Cosmic rays emitted by primordial black holes in a five-dimensional Randall–Sundrum braneworld

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Abstract. We probe the Randall–Sundrum braneworld cosmology via the radiative nature of primordial black holes (PBHs). The effects of higher-dimensionality on the cosmic-ray spectra of extragalactic photons and galactic antiprotons from PBHs are investigated. Observational implications for the braneworld geometry as well as the inflationary primordial perturbation as a seed of PBHs are provided.

1. Introduction: Primordial black holes in the Randall–Sundrum cosmology

It is expected that some portion of density contrast in the early universe went into gravitational collapse leading to formation of primordial black holes (PBHs) [1]. PBHs typically have masses much smaller than astrophysical holes thereby acquiring high enough Hawking temperature $T_H$ to emit various cosmic rays via the Hawking process [2].

The project here presented is utilisation of PBHs in an inquiry into a five-dimensional braneworld scenario proposed by Randall and Sundrum (RS) [3; 4]. The RS braneworld is modelled out of a four-dimensional (mem)brane, which confines the standard model matter together with positive tension $\lambda$, embedded in five dimensional anti-de Sitter space. The model is characterised by a length parameter $\ell$ below which five-dimensional gravity takes effect, where the experimental upper bound on $\ell$ is around 0.1 mm [5]. On the brane, cosmological expansion is governed by the modified Friedmann equation

$$H^2 = \frac{8\pi G N}{3} \rho \left(1 + \frac{\rho}{2\lambda}\right)^{1/2}.$$ (1)

This implies the presence of an exotic early radiation-dominated era in which $\rho^2/\lambda$ term dominates thereby leading to the expansion law $a(t) \propto t^{1/4}$. It is in fact what happens when the size of the universe is below $\ell$. See e.g. [6] for a review of the model.

Thanks to the following facts, the utility of PBHs to prove such an exotic cosmology is evident. (i) The PBH mass function is sensitive to the expansion history in the early universe since the size of PBHs is closely related to the scale of the Hubble horizon $H_{\text{H}} \propto t^{2/3}$, where $0 < F \lesssim 1$ parameterises the efficiency of accretion [9; 10]. (ii) Moreover, it has been inferred that in the “$\rho^2$” phase, accretion causes power-law growth of the PBH mass as $M_{\text{bh}} \propto t^{2F/\pi}$, where $0 \leq F \leq 1$ parameterises the efficiency of accretion [9; 10]. (iii) Finally, Hawking temperature of PBHs smaller than $\ell$ is lowered. PBHs whose lifetime is the current cosmic age have a temperature as a function of $\ell$ being

$$T_H \sim 50 \left(\frac{\ell}{0.1 \text{ mm}}\right)^{-1/4} \text{ keV}.$$ (2)
The above characters all bring up quantitative differences from the conventional four-dimensional cosmology. In what follows, we shall see properties of cosmic rays emitted by such PBHs and obtain implications for the RS braneworld.

2. Observational limits on the PBH abundance
First we seek constraints on the abundance of PBH, denoted as \( \alpha_1 \), by calculating two sorts of cosmic-ray spectra emitted by PBHs.

In figure 1, spectra of diffuse photons [11] are shown to be compared with the observations of the extragalactic background [12–15]. The almost black-body spectra directly reflect the Hawking temperature given in equation (2). It will be therefore possible to determine the size of the extra dimension \( \ell \) if the PBH-origin component is identified in the future observations. At this moment, each spectrum determines an upper bound on the PBH abundance for given values of \( \ell \) and \( F \).

The other cosmic ray, primary antiprotons from PBHs in the Milky Way dark halo [16], is shown in figure 2 together with the standard secondary component. Antiprotons from PBHs typically have sub-GeV energies irrespective of \( \ell \) because of the threshold around GeV, the antiproton mass. The PBH-origin antiprotons in the sub-GeV region actually improve the fit to the corresponding observations [17–19], however, here we conservatively find upper limits on the PBH abundance. An investigation reveals that the antiproton flux from PBHs is a decreasing function of the size of the extra dimension \( \ell \) [16].

![Figure 1](image1.png)

**Figure 1.** Figure taken from [11]. Each spectrum corresponds to maximal PBH abundance for different values of \( \ell \) and \( F \), where \( \ell_4 \) is the Planck length.

![Figure 2](image2.png)

**Figure 2.** Figure taken from [16]. Sub-GeV antiproton component near its upper limit for parameters \( \ell = 10^{31} \ell_4 \sim 0.1 \text{ mm} \) and \( F = 1.0 \) is presented.

3. Constraints on the RS braneworld
From the above considerations, we find the allowed region in the parameter space \( (\ell, F, \alpha_1) \) [11; 16]. Its projection onto the \( (\ell, F) \)-plane are shown in figure 3, where the left-hand side is allowed for the lines each corresponding to a fixed \( \alpha_1 \). We find that when \( \alpha_1 \sim 10^{-26}–10^{-28} \), constraints from the two cosmic-rays cooperate. In particular, they imply that if the apparent sub-GeV excess of the antiproton observations is really due to PBH evaporation, then an upper bound on the size of the extra dimension is set around \( 10^{-11} \text{ m} \) [16].

Finally the upper limits on the PBH abundance \( \alpha_1 \) are translated into those on the power spectrum of the inflationary perturbation. The PBH mass function is related to the comoving curvature perturbation spectrum \( \mathcal{P}_R \) [8]. The upper bounds on the perturbation amplitude are summarised in figure 4 [20]. We can read off from the figure that the comoving length scale of
concern approximately ranges between 1–1000 km depending on the size of the extra dimension and the efficiency of accretion.

![Figure 3](image1.png) **Figure 3.** Figure taken from [16]. For each fixed $\alpha_i$, only parameters in the left-hand side of corresponding boundary are allowed.

![Figure 4](image2.png) **Figure 4.** Figure taken from [20]. Upper bounds on the inflationary comoving curvature perturbation are plotted.

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**References**

[1] Carr B J 1975 *Astrophys. J.* 201 1–19
[2] Hawking S W 1975 *Commun. Math. Phys.* 43 199–220
[3] Randall L and Sundrum R 1999 *Phys. Rev. Lett.* 83 3370–3373
[4] Randall L and Sundrum R 1999 *Phys. Rev. Lett.* 83 4690–4693
[5] Kapner D J et al. 2007 *Phys. Rev. Lett.* 98 021101
[6] Maartens R 2004 *Living Rev. Rel.* 7 7
[7] Guedens R, Clancy D and Liddle A R 2002 *Phys. Rev. D* 66 043513
[8] Sendouda Y, Nagataki S and Sato K 2006 *J. Cosmol. Astropart. Phys.* JCAP06(2006)003
[9] Majumdar A S 2003 *Phys. Rev. Lett.* 90 031303
[10] Guedens R, Clancy D and Liddle A R 2002 *Phys. Rev. D* 66 083509
[11] Sendouda Y, Nagataki S and Sato K 2003 *Phys. Rev. D* 68 103510
[12] Gruber D E, Matteson J L, Peterson L E and Jung G V 1999 *Astrophys. J.* 520 124–129
[13] Kinzer R L, Jung G V, Gruber D E, Matteson J L and Peterson L E 1997 *Astrophys. J.* 475 361–372
[14] Sreekumar P et al. (EGRET) 1998 *Astrophys. J.* 494 523–534
[15] Strong A W, Moskalenko I V and Reimer O 2004 *Astrophys. J.* 613 956–961
[16] Sendouda Y, Kohri K, Nagataki S and Sato K 2005 *Phys. Rev. D* 71 063512
[17] Matsunaga H et al. (BESS) 1998 *Phys. Rev. Lett.* 81 4052–4055
[18] Orito S et al. (BESS) 2000 *Phys. Rev. Lett.* 84 1078–1081
[19] Maeno T et al. (BESS) 2001 *Astropart. Phys.* 16 121–128
[20] Sendouda Y 2007 Ph.D. thesis University of Tokyo