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Ultra High Energy Cosmic Rays from Early Decaying Primordial Black Holes

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Origin of ultra high energy cosmic rays is an unsolved problem in physics. Several proposals such as Z-burst, decay of super massive matter, susy particles as a primary, neutrino as a primary in extra dimension models exist in the literature which try to address this issue. Many of these proposals solve the problem of propagation of cosmic rays over cosmological distances by introducing new physics. However these do not explain the origin of such high energy cosmic rays. The possible astrophysics sites, such as active galactic nuclei, are highly constrained. Here we determine whether these cosmic rays originated from the decay of some exotic objects, such as the Primordial Black Holes (PBHs) in Brane World scenario, present in the early universe. In contrast to the usual Top Down scenario we do not assume that this exotic object necessarily has to decay in our astrophysical neighbourhood since we assume a beyond the standard model scenario, where the propagation problem is absent. We first consider the standard 4-dimension PBHs decaying in the early universe. We calculate UHE neutrino and proton flux from such PBHs. The density of these PBHs is constrained by low energy cosmic ray fluxes and cosmological observations. We repeat the flux calculation in the Brane World scenario. We find that in both cases it is unable to produce the observed ultra high energy cosmic ray flux. It will be interesting to repeat our calculations for other superheavy particles, decaying in the early universe, which may contribute to the ultra high energy cosmic ray flux.

1. Introduction

The observation of cosmic rays with energies in excess of $10^{20} eV$ present a major challenge to astro-particle physics. Due to the presence of cosmic microwave background radiation it was predicted that cosmic rays with energies above $10^{20} eV$ will not be observed. This is because protons are unable to propagate over cosmological distances at such energies. Energies of nuclei and photons are similarly bounded. This upper limit on the energy of the cosmic rays is called the GZK cut-off. The presence of GZK violating events implies new physics unless the source of these events lies within our astrophysical neighbourhood. However there doesn't appearto be any source within 100 Mpc distance from earth which can accelerate particles to such high energies and hence we are unable to explain these events within Standard Model(SM). There exists many proposals in the literature to explain these events. Examples of these explanations include violations of lorentz invariance, existence of magnetic monopoles, topological defects, Z-burst, a strongly interacting neutrino at ultra high energies(UHE) etc. However most of parameter space in the models like Z-burst and top-down scenarios are severly constrained by existing experiments or future planned experiments. Non-observation of UHE neutrinos in experiments by the year 2006 will rule out these models [1].

Astrophysical sources for UHE neutrinos are mainly Active Glactic Nuclei (AGN) and Gamma Ray Bursts(GRB). In the scenario where neutrino acts as a strongly interacting particle at ultra high energies in low scale gravity models, astrophysical sources like AGNs and GRBs may not be able to produce enough flux at GZK energies or above because of the strongly interacting nature of the particles at such high energies. In such case only topological defects act as the only UHE neutrino source for these models. However topological defect models are severely constrained by the existing data. Therefore this motivates us to look for alternative sources for UHE neutrinos. Here we consider one of such possiblility that is Primordial black holes. These objects are interesting to study because they can survive till today and evaporate to produce all sorts of particles. Primordial black holes(PBH) as a source of UHECR are studied by the Ref. [6].

In this paper we consider the production of UHE protons and neutrinos from PBHs deacying today and also PBHs which are decayed in early epoch of the cosmological evolution of the universe. We calculate UHE fluxes in standard 4-dimensional PBHs as well as in 5-dimensional braneworld PBHs. Next two sections we review the 4D PBHs and 5D brane world 5D PBHs.

2. Standard 4D Primordial Black Holes

It is known that black holes would have formed in very early universe through the density fluctuation[2]. If one assumes the production of the black hole of mass of the order of horizon mass at some time 't' in the evolution universe then mass of the hole is

$$M_{BH}(t) \approx \frac{c^3 t}{G} \approx 10^{15}\left(\frac{t}{10^{-23}s}\right) g. \tag{1}$$

Then a black hole of mass 10^{15}g would be evaporating now. Masses less than 10^{15}g would have evaporated by now. For example, the black hole of mass lies between 10^{10} g and 10^{13}g would have completed their evaporation between 10^3 sec and 10^{12} sec.

Hawking showed that a black hole emits particles thermally with a temperature that depends only on its mass, charge and angular momentum. A black hole emits particles of spin $1/2$ with energy in the range $(E, E + dE)$ at a rate

$$\frac{\mathrm{d}^2 N}{\mathrm{d}t\mathrm{d}E} = \frac{\Gamma_{1/2}(E,T)}{\exp\left(\frac{E}{kT}\right) + 1} \tag{2}$$

per particle degree of freedom. Here T is the temperature of the hole and $\Gamma_{1/2}(E,T)$ is the absorption coefficient.

The above spectrum does not represent a perfect black body spectrum because $\Gamma_{1/2}(E,T)$ is energy dependent. In the limit $E/(kT) \gg 1$, the spectrum is that of a black body with a temperature of

$$T \approx 1.06 \times 10^{13}\left[\frac{1g}{M}\right] \tag{3}$$

where M is the mass of the black hole. For relativistic particles $\Gamma_{1/2}(E,T)$ is given by,

$$\Gamma_{1/2}(E,T) = \frac{27E^2}{64\pi^2(kT)^2} \tag{4}$$

Black hole emits standard model particle by Hawking mechanism. Generally black hole loses mass at a rate

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{\alpha(M)}{M^2}, \tag{5}$$

where $\alpha(M)$ counts the degrees of freedom of the emitted particles. As the black hole radiates, its temperature rises at an increasing rate because $\alpha(M)$ increases smoothly at the rest mass threshold for each new massive particle. For standard model

$$\alpha(M) \approx 10^{26} g^3 s^{-1} \tag{6}$$

above top quark production threshhold. From Eq. 3 and Eq. 5, we find

$$dt_* = 1.5 \times 10^{-15} \frac{dT_*}{T_*^4} \tag{7}$$

where $t_* = t/(1sec)$ and $T_* = T/(1EeV)$. Particle with energies above 1 EeV will be produced instantly when the temperature of the black hole reaches a $kT \geq 1EeV$. Characteristic time for the production of EeV energy particles will be order of 10^{-18} sec [6]. Similarly characteristic time required to produce particles with planck energy $10^9 EeV$ will be order of 10^{-43} sec. Hence duration of the emission of these high energy partcles by PBHs is unimportant compared to the evolution time of the universe. In next section we review the properties of brane world PBHs.

3. BraneWorld Primordial Black Holes(BWPBH)

There are different models which is valid in very early universe and simultaneously explain current constraints of standard cosmology. One of such thing occurs in Brane cosmological models. In this scenario PBHs can be formed in very early universe by density perturbation [8].

3.1 Evaporation rate of Brane World PBHs

In ref. [8] authors have calculated a mass-lifetime relation for black holes formed on the brane due to collapse of matter on the brane. If the size of the Black holes $r_0 \ll l$ then geometry of black holes is described by 5D schwarchild black holes. These black holes will emit hawking radiation into the brane as well as to the brane. In this approximation, radius, area and temperature of the black hole are given by,

$$r_0 = \sqrt{\frac{8}{3\pi}} \left(\frac{l}{l_4}\right)^{1/2} \left(\frac{M}{M_4}\right)^{1/2} l_4 \tag{8}$$

and

$$T_{bh} = \frac{1}{2\pi r_0} \; . \tag{9}$$

Mass loss rate of these black holes is given by,

$$\frac{dM}{dt} \approx -\frac{16\pi}{3} \tilde{g} T^2 \tag{10}$$

where

$$\tilde{g} = \frac{1}{160} g_{brane} + \frac{9\zeta(5)}{32\pi^4} g_{bulk} \; . \tag{11}$$

In our case g_{brane} is the dominant one and most of energy goes to the brane. In case of the Standard Model $g_{brane} = 100$.

From Eq. 10 we can derive the lifetime t_{evap} of a black hole of initial mass M. Lifetime t_{evap} is

$$t_{evap} \approx \tilde{g}^{-1} \frac{l}{l_4} \left(\frac{M}{M_4}\right)^2 \; . \tag{12}$$

Eq. 10 gives a relation between time and temperature of the BH as

$$dt_* = \frac{.009 \tilde{g}^{-1}}{512\pi A} \frac{dT_*}{T_*^5} \; , \tag{13}$$

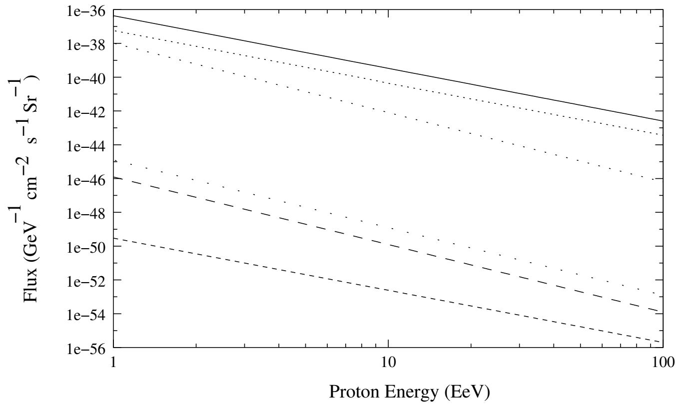

Figure 1. Proton flux today from 4d PBHs evapoarting at redshift $z = 0$(solid), $z = 1000$ (dotted) and $z = 10^6$ (small spaced dots). Similarly Proton flux today from 5d BWPBHs evapoarting at redshift $z = 0$(large spaced dots), $z = 1000$(long dashed) and $z = 10^6$ (short dashed).

where $t_* = t/1sec$, $T_* = T/1EeV$ and $A = \frac{l}{l_4}$. A basically determines the at which l 5D BHs dominate the dynamics. A is a parameter in our theory and can atmost take value 10^{31}. This value comes from upper limit on the size of extra dimension constrained by sub-mm gravity experiments. A PBH behaves as 5-dimensional when $r_0 \ll l$. From mass-lifetime relation we get the range of l, T, M over which PBH acts as a 5 dimensional black hole.

4. Mass distribution of black hole

Different mass function for 4D PBHs formed by the collapse of density perturbatiions has been derived by [3]. Here we assume a initial mass function for a single initial 4D PBH mass as given in [4]. In this case a distribution of the PBHs present throughout the evolution of the universe from their time of formation by taking into account only redshift effect which is expressed as,

$$n(M) = N(1+z)^3 \,, \tag{14}$$

where z is the redshift at time t. Here we neglect the evaporation of PBHs from their formation time to their time of evaporation. Similar mass function we assume to hold for 5D brane world PBHs.

5. Neutrino Flux

Let $f(E_\nu, T)$ represent the total neutrino flux of energy E_ν given in Eq. 2, then the diffuse direct flux per unit area today is:

$$\frac{dN_\nu}{dE_{\nu 0}} = \frac{1}{4\pi} \times 1.5 \times 10^{-15} \int_{z_{min}}^{z_{max}} \int_{kT_{i*}(1+z)}^{kT_{pl*}} \frac{d(kT_*)}{(kT_*)^4} \frac{1}{(1+z)^2} \frac{dn}{dz} f(E_\nu, T) dz \tag{15}$$

where $E_\nu = E_{\nu 0}(1+z)$, z is the redshift at the time of emission, z_{max} corresponds to max redshift from which particles of energies $100EeV$ can reach us and z_{min} corresponds to minimunm redshift and $E_{\nu 0}$ is energy of

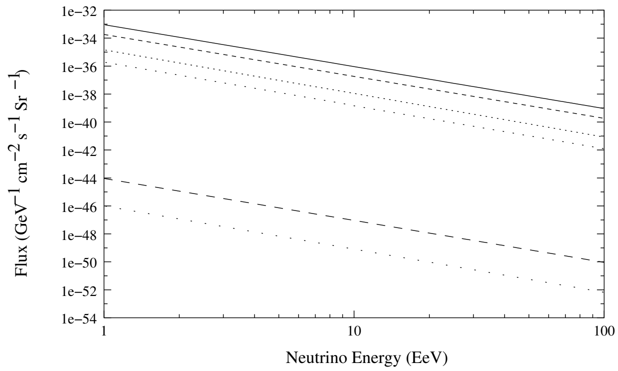

Figure 2. Direct Neutrino flux today from 4d PBHs evapoarting at redshift $z = 0$(solid), $z = 1000$(short dashed) and $z = 10^6$ (long dashed). Similarly indirect neutrino flux today from 4d PBHs evapoarting at redshift $z = 0$(dottted), $z = 1000$(small spaced dots) and $z = 10^6$ (large spaced dots).

neutrino at redshift z_{min}. As we know high energy particles produce by a 4D BH contributing to flux at energy of $100 EeV$ can atmost achieve energy of $10^{19} GeV$ which suggests $z_{max} \leq 10^7$.

Indirect flux is evaluated by incorporating fragmentation functions and modified $f(E_\nu, T)$ in Eq. hawking1. Contribution to indirect flux comes 1. from the decays of μ^+, μ^- and pions. 2. from the fragmentation of quarks into pions and then through the following channel $\pi \to \mu \to \nu$. 3. from the decays of evaporated W-bosons through the following channel $W \to e + \nu$ and $W \to \mu \to \nu$.

Similarly we calculate proton flux by incorporating fragmentation fuction for protons in Eq. hawking1.

The above procedure we repeat for BWPBHs for calculating direct, indirect neutrino flux and proton flux.

6. Discussion

The observational constraints with reason on the mass fraction of black holes at evaporation is given in [7]. As we see from Fig. 2 and 3, neutrino flux at energy $10^{20} eV$ from PBHs evapoarting today is roughly ten orders of magnitude smaller compared to the existing neutrino flux limit. For early decaying PBHs it can be noticed that neutrino flux at $10^{20} eV$ is even smaller.

We observe that UHE neutrino fluxes from BWPBHs are incredibly smaller compared to 4D PBHs even for maximum densities. This is obvious because the temperature of 5D PBHs is smaller than the 4D PBHs of same mass.

$t_{evap}(sec)$	10^{17}	10^{12}	10^4
$l_{min}(cm)$	6.214×10^{-14}	1.338×10^{-15}	2.885×10^{-18}
$l_{max}(cm)$	.01	.01	.01
$M_{min}(g)$	1.549×10^9	$4.898 \times 10^6 g$	4.898×10^2
$M_{max}(g)$	3.175×10^{14}	1.339×10^{13}	2.885×10^{10}
T_{min}	$2.3 \times 10^{-23} T_4$	$2.45 \times 10^{-22} T_4$	$2.45 \times 10^{-20} T_4$
T_{max}	$1.71 \times 10^{-20} T_4$	$4.053 \times 10^{-19} T_4$	$1.88 \times 10^{-16} T_4$

Table 1. Mass, temperature ranges for BW PBHs at three different epochs.

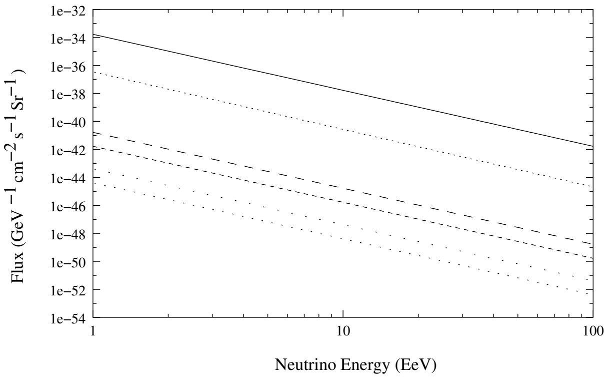

Figure 3. Direct Neutrino flux today from 5d BWPBHs evapoarting at redshift $z = 0$(solid), $z = 1000$(dotted) and $z = 10^6$ (short dashed). Similarly indirect neutrino flux today from 4d PBHs evapoarting at redshift $z = 0$(dottted), $z = 1000$(long dashed) and $z = 10^6$ (large spaced dots).

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