Hawking evaporation of cosmogenic black holes in TeV-gravity models

P Draggiotis\textsuperscript{1}, M Masip\textsuperscript{1} and I Mastromatteo\textsuperscript{1,2}

\textsuperscript{1} CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain
\textsuperscript{2} Dipartimento di Fisica Teorica, Università degli Studi di Trieste, I-34014 Trieste, Italy
E-mail: pdrangiotis@ugr.es, masip@ugr.es and iacopomas@infis.univ.trieste.it

Received 16 May 2008
Accepted 26 June 2008
Published 22 July 2008

Abstract. We study the properties of black holes of mass $10^4$–$10^{11}$ GeV in models with the fundamental scale of gravity at the TeV. These black holes could be produced in the collision of a ultrahigh energy cosmic ray with a dark matter particle in our galactic halo or with another cosmic ray. We show that QCD bremsstrahlung and pair production processes are unable to thermalize the particles exiting the black hole, so a chromosphere is never formed during Hawking evaporation. We evaluate with HERWIG the spectrum of stable four-dimensional particles emitted during the Schwarzschild phase and find that in all cases it is peaked at energies around 0.2 GeV, with an approximate 43% of neutrinos, 28% of photons, 16% of electrons and 13% of protons. Bulk gravitons are peaked at higher energies; they account for 0.4% of the particles (16% of the total energy) emitted by the most massive black holes in $n = 6$ extra dimensions or just the 0.02% of the particles (1.4% of the energy) emitted by a 10 TeV black hole for $n = 2$.

Keywords: ultra high energy cosmic rays, black holes, extra dimensions, quantum gravity phenomenology
1. Introduction

The coexistence of the electroweak and the Planck scales has been the main motivation for model building in particle physics during the past 30 years. Early proposals like technicolor or supersymmetry could explain dynamically the hierarchy between these two scales, although the new physics that they suggest has been so far absent in collider experiments. More recent proposals offer new and very interesting possibilities. In particular, the presence of extra dimensions could imply a fundamental scale of gravity $M_D$ much lower than $M_P = G_N^{−1/2} ≈ 10^{19}$ GeV [1]. If $M_D$ were near the TeV region, then the electroweak scale would just introduce a little hierarchy problem, which could be easier to solve consistently with collider data [2].

In contrast with the usual scenario, an amusing feature in these TeV-gravity models is that $M_D$ is at accessible energies and the transPlanckian regime can in principle be probed [3]. Actually, due to the spin 2 of the massless graviton the collision of two point-like particles at transPlanckian energies ($\sqrt{s} \gg M_D$) and large distances ($b \gg M_D^{−1}$) should be dominated by gravity. In such collisions one would expect the collapse of the two particles into a black hole (BH) of mass $M \approx \sqrt{s}$ with an approximate cross section

$$\sigma = \pi r_H^2,$$

where $r_H$ is the radius of the BH horizon. Note also that the exchange of the large momenta required to see string resonances [4] or other quantum gravity effects would take place here at shorter distances: all the details of the complete theory that describes quantum gravity will be screened by the BH horizon. As the collision energy increases, $r_H$ grows and the collapse into a BH involves larger distances, a regime where classical gravity (strongly coupled but with no loops [5]) should work well.

The production of microscopic BHs at the LHC has been extensively considered in the literature [5]–[9]. It seems difficult, however, to imagine a framework able to accommodate such expectations. First of all, the mechanism that defines a consistent theory of gravity should also manifest below $M_D$ while being consistent with all precision data. If, for
example, gravity derives from string theory, the string scale $M_S$ will be a loop factor smaller than $M_D$ [4]:

$$M_S^{n+2} = \frac{g^4}{8\pi} M_D^{n+2},$$

(2)

with $n$ the number of large extra dimensions$^3$. Second, even if $M_D$ is as low as a few TeV, the $\sqrt{s}$ at the parton level accessible at the LHC cannot be much larger. The BHs that one may expect there will be near the threshold $M_D$, where they would appear almost indistinguishable from a massive string mode.

In this paper we focus on much larger mini-BHs, of masses up to $10^{11}$ GeV. They could result from the collision of a cosmic ray (a proton or a cosmogenic neutrino) with a dark matter particle in our galactic halo or with another cosmic ray. First we estimate the production rate of these cosmogenic BHs. Then we describe their Hawking evaporation (temperature, emission rate, lifetime) including in the evaluation the graybody factors for the different particle species. An important point that we address is the formation of a chromosphere or a photosphere around the BH during its evaporation. We show that, despite the large temperature (between 1 and 300 GeV$^1$), strong or electromagnetic interactions are unable to thermalize the particles exiting the BH, so their energy is not altered by this factor. Finally, using the code HERWIG [11] (which simulates the fragmentation of colored particles as well as particle decay) we derive the spectrum of stable species (protons, electrons, photons and neutrinos) and of bulk gravitons produced in the evaporation of a BH of given mass. Previous works on BH production by cosmic rays refer to the collision of a cosmogenic neutrino with an atmospheric nucleon [12] or a cosmic ray with a nucleon in the interstellar medium [13].

2. Black hole production at ultrahigh energies

We observe a flux of cosmic rays (most of them are protons free or bound in nuclei) [2] that reach the Earth with energies of up to $10^{11}$ GeV. Their production and propagation induces a flux of (still unobserved) cosmogenic neutrinos peaked at energies near $10^9$ GeV [14]. For example, a km$^2$ area in the upper limit of the atmosphere would receive around $10^4$ protons and $10^5$ neutrinos$^4$ of energy between $10^8$ and $10^{11}$ GeV yr$^{-1}$.

In addition, it is thought that 90% of the matter in our galaxy ($10^{12}$ solar masses) is dark: $10^{69}$ GeV of mass in a sphere of 200 kpc, with an approximate density profile$^5$

$$\rho(r) \approx \frac{\rho_0}{(r/R) (1 + r/R)^2},$$

(3)

with $R = 20$ kpc (we are at 8 kpc from the center, 1 kpc = $3 \times 10^{19}$ m). This dark matter would be constituted by a weakly interacting massive particle $\chi$ of mass $m_\chi \approx 100$ GeV, although $m_\chi$ could go from 10 MeV to 10 TeV if its interaction strength goes from gravitational to strong [15].

$^3$ See the appendix in [10] for the relation of $M_D$ to $M_*$.  
$^4$ We take the neutrino flux in figure 2 of [14].  
$^5$ We assume a CUSP dark matter distribution [16].
Hawking evaporation of cosmogenic black holes in TeV-gravity models

Figure 1. Cross sections to produce a BH for $n = 2$ and $M_D = 1$ TeV.

Therefore, we find two types of elementary processes involving center-of-mass energies above $M_D$.

(i) The collision of a cosmic ray of energy $E$ with a dark matter particle. Here $\sqrt{s} = \sqrt{2m_\chi E}$ may go up to $10^7$ GeV. The number of interactions to produce a BH per unit time and volume in terms of the dark matter density ($\rho_\chi = \rho/m_\chi$), the flux (integrated over all solid angles) and the cross section is

$$\frac{d^2 N}{dt dV} = 4\pi \int dE \sigma_{i\chi}(s) \frac{d\phi_i}{dE} \rho_\chi.$$  (4)

(ii) The collision of two cosmic rays. The center-of-mass energy for a relative direction $\theta$ between the two particles is $\sqrt{s} = \sqrt{2E_1E_2(1 - \cos \theta)}$, which can reach $10^{12}$ GeV. Given the two fluxes and the cross section, the number of interactions producing BHs is just

$$\frac{d^2 N}{dt dV} = 16\pi^2 \int dE_1 dE_2 d\cos \theta \sigma_{ij}(s) \sin \theta/2 \frac{d\phi_i}{dE_1} \frac{d\phi_j}{dE_2}.$$  (5)

It is then necessary to evaluate the BH production cross section $\sigma_{ij}$, where $i, j$ label a proton, a neutrino or a $\chi$. We will assume that all particles except for the graviton live on a four-dimensional brane, that there are $n$ flat extra dimensions of common length, and that $r_H$ is just the higher-dimensional Schwarzschild radius:

$$r_H = \left(\frac{2^n\pi^{n-3}/2 \Gamma((n+3)/2)}{n+2}\right)^{1/(n+1)} \left(\frac{M}{M_D}\right)^{1/(n+1)} \frac{1}{M_D},$$  (6)

where $M \approx \sqrt{s}$ is the BH mass. It is then easy to find the cross section $\sigma_{\nu\nu}$ (or $\sigma_{\nu\chi}$) between two point-like particles; we plot it in figure 1 for $n = 2$ and $M_D = 1$ TeV.

The calculation is not that simple in $p\nu$ or $pp$ collisions, as at short distances the interaction involves partons. Actually, the expression for point-like particles still holds at very large energies, when $r_H > 1$ fm and the BH is large enough to contain the proton. In that case the neutrino interacts coherently with the whole proton and $\sigma_{p\nu}(s)$ just
Hawking evaporation of cosmogenic black holes in TeV-gravity models coincides with $\sigma_{\nu\nu}(s)$. At low $s$, the case extensively discussed in the previous literature, the neutrino interacts with a single parton carrying a fraction $x$ of the proton momentum and they collapse into a BH of mass $M = \sqrt{x s}$. The cross section is

$$\sigma_{p\nu}(s) = \int_{M_D^2/s}^{1} dx \left( \sum_i f_i(x, \mu) \right) \sigma(x s). \quad (7)$$

At higher energies more partons in the low $x$ region are able to produce BHs, $\sigma_{p\nu}$ quickly grows and equation (7) becomes no longer reliable. A value of $\sigma_{p\nu} \approx 20$ mb indicates that all neutrinos approaching with impact parameters smaller than the proton radius will interact with a parton to form a BH. Obviously, increasing the energy in the collision we cannot get larger cross sections unless the typical BH produced has a $r_H$ similar to the proton radius (the regime discussed before).

Therefore, we distinguish three regimes in the $p\nu$ interaction to produce a BH. At low energies the neutrino interacts with a single parton, the cross section grows with $s$ but the average mass $M$ of the BH is roughly constant and close to the threshold $M_D$. Once it approaches 20 mb, the cross section remains constant, but the typical BH mass increases with the energy. In this regime the process involves multiple scattering, in the sense that the BH produced in the collision will also trap spectator partons. Finally, at higher energies (not in the plot) the proton becomes point-like and the cross section grows just like $\sigma_{p\nu}$. In figure 1 we have modeled a smooth transition between these regimes by discretizing the proton and discounting the overlapping between parton cross sections. The $pp$ collision (also in figure 1) is completely analogous, although the 20 mb bound on $\sigma_{pp}$ is saturated at $\sqrt{s} \sim 10^7$ GeV (notice that this effect is still negligible at LHC energies).

We can now estimate the BH production rate in the two types of processes discussed above. In figure 2 we plot the number and mass distribution of BHs produced in the collision of a cosmic ray (a proton or a cosmogenic neutrino) with another cosmic ray or with a dark matter particle per year and per cubic astronomical unit (1 AU = $1.5 \times 10^{11}$ m, the mean Earth–Sun distance). We have taken the expected dark matter density at our position in the galaxy ($\rho = 0.3$ GeV cm$^{-3}$) and $m_\chi = 100$ GeV.

### 3. Black hole evaporation

Once produced the BH will go through a fast balding phase, where it loses its gauge hair and asymmetries, and a relatively brief spin-down phase [8]. For most of its lifetime the BH will be Schwarzschild-like, and it will emit Hawking radiation [17] with an approximate black body spectrum of temperature

$$T = \frac{n + 1}{4\pi r_H^2}. \quad (8)$$

Notice that, given $r_H$, the energy radiated by the BH will not depend (up to factors of order one) on the number of extra dimensions: on dimensional grounds $\dot{E} \sim A_{2+n} T^{4+n} \sim 1/r_H^2 \sim T^2$. Since a bulk and a brane field see a BH of the same temperature ($T$ is constant along the BH surface), the BH will emit a similar amount of energy of both fields [18].
Hawking evaporation of cosmogenic black holes in TeV-gravity models

Figure 2. Spectrum of BHs produced in cosmic ray collisions for $n = 2$, $M_D = 1$ TeV, $m_\chi = 100$ GeV, and the upper neutrino flux in [14].

The spectrum of particles exiting the BH must cross the strong gravitational potential near the horizon in order to escape to infinity [19]. This effect is usually described in terms of the graybody factors $\Gamma_s = \sigma_s / A_{2+n}$, where $\sigma_s$ is the absorption cross section for a particle of spin $s$ living in $4 + n$ dimensions and $A_{2+n}$ is the BH area seen by that particle. The average emission rate for a four-dimensional particle of energy $\omega$ is then

$$\frac{d^2 N_i}{d\omega dt} = \frac{A_2}{8\pi^2} \frac{c_i \Gamma_s \omega^2}{\omega^2 - (-1)^{2s}}.$$  \hspace{1cm} (9)

ci being the multiplicity of the species. Throughout the paper we use for the four-dimensional particles the (numerical) graybody factors given in [20], together with the expressions in [21] for the higher-dimensional graviton. The emission into bulk gravitons can be significant for a large number of extra dimensions, for example, it accounts for 16% (1.6%) of the radiated energy for $T = 10$ GeV and $n = 6$ ($n = 2$). In our numerical estimates we will only consider the emission of (relativistic) particles lighter than the BH temperature, including at $T < 1$ GeV no colored particles but pions as fundamental degrees of freedom. Notice that the emission will be dominated by quarks and gluons, as these cosmogenic BHs have a temperature above $\Lambda_{QCD}$.

It is straightforward to integrate (9) over all frequencies and sum over all particle species to deduce the BH mass loss per unit time. In figure 3 we plot the correlation between lifetime, mass and temperature for $M_D = 1$ TeV and $n = 2, 6$. We see, for example, that a $10^{13}$ GeV BH lives (at rest) around $10^{-14}$ s and has an initial temperature of 0.6 GeV for $M_D = 1$ TeV and $n = 2$.

4. Chromosphere around evaporating black holes

An important point raised by Heckler in 1996 [22] is that BHs above some critical temperature $T_c \approx m_e / \alpha^{5/2}$ may form a surrounding photosphere (a plasma of electrons and photons) of outer temperature $T \approx m_e$. The photosphere would thermalize to this low temperature the particles exiting the BH, changing dramatically the initial graybody spectrum. Moreover, he argued that QCD processes would also define a chromosphere.
Hawking evaporation of cosmogenic black holes in TeV-gravity models

**Figure 3.** Correlation between mass, temperature, and lifetime of a BH for $M_D = 1$ TeV and $n = 2, 6$.

in BHs of $T > \Lambda_{QCD}$, a fact that could affect, for example, the Page–Hawking limits on primordial BHs. After Heckler’s initial claim there have been several analyses of photo/chromosphere formation \[23,24\], although their existence has been considered controversial. In particular, none of the several codes simulating BH production at the LHC \[7\] has included its effect.

Recently two different groups (Alig, Drees and Oda \[25\], and Carr, MacGibbon and Page \[26\]) have reanalyzed this issue and have concluded that bremsstrahlung and pair production processes are not able to form a photo/chromosphere around evaporating BHs. The key argument is that the scattering of two particles radiated away from a BH cannot be treated in the same way as the ordinary collision of a particle against a target, since the kinematics are completely different. In the radial case the particles are not coming from an infinitely far past, they are created in a definite point of space–time. In addition, the two particles are always separating (never approaching), a fact that introduces a maximum radius in which the process can take place. Although a general formalism to describe the radial scattering is not available, it is clear that the calculation of the interaction rate as

$$\Gamma = \langle \sigma v \rho \rangle \quad (10)$$

can lead to incorrect results. In this section we use the approach in \[26\] to show that the higher-dimensional BHs of mass up to $10^{11}$ GeV under analysis here do not form a chromosphere: quarks and gluons escape the BH (at distances around $1/\Lambda_{QCD}$ they fragment into hadrons, see section 5) with basically the initial energy. This result is consistent with the detailed Monte Carlo simulation in \[25\].

To be definite we will take a very hot (LHC-like) BH, with a temperature around $T = 100$ GeV, and $M_D = 1$ TeV for $n = 3$. We find that such BH emits quarks or antiquarks of energy $E \approx 3T$ with a frequency of one per $\tau \approx 0.8/E = 0.8/\gamma m_q$ (see table 1). Once a quark exits the BH, it will be localized along an approximate radial distance of $\lambda \approx 1/E$ (its reduced Compton wavelength). Therefore, it can overlap significantly only with two or three other quarks, the rest of the quarks being separated by a distance of order $1/E$ or larger.
Hawking evaporation of cosmogenic black holes in TeV-gravity models

Figure 4. In a regular scattering $q_1$ comes from $-\infty$ with impact parameter $b$, whereas here $q_1$ is created at a minimal distance $d$.

Table 1. Average distance between consecutive electrons $(1/\nu_e)$ and quarks $(1/\nu_q)$ in reduced Compton wavelength units $(1/E)$. The last line refers to the primordial four-dimensional BHs in [26].

| n  | $1/\nu_e$ | $1/\nu_q$ |
|----|-----------|-----------|
| 2  | 16        | 1.3       |
| 3  | 9         | 0.8       |
| 4  | 7         | 0.7       |
| 5  | 5         | 0.4       |
| 6  | 4         | 0.3       |
| 0  | 175       | 20        |

It is easy to see that the probability that the quark interacts with one of these non-overlapping quarks is negligible just because they are too far. The argument goes as follows. Suppose that the quark $q_1$ exiting the BH interacts with a quark $q_0$ at a distance of $k > 1$ Compton wavelengths $(1/E)$ in the BH frame. The bremsstrahlung process is best understood in the rest frame of $q_0$; there $q_1$ interacts with the field generated by the static $q_0$, goes off-shell and emits a gluon. Since the world line of $q_1$ has a beginning, its shorter distance $d$ with $q_0$ will correspond to the moment when it appears in the BH horizon (except if it is emitted within a small solid angle of order $1/\gamma$, see below). Suppose that right in that moment $q_1$ receives a gluon previously emitted by $q_0$; it is straightforward to find that this gluon has been traveling a time/distance$^6$

$$t = d \approx k \gamma/E = k/m_q$$

in the $q_0$ frame. Since $d \approx k/m_q \sim k/\Lambda_{\text{QCD}}$ is the minimal distance with $q_1$ that $q_0$ may detect, the interaction will take place at typical distances where QCD is not effective (or, equivalently, through the exchange of momenta below the infrared cutoff $\Lambda_{\text{QCD}}$). In [26] the suppression in this radial cross section with minimal distance $d$ is estimated by the contribution of impact parameters $b \geq d$ in a regular cross section (see figure 4). This suppression for the interaction between the two quarks can also be understood in the BH or the center-of-mass frames. There the time/distance that the gluon has been traveling is much shorter, $t' \approx k/E$. However, this time is already too large for the virtual gluon of energy of order $E$ required by the bremsstrahlung kinematics. Notice that it is the energy

$^6$ The contributions out of the light cone are exponentially suppressed in the propagator.
of this virtual gluon, and not its invariant off-shellness $Q^2 \geq \Lambda_{\text{QCD}}^2$, that determines the maximum time that it can travel without violating the Heisenberg uncertainty principle.

The causality or minimal distance argument just outlined suffices to disregard the formation of a photosphere (chromosphere) in high temperature four-dimensional BHs. The reason is that the average distance $(\nu_e E)^{-1}$ (or $(\nu_q E)^{-1}$) between consecutive electrons (quarks) emitted by the BH is 175 (20) times larger than the typical distances dominating the QED (QCD) bremsstrahlung cross section. Moreover, this distance (in reduced Compton wavelength units) does not depend on the BH temperature, as both the number of particles and their typical energy grow linearly with $T$. In $4+n$ dimensions we find (see table 1) that this argument always suppresses the formation of a photosphere, but not of a chromosphere if $n > 2$. In these cases the distance between a quark and two or three other quarks is small (they overlap). We will then use a second argument [25]–[27] that disfavors the multiple interactions required to form a chromosphere: the existence of a maximum radius, $r_{\text{brem}} \approx 1/\Lambda_{\text{QCD}}$ in the BH frame, where the interaction can take place.

This maximum radius appears in the interaction of two particles moving with a relative angle larger than $1/\gamma$; if they move in the same direction their distance may not increase, but the density in their center-of-mass frame is diluted by a Lorentz factor and becomes too low to give interactions [26] ($\theta < 1/\gamma$ defines an exclusion cone). The key observation is that each quark can complete at most one bremsstrahlung interaction before crossing $r_{\text{brem}}$, so after that interaction its (transverse) distance with the particles out of the exclusion cone will be much larger than $1/\Lambda_{\text{QCD}}$. To understand that, let us suppose that, right when it is created next to the BH horizon, a quark $q$ absorbs a virtual gluon of $Q^2 \approx \Lambda^2$ and goes off-shell. In the $q$ rest frame both its energy and its off-shellness after absorbing the gluon are of order $\Lambda$, which in a QCD bremsstrahlung should be just above $\Lambda_{\text{QCD}}$. Then the virtual $q$ lives a time of order $1/\Lambda$ and decays into the final quark and gluon. Now, going back to the BH frame we observe the lifetime of the virtual gluon a Lorentz factor larger, so the typical distance that it travels will be of order $\gamma/\Lambda \gg 1/\Lambda_{\text{QCD}} \approx r_{\text{brem}}$. Except for small values of $\gamma$ (i.e. non-relativistic quarks emitted by BHs of temperature close to $\Lambda_{\text{QCD}}$) this argument establishes that quarks exiting the BH cannot interact with each other more than once, as would be necessary to form a chromosphere. Our conclusion agrees with the simulation of BH production and evaporation at the LHC in [25].

5. Spectrum of stable particles

The cosmogenic BHs under study here are produced at astrophysical distances from the Earth. Therefore, unstable particles resulting from their evaporation have plenty of time to decay. A BH emits stable neutrinos, electrons, photons and gravitons, but mostly it emits quarks and gluons that will fragment into hadrons and then shower into stable particles. In this section we evaluate the total spectrum of stable species from a BH of mass up to $10^{11}$ GeV. Our results are analogous to the ones obtained by MacGibbon and Webber in [28] for primordial BHs [29]. Of course, we use an updated Monte Carlo jet code (HERWIG 6.5 [11]) and include the effects of the extra dimensions, namely, appropriate graybody factors and bulk graviton emission. In addition, while in primordial BHs the spectrum corresponds to a given temperature ($T$ changes only within astrophysical
time scales), here we evaluate the total spectrum resulting from the complete evaporation of the BH, which includes a (relatively small) contribution from the high temperatures briefly reached at the end of its lifetime.

Several comments are in order here. As we have explained in the previous section, when the particles exit the BH their probability of interaction is small. We will then assume that the jets that they define are similar to the ones produced in $e^+e^-$ collisions to $q\overline{q}$ or (the fictitious process) $gg$. We have used HERWIG [11] to simulate the jets produced by any particle that is light at a given temperature, including massive gauge bosons and the top quark (but not the Higgs boson nor a dark matter particle). Finally, we have added together the number of particles and antiparticles (they are produced at the same rate) and the three (Majorana) neutrino species (at astrophysical distances their flavor oscillates).

In figure 5 we plot the power spectrum emitted by a BH of $T = 10$ GeV for $n = 2, 6$. We observe that it is dominated by energies around $\Lambda_{\text{QCD}}$, although the primary graybody spectrum peaks at 30 GeV. This is manifest in the flux of gravitons, since they decouple (their number is not increased by the showering of unstable particles). At high energies it is possible to distinguish the primary graybody spectra for some of the particle species. At this temperature the particles emitted onto the brane consist of an approximate 43% of neutrinos, 28% of photons, 16% electrons and 13% of protons. The bulk gravitons are 0.02% of the total emitted particles for $n = 2$ or 0.4% for $n = 6$. Their typical energy is higher, so they account for 1.4% ($n = 2$) or 16% ($n = 6$) of the total energy radiated.

In figure 6 we give the total spectrum from BHs of mass 10 TeV and $10^{10}$ GeV for $n = 2$. These masses correspond to initial temperatures of 120 and 1.2 GeV, respectively. We find that the spectra are dominated by the emission at these initial temperatures. In particular, 90% of the energy is emitted by the $10^{10}$ GeV BH when its temperature has only increased from 1.2 to 2.6 GeV (see figure 3). The dominance of energies around 0.2 GeV and the approximate fraction of different species are features that depend very mildly on the BH mass, as is apparent in these plots. Of course, in smaller BHs of higher
Initial temperature the relative weight of high energies in the spectrum is larger.

6. Summary and discussion

Models with the scale of gravity at the TeV must confront the fact that in nature there are processes at much higher energies. In particular, in the collision of two cosmic rays the center-of-mass energy can go up to $10^{11}$ GeV. At these energies for impact parameters short enough the particles will be trapped inside a gravitational horizon and form a mini-BH. We have estimated the production rate of these cosmogenic BHs (in figure 2) and have analyzed their properties.

(i) We have found that their lifetime goes from $10^{-26}$ s for a light BH of $M = 10$ TeV to $10^{-14}$ s for $M = 10^{11}$ GeV. In figure 3 we plot the correlation between BH mass, temperature and lifetime for $n = 2, 6$.

(ii) We have shown that bremsstrahlung interactions between the particles exiting the BH are unable to form a chromosphere. Although the average separation between these particles (in table 1) can be, in some cases, small, a QCD process requires a typical time to develop, and this time is such that the particle cannot interact more than once at $r < 1/\Lambda_{\text{QCD}}$ in the BH frame.

(iii) The graybody spectrum emitted by the BH onto the brane is dominated by colored particles. These form jets that result in a spectrum of stable particles peaked at $\Lambda_{\text{QCD}}$. We obtain an approximate 43% of neutrinos, 28% of photons, 16% electrons and 13% of protons. These two features in the spectrum depend very mildly on the number of extra dimensions (figure 5) or the BH mass (figure 6).

(iv) Bulk graviton emission is relatively larger for high BH masses and large numbers of extra dimensions, and it is peaked at higher energies than for the rest of the species. It accounts for 0.4% of the total particles (16% of the energy) emitted by a $10^{10}$ GeV BH for $n = 6$ or just 0.02% (1.4% of the energy) for $M = 10$ TeV and $n = 2$. 
We find it remarkable that, even though there is no chromosphere, the spectrum of stable particles from the evaporation is equally peaked at low (0.2 GeV) energies: the spectrum provided by one of these BHs at astrophysical distances would not be too different whether there is or there is not a chromosphere around it. In both cases the scale is fixed by $\Lambda_{\text{QCD}}$. Notice, however, that the signal at the LHC in one case or the other would be clearly different (10 jets of 100 GeV each versus an expanding shell of 1000 hadrons).

We think that the analysis presented here is a necessary first step in the search for possible observable effects from BH production by cosmic rays.

Acknowledgments

This work has been supported by MEC of Spain (FPA2006-05294), by Junta de Andalucía (FQM-101 and FQM-437) and by the European Community’s Marie-Curie Research Training Network under contract MRTN-CT-2006-035505 Tools and Precision Calculations for Physics Discoveries at Colliders. IM acknowledges a grant from C F Luciano Fonda (Italy).

References

[1] Arkani-Hamed N, Dimopoulos S and Dvali G R, 1998 Phys. Lett. B 429 263 [SPIRES]
Antoniadis I, Arkani-Hamed N, Dimopoulos S and Dvali G R, 1998 Phys. Lett. B 436 257 [SPIRES]
[2] Yao W M et al (Particle Data Group), 2006 J. Phys. G: Nucl. Part. Phys. 33 1 [SPIRES]
[3] Banks T and Fischler W, A model for high energy scattering in quantum gravity, 1999 Preprint hep-th/9906038
Emparan R, 2001 Phys. Rev. D 64 024025 [SPIRES]
Giddings S B and Thomas S D, 2002 Phys. Rev. D 65 055010 [SPIRES]
Eardley D M and Giddings S B, 2002 Phys. Rev. D 66 044011 [SPIRES]
[4] Cullen S, Perelstein M and Peskin M E, 2000 Phys. Rev. D 62 055012 [SPIRES]
Cornet F, Illana J I and Masip M, 2001 Phys. Rev. Lett. 86 4235 [SPIRES]
Giudice G F, Rattazzi R and Wells J D, 2002 Nucl. Phys. B 630 293 [SPIRES]
[5] Cullen S, Perelstein M and Peskin M E, 2000 Phys. Rev. D 62 055012 [SPIRES]
Cornet F, Illana J I and Masip M, 2001 Phys. Rev. Lett. 86 4235 [SPIRES]
Cappo R, 2001 Phys. Rev. Lett. 87 161602 [SPIRES]
Cheung K, 2002 Phys. Rev. D 66 036007 [SPIRES]
Rizzo T G, 2002 J. High Energy Phys. JHEP02(2002)011 [SPIRES]
Chamblin A and Nayak G C, 2002 Phys. Rev. D 66 091901 [SPIRES]
Casadio R and Harms B, 2002 Int. J. Mod. Phys. A 17 4635 [SPIRES]
Cavaglia M, 2003 Phys. Lett. B 569 7 [SPIRES]
Mocioi I, Nara Y and Sarcevic I, 2003 Phys. Lett. B 557 87 [SPIRES]
Cavaglia M, Das S and Maar tens R, 2003 Class. Quantum Grav. 20 L205 [SPIRES]
Barrau A, Grain J and Alexe yev S O, 2004 Phys. Lett. B 584 114 [SPIRES]
Harris C M, Palmer M J, Parker M A, Richardson P, Sabetfakhri A and Webber B R, 2005 J. High Energy Phys. JHEP05(2005)053 [SPIRES]
Tanaka J, Yamamura T, Asai S and Kanzaki J, 2005 Eur. Phys. J. C 41 19
Hewett J L, Lillie B and Rizzo T G, 2005 Phys. Rev. Lett. 95 261603 [SPIRES]
Koch B, Bleicher M and Hosenfelder S, 2005 J. High Energy Phys. JHEP10(2005)053 [SPIRES]
Gingrich D M, 2006 Int. J. Mod. Phys. A 21 6653 [SPIRES]
Humanc H J, Koch B and Stoecker H, 2007 Int. J. Mod. Phys. E 16 841
Alberghi G L, Casadio R and Tronconi A, 2007 J. Phys. G: Nucl. Part. Phys. 34 767
Rizzo T G, 2007 Phys. Lett. B 647 43 [SPIRES]
Cavaglia M, Godang R, Cremaldi L M and Summers D J, 2007 J. High Energy Phys. JHEP06(2007)055 [SPIRES]
Dvali G and Shifryakov S, 2008 J. High Energy Phys. JHEP03(2008)007 [SPIRES]
[7] Harris C M, Richardson P and Webber B R, 2003 J. High Energy Phys. JHEP08(2003)033 [SPIRES]
Hawking evaporation of cosmogenic black holes in TeV-gravity models

Cavaglia M, Godang R, Cremaldi L, Summers D, Dai D C, Starkman G, Stojkovic D, Issever C, Rizvi E and Tseng J, 2008 Phys. Rev. D 77 076007 [SPIRES]

[8] Winstanley E, Hawking radiation from rotating brane black holes, 2007 Preprint 0708.2656 [hep-th]

[9] Meade P and Randall L, Black holes and quantum gravity at the LHC, 2007 Preprint 0708.3017 [hep-ph]

[10] Cavaglia M, 2003 Int. J. Mod. Phys. A 18 1843 [SPIRES]

[11] Corella G et al., 2001 J. High Energy Phys. JHEP01(2001)010 [SPIRES]

[12] Feng J L and Shapere A D, 2002 Phys. Rev. D 65 124027 [SPIRES]

[13] Barrau A, Feron C and Grain J, 2005 Astrophys. J. 630 1015 [SPIRES]

[14] Semikoz D V and Sigl G, 2004 J. Cosmol. Astropart. Phys. JCAP04(2004)003 [SPIRES]

[15] Feng J L and Kumar J, The WIMPless miracle, 2008 Preprint 0803.4196 [hep-ph]

[16] Illana J I, Masip M and Meloni D, 2004 Phys. Rev. Lett. 93 151102 [SPIRES]

[17] Hawking S W, 1974 Nature 248 30 [SPIRES]

[18] Emparan R, Horowitz G T and Myers R C, 2000 Phys. Rev. Lett. 85 499 [SPIRES]

[19] Page D N, 1976 Phys. Rev. D 13 198 [SPIRES]

[20] Harris C M and Kanti P, 2003 J. High Energy Phys. JHEP10(2003)014 [SPIRES]

[21] Cline J M, Mostoslavsky M and Servant G, 1999 Phys. Rev. D 59 063009 [SPIRES]

[22] Daghigh R G and Kapusta J I, 2002 Phys. Rev. D 65 064028 [SPIRES]

[23] Casanova A and Spallucci E, 2006 Class. Quantum Grav. 23 R45 [SPIRES]

[24] Anchordoqui L and Goldberg H, 2003 Phys. Rev. D 67 074019 [SPIRES]

[25] Aliq C, Drees M and Oda K Y, 2006 J. High Energy Phys. JHEP12(2006)049 [SPIRES]

[26] MacGibbon J H, Carr B J and Page D N, Do evaporating black holes form photospheres?, 2007 Preprint 0709.2380 [astro-ph]

[27] Klein S, 1999 Rev. Mod. Phys. 71 1501 [SPIRES]

[28] MacGibbon J H and Webber B R, 1990 Phys. Rev. D 41 3052 [SPIRES]

[29] Carr B J, Primordial black holes: do they exist and are they useful?, 2005 Preprint astro-ph/0511743