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Primordial braneworld black holes: Significant enhancement of lifetimes through accretion

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Abstract. The Randall–Sundrum (RS-II) braneworld cosmological model with a fraction of the total energy density in primordial black holes is considered. Due to their 5d geometry, these black holes undergo modified Hawking evaporation. It is shown that during the high-energy regime, accretion from the surrounding radiation bath is dominant compared to evaporation. This effect increases the mass of the black holes till the onset of matter (or black hole) domination of the total energy density. Thus black holes with even very small initial masses could survive till several cosmologically interesting eras.

Keywords. Braneworld; black holes; accretion.

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Primordial black holes are formed through various mechanisms [1] in the early universe. Depending on their evolution and evaporation time, relic black holes could have significant cosmological consequences. For instance, they could be responsible for the generation of the observed baryon asymmetry in the universe [2]. Futhermore, depending on how long the relic black holes survive, these could also serve as viable candidates for cold dark matter [3]. The key question in the cosmology of primordial black holes is the duration of their lifetimes, vis-a-vis their initial mass spectrum and formation times. In this article we focus on this issue in the context of the RS-II [4] braneworld model.

In the RS-II braneworld scenario, matter and radiation are confined to the 3-brane, whereas gravity propagates also in the bulk. The cosmological ramifications of this model have received much attention recently [5]. In this model there exists a regime during the early stages when the expansion rate of the universe is proportional to its energy density. However, the standard cosmological evolution is recovered for times $t \gg t_c$, where t_c is related to l, the size of the extra dimension. The present experimental limit [6] to this size is $l \leq 0.1$ mm. Our purpose here is to consider the black holes which are formed in the early (high energy) phase of this braneworld model. Such black holes obey a modified Hawking evaporation law due to a different induced metric on the brane (compared to standard 4d black holes) and also because of the radiation of a part of the gravitational energy into the bulk [7]. Moreover, accretion from the surrounding radiation bath could have a significant effect on the evolution of these black holes [8,9]. In what follows we describe in detail the effects of the interplay of evaporation and accretion on the lifetime of a population of primordial black holes in the braneworld.

We begin with an early era in the high-energy braneworld phase in which a certain number density $n_{\rm BH}$ of primordial black holes with individual mass M exchange energy with the surrounding radiation by accretion and evaporation. Let the fraction of the total energy in black holes at some initial time t_0 be β. Hence, the cosmological evolution will be governed by the Friedmann equation, the evolution equation for black hole mass, and the equation for radiation density incorporating the effects of evaporation and accretion. These three equations (for $t \ll t_c$) are given by

$$\frac{\dot{a}^2}{a^2} = \left(\frac{8\pi t_c}{3M_4^2}\right)^2 \left(M n_{\rm BH} + \rho_R\right)^2, \tag{1}$$

$$\dot{M} = -\frac{AM_4^2}{Mt_c} + \frac{64 M \rho_R t_c}{3M_4^2} \tag{2}$$

and

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\rho_R(t) a^4(t)\right) = -\dot{M}(t) n_{\rm BH}(t) a(t), \tag{3}$$

where $A \simeq 3/(16)^3\pi$ and M_4 (l_4) are the 4d Planck mass (length).

A full numerical integration of the above equations would lead to the general description of the cosmology we are considering. However, here we assume the condition of radiation domination, i.e., $\beta \ll 1$ ($\rho_R \gg M n_{\rm BH}$) to hold. (Note that we have already made another simplifying assumption by choosing the same initial mass M_0 and formation time t_0 for all black holes, instead of considering a realistic mass spectrum). Under these assumptions eqs (1) and (3) simplify to yield $a \propto t^{1/4}$ and $\rho_R \propto 1/t$ during the high-energy brane phase, i.e., for $t \leq t_c$. For later times, the standard radiation dominated expansion is recovered. It was shown in [8] that during the radiation dominated high-energy phase, the solution of the black hole equation (2) is such that the mass of an individual black hole continues to grow as

$$\frac{M(t)}{M_0} \simeq \left(\frac{t}{t_0}\right)^B, \tag{4}$$

where $B \simeq 2/\pi$. Due to an imperfect efficiency of accretion, the value of the number B might get reduced by an $O(1)$ factor [9]. Nevertheless, this result indicates the dominance of accretion over evaporation in the dynamics of primordial braneworld black holes.

It can be further shown [8] that for the condition of radiation domination to hold up to t_c, one must have

$$\frac{\beta}{1-\beta} < \left(\frac{t_0}{t_c}\right)^{B+1/4}. \tag{5}$$

Beyond t_c, the cosmology enters the standard low-energy phase. During this stage the black hole masses continue to grow up to a certain time t_t after which the surrounding radiation gets diluted enough for accretion to become negligible. Henceforth, evaporation takes over the dynamics, and the solution of the black hole eq. (2) can be approximated by

$$M(t) = \left[M^2(t_t) - \frac{2AM_4^2}{t_c}(t - t_t)\right]^{1/2}. \tag{6}$$

From eq. (6) the lifetime of black holes is derived [8] to be

$$\frac{t_{\rm end}}{t_4} \simeq \frac{4}{A}(2\sqrt{2})^B \left(\frac{M_0}{M_4}\right)^{2-B} \frac{t_c}{t_4}\left(\frac{t_t^2}{t_c t_4}\right)^B. \tag{7}$$

The exact computation of t_t can only be done by a full numerical simulation of eqs (1)–(3). In comparison with the results for primordial black holes in standard cosmology, one finds that the lifetime of braneworld black holes are significantly longer. Although the modified evaporation law and accretion are both responsible for this effect, the latter is certainly the more effective reason. For example, with the inclusion of accretion in a suitable parameter range, subPlanckian ($M_0 < M_4$) black holes could survive up to the era of nucleosynthesis, and those with initial mass $M_0 \simeq 10^3$ g could survive up to the present era [8].

To summarize, we have seen that accretion from the surrounding radiation bath is an important effect for primordial black holes in the high-energy phase of the RS-II braneworld scenario. For a wide range of values of the initial black hole mass and the size of the extra dimension, accretion indeed dominates over evaporation. Significant enhancement of the black hole lifetime occurs. Consequently, several astrophysical constraints on primordial black holes are impacted [9]. The multifarous consequences of long-lived black holes in cosmology need to be investigated in detail.

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