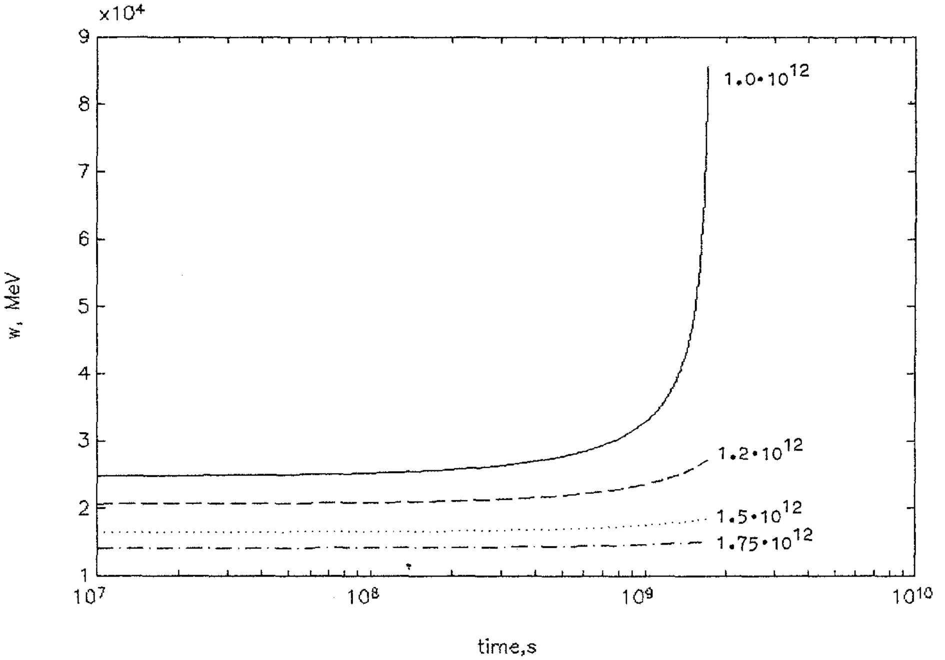

Fig. 3. Variations of maximum in energy spectrum ($\omega_{\max}$) for BH with $M_0 = 10^{12}$ g with time.

4. Absorption in Matter

In order to solve the question on neutrino flux registration from BHs localized presumably in planets let us consider estimations for cross sections of neutrino absorption, e.g., ν_e, due to the interaction with electrons in non-degenerated electron gas (interactions with protons and neutrons have less cross sections), that can occur by neutrino detection. The value of the cross section depends in a great extent on energetics and is determined for high energies $E_\nu \gg mc^2$, according to the following formulae (Lang, 1974)

$$\sigma \approx 0.85 \times 10^{-44}(E_\nu/mc^2)\,, \qquad (9)$$

where m is the electron mass.

It can be noticed that in both the cases the detection of particles of more high energy is more probable, contribution of them is high for BHs of less mass. In contrast to solar neutrino energies, terrestrial BHs can emit neutrinos with energies > 1 GeV that by a factor of 10^2–10^3 is higher than the absorption cross section. Consequently, the location of neutrino detectors of existing constructions near the presupposed places of BH localization (outcomes to the surface) is to be lead to abrupt excess of particle flow as compared with background and solar one should be registered. Its direction will evidence on possible localization of its source, i.e., BHs. Active volcanos are ones such proposed placed, but neutrino detectors are located respectlessly to the geological activity, because of that no anomalous high flux from localized sources could be detected in current experiments since it decays fastly removing from a source.

Another particle of superhigh energy which also can have the high penetrativeness in matter (Ginzburg, 1981) (of course, lower than ν) and can be detected as bursts with the characteristics similar to those for neutrino flux. At high energies ionization losses of a high energy particle in matter decrease according to the familiar Bethe–Bloch formula

$$-(\mathrm{d}E/\mathrm{d}l) = (2\pi e^4 N/mc^2)[\log(E^3/mc^2E_i^2) - 2], \quad E \gg mc^2, \tag{10}$$

where e and m are charge and mass of electron, N is concentration of electrons in matter being ionized (E_i – ionization potential, $E_i \ll E$) by penetrating particles. According to this formula there is no essential growth of ionization losses with increase of E, and particles with high amount of initial energy can have very long paths in the Earth's matter. For instance, particles with $E > 10^6$ MeV (emitted by BHs with $M \geqslant 10^{10}$ g) could pass thousands of km.

There exist another hypothetical propositions about objects similar to micro-BHs in their manifestation, and they also could be entered planets, in particular, the Earth: maximons of the Planckian mass, $\sim 10^{-5}$ g (Markov, 1966), nuclearities – objects of the density intermediate between BH and neutron stars (De Ru'jula and Glashow, 1984), tachyons (Gurin and Trofimenko, 1990) which also can weakly interact with matter, in particular in the higher-dimensional interpretation of superluminal objects with no violating causality problem (Gurin and Trofimenko, 1990). Moreover, features of space-time structures of tachyonic field (Gurin, 1985) can provide itself the appearance of a Hawking-like radiation. Thus, all above objects with highly penetrativeness in matter ought to become sources of high energetic radiation including the neutrino component.

Absorption in matter due to the process of pair creation, likely, will the leading one for photons emitted from BHs. Its effectivity does not depend practically on energy of quanta in the range $E > 100$ MeV – 1 GeV, and decay of photon intensity can be expressed by the formula by Perkins (1987), of the form

$$I = I_0 \exp(-\rho l/l_0), \tag{11}$$

where ρ is density of matter, and l_0 does the characteristic length which is specific for each material. For most of the substances which constitute the Earth it varies in range 10–50 g/cm^2. Photons will be adsorbed very noticeably, and we can see that even if their initial flux is very high, e.g. $\mathrm{d}N/\mathrm{d}t > 10^{20}\,\mathrm{s}^{-1}$ possible for $M_{\mathrm{BH}} < 10^{12}$ g, so radiation can be detected only from a surface source (not deeper several meters). However, peculiarities of radiation flux from micro-BH also will be from these sources, and simplicity of detecting devices for photons provides possibility of search of similar sources with BH-like features.

5. Conclusions

Thus, micro-BHs in the Earth can become in the case of their discovery the very fruitful 'laboratory' of superhigh energy physics for justification of theoretical schemes in the ranges not available by means of most powerful modern accelerators. Technique of high energy beam registration must be applied to investigation of neutrino (and other particles) flux from BHs (Steinberger, 1989).

The most specific features of particle radiation flux from micro-BHs which must be used for their detection or for analysis of data obtained up to now from the point of view BH-like bursts:

(i) Wide energetic spectrum up to the range 1 TeV and higher and the shift to the higher energies of must occur by exhausting of BH mass.

(ii) Radiation is to possess the thermal spectrum, its maximum depends on value of BH mass (and other its parameters).

(iii) Transient character of radiation for small BH masses, increasing during several days with the final high energetic burst;

(iv) Explicit direction of radiation and abrupt decay of intensity depending on the distance up to a presupposed source.

On the basis of these data one can propose the implication of neutrino detectors (for example, Kamiokande, IMB) for registration of particle flux from the Earth interior in the ranges of energies 10–100 MeV and also the search of neutrino fluxes with superhigh energy (100 GeV – 1 TeV and more) showing a transientness or explicit variability with time in the projects of DUMAND and BAIKAL.

For other kinds of particles (electrons, muons) there are many sources which will make intensive background for discovery of BH radiation. Above features should be used for analysis of different transient sources, and correlation with another BH-like 'signals' (neutrino bursts, variation of gravitational potential) could evidence in support of the hypothesis of planetary BHs (otons).

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