ASTROPHYSICAL PRODUCTION OF MICROSCOPIC BLACK HOLES IN A LOW–PLANCK-SCALE WORLD

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ABSTRACT

In the framework of brane-world models lowering the Planck scale to the TeV range, it has recently been pointed out that small black holes could be formed at particle colliders or by neutrino interactions in the atmosphere. This article aims to review other places and epochs where microscopic black holes could form: the interstellar medium and the early universe. The related decay channels and the propagation of the emitted particles are studied, and we conclude that, in spite of the large creation rate for such black holes, the quantity of particles produced does not conflict with experimental data. This shows, from the astronomical viewpoint, that models with large extra dimensions, making the gravity scale much lower, are compatible with observations.

Subject heading: black hole physics

1. INTRODUCTION

It has recently been shown that black holes could be formed at future colliders if the Planck scale is of the order of a TeV, as is the case in some extra-dimension scenarios (Dimopoulos & Landsberg 2001; Giddings & Thomas 2002). This idea has sparked a considerable amount of interest (see, e.g., Kanti & March-Russell 2002, 2003; Casadio & Harms 2002; Chamblin & Nayak 2002; Cheung 2002; Frolov & Stojkovic 2002; Hossenfelder et al. 2002; Cavaglia 2003). The same phenomenon could also occur (and be detected) due to ultrahigh-energy neutrino interactions in the atmosphere (Feng & Shapere 2002; Anchordoqui & Goldberg 2002; Ringwald & Tu 2002; Emparan et al. 2002; Anchordoqui et al. 2002; Ahn et al. 2003). Such possibilities open very exciting ways to search for new physics (e.g., quantum-gravitational effects through a Gauss-Bonnet term in the action [Barrau et al. 2004b], Higgs production [Landsberg 2002], or a D-dimensional cosmological constant [Kanti et al. 2005]). This article aims to clarify the situation regarding the possible consequences of an astrophysical and cosmological production of microscopic black holes (μBH) in the universe. This is especially important as it has been argued that a low Planck scale could already be excluded by the available data on Galactic cosmic rays. Section 1 summarizes the general framework of TeV Planck-scale models and the basics of cross section computations. Section 2 is devoted to the investigation of black hole production by the interaction of high-energy cosmic rays with the interstellar medium (ISM). The subsequent decay of those black holes and the propagation of the emitted particles are also studied. Section 3 deals with a few other exotic possibilities, including black hole relics and thermal creation of black holes in the early universe. Finally, we conclude that scenarios lowering the Planck scale in the TeV era are viable from the astrophysical point of view.

2. TeV PLANCK-SCALE FRAMEWORK

The “large extra dimensions” scenario (Arkani-Hamed et al. 1998, 1999; Antoniadis et al. 1998) is a very elegant way to geometrically address the hierarchy problem (among others), allowing only the gravity to propagate in the bulk. The Gauss law relates the Planck scale of the effective four-dimensional low-energy theory M_P with the fundamental Planck scale M_P through the volume of the compactified dimensions, V_D−4, via

\[ M_D = \left( \frac{M_P^2}{V_D^{-4}} \right)^{1/(D-2)} \]

It is thus possible to set M_D ~ 1 TeV without being in contradiction with any currently available experimental data. This translates into radii values between a fraction of a millimeter and a few Fermi for the compactification radius of the extra dimensions (assumed to be of the same size and flat, i.e., of toroidal shape). Furthermore, such a small value for the Planck energy is not artificial and could be somehow expected to minimize the difference between the electroweak and Planck scales, as motivated by the construction of this approach. In such a scenario, at subweak energies, the standard model (SM) fields must be localized to a four-dimensional manifold of weak-scale “thickness” in the extra dimensions. As shown in Arkani-Hamed et al. (1998, 1999) and Antoniadis et al. (1998) as an example based on a dynamical assumption with D = 6, it is possible to build such a SM field localization. This is, however, the nontrivial task of those models.

Another important way to realize TeV-scale gravity arises from properties of warped extra-dimensional geometries used in Randall-Sundrum scenarios (Randall & Sundrum 1999). If the warp factor is small in the vicinity of the standard model brane, particle masses can take TeV values, thereby giving rise to a large hierarchy between the TeV and conventional Planck scales (Giddings & Thomas 2002; Giddings & Katz 2001). Strong gravitational effects are therefore also expected in high-energy scattering processes on the brane.

In those frameworks, black holes could be formed by any interaction above the Planck scale. Two elementary particles with a center-of-mass energy \( \sqrt{s} \) moving in opposite directions, with an impact parameter less than the horizon radius \( r_h \), should form a black hole of mass \( M \approx \sqrt{s} \) with a cross section expected to be of order \( \sigma \approx \pi r_h^2 \). Those values are in fact approximations, as the black hole mass will be only a fraction of the center-of-mass energy whose exact value depends on the dimensionality of the spacetime and on the angular momentum of the produced
black hole. A significant part of the incoming energy is lost to gravitational radiation. In particular, lower limits on the inelasticity (ratio of the mass of the formed black hole to the incoming parton energy) were derived in Yoshino & Nambu (2003) as a function of the impact parameter. Although those bounds were slightly increased in Yoshino & Rychkov (2005), they still can be considered reasonable estimates of the consequences of the inelasticity and were shown in Anchordoqui et al. (2004) to drastically reduce the expected number of produced black holes. To remain conservative (except where stated otherwise) the computations performed in this article use a unity inelasticity to maximize the emitted flux and strengthen the conclusions.

To compute the real probability to form black holes in a nuclei collision, it is necessary to take into account that only a fraction of the total center-of-mass energy is carried out by each parton collision, it is necessary to take into account that only a fraction of the total center-of-mass energy is carried out by each parton collision, it is necessary to take into account that only a fraction of the total center-of-mass energy is carried out by each parton collision, it is necessary to take into account that only a fraction of the total center-of-mass energy is carried out by each parton collision, it is necessary to take into account that only a fraction of the total center-of-mass energy is carried out by each parton collision, it is necessary to take into account that only a fraction of the total center-of-mass energy is carried out by each parton collision. Although those bounds were slightly increased in Yoshino & Nambu (2003) as a function of the impact parameter, they still can be considered reasonable estimates of the consequences of the inelasticity and were shown in Anchordoqui et al. (2004) to drastically reduce the expected number of produced black holes. To remain conservative (except where stated otherwise) the computations performed in this article use a unity inelasticity to maximize the emitted flux and strengthen the conclusions.

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3. BLACK HOLE PRODUCTION BY COSMIC-RAY INTERACTIONS ON THE ISM

The number of black holes produced by cosmic rays interacting on the ISM per unit of time, volume, and mass can be written as

\[
\frac{dN}{dM_{BH} \, dt \, dV} (M_{BH}) = \int_{M_{BH}}^{\infty} 4\pi \phi(E_{CR}) n \frac{d\sigma}{dM_{BH}} (M_{BH}, E_{CR}) dE_{CR},
\]

where \( n \) is the ISM proton density, and \( \phi(E_{CR}) \) is the cosmic-ray differential spectrum at energy \( E_{CR} \). Assuming that the ISM is made of 90% hydrogen and 10% helium, \( n \) can be taken as \( \sim 1.3 \, \text{cm}^{-3} \). As we deal with a diffusion process insensitive to local overdensities or underdensities, this average approximation holds very well. For \( M_D \sim 1 \, \text{TeV} \), which is the order of magnitude of the lowest Planck scale value compatible with experimental data (see references in Kanti 2004), the threshold energy for cosmic rays is \( 5 \times 10^{14} \, \text{GeV} \), which lies just below the knee. Measurements from the KASKADE experiment (Roth et al. 2003) were used to evaluate \( \Phi(E_{CR}) \), taking into account the different contributions from hydrogen, helium, carbon, silicon, and iron.

The cross sections have been derived following Dimopoulos & Landsberg (2001) by the method given in § 2. Table 1 gives the resulting differential numbers of \( \mu \) BHs produced and their initial temperatures as a function of their mass for two different Planck scales and two extreme numbers of dimensions \( (D = 5) \) is not included, as a very low Planck scale is excluded in this case on the grounds of the dynamics of the solar system.

It can be seen that the production rate is small, due to the low value of the flux in this PeV–EeV range. It is also very sensitive to the \( \mu \) BH mass because the cross section for \( p + p \rightarrow BH \) is a fast-decreasing function of \( M_{BH} \). Nevertheless, when the volume of our Galaxy, \( \sim 10^{67} \, \text{m}^3 \), is taken into account, this leads to \( \sim 10^{13} \mu BHs created per second within the Milky Way for \( M_D = 1 \, \text{TeV} \). The \( D \)-dependence is very weak and not included in the table, as uncertainties clearly dominate at this level of accuracy.

To investigate the experimental consequences of those potentially formed black holes, their evaporation should be taken into account. As already studied for four-dimensional primordial black holes (Maki et al. 1996; Barrau et al. 2002; Barrau & Ponthieu 2004), antiprotons are very promising for this purpose, as their abundance is both well known and very small when compared to matter cosmic rays (\( \bar{p}/p \sim 10^{-5} \); Donato et al. 2001). The source term for this process can be written as

\[
\frac{dN_{\bar{p}}}{dE_{\bar{p}} \, dV} = \int_{E_{\bar{p}} = M_D}^{\infty} \int_{E_{p} = M_{BH}/2m_p}^{\infty} \left[ \sum_i \frac{d\sigma}{dM_{BH}} (M_{BH}, E_{CR}) \right] \times n \phi(E_{CR}) \varphi(M_{BH}) n \frac{d\sigma}{dE_{\bar{p}}} (E_{\bar{p}}, M, E_{CR}) \right] dE_{CR} dM_{BH},
\]

where \( \varphi \) stands for the number of emitted quanta by a black hole of mass \( M_{BH} \) and temperature \( T_{BH} \), \( \varphi \sim M_{BH}/(2T_{BH}) \sim 2\pi r, M_{BH}/(D - 3) \). The relative number of quarks or gluons of

| \( M_D \) (TeV) | \( M_{BH} \) (M⊙) | \( dN/dM_{BH} dE_{CR} / dV \) (GeV⁻¹ s⁻¹ m⁻³) | \( D \) | \( T_{BH} \) (GeV) |
|----------------|-----------------|---------------------------------|----------|----------------|
| 1              | 10⁻⁴¹          | 11                              | 434      |
| ...            | ...            | 6                               | 172      |
| 10             | 10⁻⁴⁵          | 11                              | 325      |
| ...            | ...            | 6                               | 80       |
| 100            | 10⁻⁵⁰          | 11                              | 244      |
| ...            | ...            | 6                               | 37       |
| 10             | 10⁻⁵⁰          | 11                              | 4340     |
| ...            | ...            | 6                               | 1725     |
| 10             | 10⁻⁵⁰          | 11                              | 3258     |
| ...            | ...            | 6                               | 800      |
| 100            | 10⁻⁵⁵          | 11                              | 2443     |
| ...            | ...            | 6                               | 371      |
type $i$ is $N_i$, and the fragmentation function for such a parton of energy $T_{BH}$ into an antiproton of kinetic energy $E_{\bar{p}}$ is given by $d\gamma_i/dE_{\bar{p}}$. This term also depends on $E_{CR}$, as the produced $\mu$BH is Lorentz boosted with respect to the Galactic frame. It has been determined using the Lund model PYTHIA (Sjostrand 1994) Monte Carlo generator, between the thresholds $E_{\min} \approx \gamma_{BH}T_{BH}(1-\beta_{BH})$ and $E_{\max} \approx \gamma_{BH}T_{BH}(1+\beta_{BH})$, as shown by the example given in Figure 1, in which the important role played by the center-of-mass velocity can be easily seen.

4. DECAY AND RELATED SPECTRA

Once this source term is established, the produced antiprotons should be allowed to propagate within the Galaxy. For this purpose, a two-zone diffusion model described in Donato et al. (2001) and Maurin et al. (2001) has been used. In this approach, the geometry of the Milky Way is a cylindrical box embedded in a diffusion halo whose extension is still subject to large uncertainties. The five parameters used are $K_0$, $\delta$ [describing the diffusion coefficient $K(E) = K_0(3R^2)$], the halo half-height $L$, the convective velocity $V_c$, and the Alfvén velocity $V_A$. They have been varied within a given range, determined by an exhaustive and systematic study of cosmic-ray nuclei data (Maurin et al. 2001), and chosen at their mean value. The spectrum is affected by energy losses when antiprotons interact with the galactic interstellar matter and by energy gains when reacceleration occurs. These energy changes are described by an intricate integro-differential equation (Barrau et al. 2002), to which a source term $q^{src}(E)$ was added, leading to the so-called tertiary component, which corresponds to inelastic but nonannihilating reactions of $\bar{p}$ on interstellar matter.

Figure 2 shows the resulting antiproton spectrum around its maximum. The different curves correspond to different astrophysical parameters and to the interstellar and “top of atmosphere” fluxes. The inelasticity has also been taken into account (Anchordoqui et al. 2002) as a simple rescaling, as those results are extremely weakly dependent on the details of the shape of the mass spectrum. In any case, they remain extremely far below the background, which lies at the level of a few $10^{-2}$ GeV$^{-1}$ sr$^{-1}$ s$^{-1}$. But it should be pointed out that the spectrum is much harder than the background. The reasons for this are quite straightforward. First, although quite high for an exotic process, the cross section for $\mu$BH production is small when compared to SM processes: it is of the order of a few hundred picobarns at the threshold, whereas the total $pp$ cross section is not far from 100 mbarn, with an antiproton multiplicity close to 1 for $\sqrt{s} \sim 1$ TeV. This explains the overall normalization around the maximum.
Furthermore, the antiproton flux results from the convolution of the primary cosmic-ray spectrum with the fragmentation function. For the secondary component (antiprotons due to $pp$ interactions), this fragmentation function is not far from a Dirac distribution, and the spectrum is expected to have roughly the same slope as the primary one. For the $^{22}\text{BH}$ component considered in this article, the fragmentation function is substantially widened by the boost and becomes the hardest function of the convolution equation. The resulting spectrum therefore exhibits the same slope and becomes much harder than that of the secondary component. The confinement effects due to the Galactic magnetic field induce a softening of the spectra below the knee, but the spectral index difference remains the same, whatever the energy. Because of this important slope difference, the antiproton flux due to $^{22}\text{BHs}$ should dominate over the secondary around $10^{10}$ GeV. Although this could allow for interesting experimental tests of low–Planck-scale theories in the distant future, this remains extremely far above the highest energies currently measured ($\sim 100$ GeV for antiprotons).

Another potential concern about the $^{22}\text{BH}$ production compatibility with data is related to the flux of emitted gamma rays. They result both from the direct emission and from the decay of neutral pions. As the number of partonic degrees of freedom dominates over the electromagnetic ones in the standard model, this latter component is clearly dominant. It is much higher than the antiproton flux due to $^{22}\text{BHs}$ should dominate over the secondary around $4 \times 10^{10}$ GeV. Although this could allow for interesting experimental tests of low–Planck-scale theories in the distant future, this remains extremely far above the highest energies currently measured ($\sim 100$ GeV for antiprotons).

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5. THERMAL PRODUCTION OF BLACK HOLES IN THE EARLY UNIVERSE, AND RELICS

It might also be thought that the possible thermal production of $^{22}\text{BHs}$ in the early universe would conflict with observations. If the temperature of the universe reached values above the $D$-dimensional Planck scale $M_D$, $^{22}\text{BHs}$ are indeed expected to have formed through the scattering of the thermal radiation. The production and subsequent evaporation of such small black holes is irrelevant as long as it takes place before the nucleosynthesis: it just contributes to the thermal bath. On the other hand, if black holes mostly decay after the nucleosynthesis, the entropy released could modify the relative abundances of light elements and contradict the observational data (as it is well known to do in the gravitino problem in inflationary cosmology). The mass of a $D$-dimensional $^{22}\text{BH}$ with lifetime $\tau$ is given by

$$M_{\text{BH}} = M_D (M_D \tau)^{(D-3)/(D-1)}.$$
until the nucleosynthesis) is of the order of $10^{20} - 10^{23}$ GeV, which is above the usual four-dimensional Planck scale and clearly meaningless. It can therefore be safely considered that $\mu$BHs thermally created in the early universe are not expected to induce any substantial changes in the sensitive primordial $^6$Li, $^3$He, $^4$He, and $^D$ abundances.

A last point to address is the possible formation of stable relics at the end of the evaporation process. Based on several different arguments (e.g., Gauss-Bonnet solutions in string gravity [Alexeyev et al. 2002], or a renormalization group modification of the Schwarzschild metric [Bonanno & Reuter 2000]), it has recently been pointed out that, in agreement with the “cosmic censorship” hypothesis, black hole relics are expected to survive Hawking evaporation, even in models with extra dimensions. In the Planck region, the semiclassical approach cannot be safely used anymore, and quantum gravitational effects must be taken into account. Although no reliable theory is yet established, most attempts trying to deal with the endpoint of the evaporation process lead to the conclusion that stable relics should be formed. Depending on the details of the underlying model, their mass is expected to lie around the Planck mass. The possible contribution of those relics to the cold dark matter budget has been extensively studied in the framework of four-dimensional black holes (see, e.g., Barrau et al. 2003, 2004a), but it should be investigated whether the $D$-dimensional black holes produced by cosmic-ray interactions on the ISM could lead to substantial remnants. The total mass induced by this process in our Galaxy can be computed by integrating the formula given at the beginning of $\S$ 2:

$$M_{\text{rel}}^{\text{tot}} = \int_{M_0}^{\infty} \int_{t_{\text{form}}}^{t_0} \int_{0}^{R_{\text{gal}}} \int_{0}^{y_{\text{gal}}} 2\pi R M_{\text{rel}} \frac{dN}{dM_{\text{BH}} dt} dR dM_{\text{BH}} dt dy,$$

where $t_0$ is the age of the universe, $t_{\text{form}}$ is the galaxy formation epoch, $R_{\text{gal}}$ and $y_{\text{gal}}$ are the Milky Way radius and height, and $M_{\text{rel}} \sim M_D$ is the relic expected mass. This leads to a tiny value, $M_{\text{rel}}^{\text{tot}} \approx 10^{-12}$ g, which means that relic dark matter is negligible and therefore remains compatible with observations.

### 6. CONCLUSION AND PROSPECTS

This study shows that the concern over $\mu$BHs created by astrophysical processes (either in the Galaxy or in the primordial universe), which could conflict with experimental data (either through the emitted cosmic rays or through the possible relics), is irrelevant. From the point of view of black hole formation, the Earth’s atmosphere and colliders are probably the only places where a TeV Planck scale should have observational consequences. Theoretical motivations for extra-dimensional models are therefore not currently contradicted by astroparticle physics phenomenology. On the other hand, some space is still open for new phenomena due to $\mu$BH evaporation in the Galaxy; as their production cross section has no suppression factor and as their coupling with any quantum during the evaporation process is purely gravitational, one can expect an abundant production of rare particles. Furthermore, because of the large center-of-mass velocity with respect to the Galactic frame, those particles are expected to lie in the high-energy range with a hard spectrum. Although this would constitute a significant difference from the usual background thermal distributions, a clear detection seems quite doubtful and would require a specific investigation.

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