ANTIMATTER FROM PRIMORDIAL BLACK HOLES

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XIVth RENCONTRES DE BLOIS, MATTER-ANTIMATTER ASYMMETRY

Antiprotons and antideuterons are considered as probes to look for primordial black holes in our Galaxy. I give a brief overview of the latest developments on the subject.

1 Introduction

Primordial black holes (PBHs) could have formed in the early universe from the collapse of overdense regions through significant density fluctuations. Their detection nowadays is a great challenge as it could allow both to check the Hawking evaporation mechanism and to probe the early universe on very small scales that remain totally out of the range investigated by CMB or LSS measurements. They have recently been searched by their gamma-ray radiation [1] [2], extremely high-energy cosmic-ray emission [3], and antiproton emission [4]. This brief paper gives the latest improvements obtained with antiprotons and antideuterons. Such antinuclei are very interesting as the background due to spallation of cosmic protons and helium nuclei on the interstellar medium is expected to be very small.

2 Source term

The Hawking spectrum [5] for particles of energy Q per unit of time t is, for each degree of freedom:

$$\frac{\mathrm{d}^2N}{\mathrm{d}Q\mathrm{d}t} = \frac{\Gamma_s}{h\left(\exp\left(\frac{Q}{h\kappa/4\pi^2c}\right) - (-1)^{2s}\right)} \tag{1}$$

where κ is the surface gravity, s is the spin of the emitted species and Γ_s is the absorption probability. As it was shown by MacGibbon and Webber [6], when the black hole temperature is greater than the quantum chromodynamics confinement scale Λ_{QCD}, quarks and gluons jets are emitted instead of composite hadrons. To evaluate the number of emitted antiprotons $\bar{p}$, one therefore needs to perform the following convolution:

$$\frac{\mathrm{d}^2 N_{\bar{p}}}{\mathrm{d}E\mathrm{d}t} = \sum_j \int_{Q=E}^{\infty} \alpha_j \frac{\Gamma_j(Q,T)}{h} \left(e^{\frac{Q}{kT}} - (-1)^{2s_j}\right)^{-1} \times \frac{\mathrm{d}g_{j\bar{p}}(Q,E)}{\mathrm{d}E} \mathrm{d}Q$$

where α_j is the number of degrees of freedom, E is the antiproton energy and $\mathrm{d}g_{j\bar{p}}(Q,E)/\mathrm{d}E$ is the normalized differential fragmentation function, *i.e.* the number of antiprotons between E and $E+\mathrm{d}E$ created by a parton jet of type j and energy Q (including decay products). The fragmentation functions have been evaluated with the high-energy physics event generator PYTHIA/JETSET[7], based on the string fragmentation model.

To evaluate the antideuterons production, we used a simple coalescence scheme implemented directly within the PBH jets. This approach is similar to the one used in Chardonnet *et al.* [8] and Donato *et al.* [9]. The hadron momenta given by PYTHIA can be compared together and each time an antiproton and an antineutron are found to lie within the same coalescence sphere, an antideuteron is created. As the coalescence momentum p_0 is not Lorentz invariant, the condition must be implemented in the correct frame, namely in the antiproton-antineutron center of mass frame instead of the laboratory one. Depending on the models and experiments the value was found to vary between 60 MeV/c and 285 MeV/c. The number of antideuterons therefore reads as

$$\frac{\mathrm{d}^2 N_{\bar{D}}}{\mathrm{d}E\mathrm{d}t} = \sum_j \int_{Q=E}^{\infty} \alpha_j \frac{\Gamma_{s_j}(Q,T)}{h} \left(e^{\frac{Q}{kT}} - (-1)^{2s_j}\right)^{-1} \times \frac{\mathrm{d}g_{j\bar{D}}(Q,E,p_0)}{\mathrm{d}E} \mathrm{d}Q \tag{2}$$

where $\mathrm{d}g_{j\bar{D}}(Q,E,p_0)/\mathrm{d}E$ is the fragmentation function into antideuterons evaluated with this coalescence model for a given momentum p_0.

In any case this spectrum is, then, convoluted with the PBH mass spectrum[10] assumed to be scaling as M^2 below $M_* \approx 5 \times 10^{14}$g and as $M^{-2.5}$ above M_* and normalised to the local density.

3 Propagation scheme

The propagation of cosmic rays throughout the Galaxy is described with a refined two–zone effective diffusion model which has been thoroughly discussed elsewhere (Maurin *et al.* [11], Donato *et al.* [12]).

The Milky–Way is pictured as a thin gaseous disc with radius $R = 20$ kpc and thickness $2h = 200$ pc (see Fig. 1) where charged nuclei are accelerated and destroyed by collisions on the interstellar gas, yielding secondary cosmic rays. The thin ridge is sandwiched between two thick confinement layers of height L, called *diffusion halo*.

The five parameters of this model are K_0, δ, describing the diffusion coefficient $K(E) = K_0 \beta \mathcal{R}^{-\delta}$, the halo half-height L, the convective velocity V_c and the Alfven velocity V_a. Actually, a confident range for these five parameters has been obtained by the analysis of cosmic ray data on charged stable nuclei [11]. This exhaustive study allows a fully consistant treatment of the problem.

The source distribution for PBHs was assumed to follow the usual isothermal halo profile.

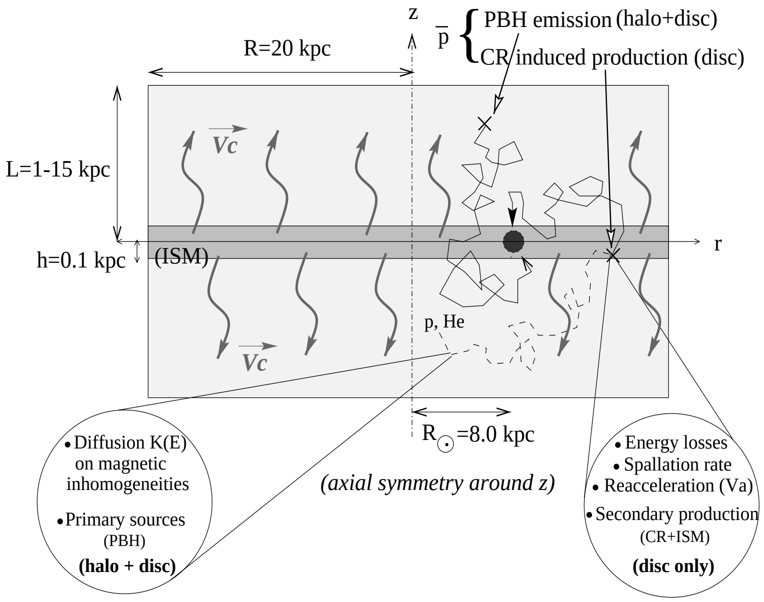

Figure 1: Schematic view of the axi-symmetric diffusion model. Secondary antiproton sources originate from CR/ISM interaction in the disc only; primary sources are also distributed in the dark halo which extends far beyond the diffusion halo. Drawing by D. Maurin.

4 Results

4.1 Upper limit on the PBH density with antiprotons

Fig. 2 gives, for a fixed set of astrophysical parameters, the antiproton flux due to the secondary and primary components[13]. The lowest curve is without any PBH whereas the upper one is for a local density $\rho_{\odot}^{PBH} = 10^{-32}$ g cm^{-3}. As expected, the experimental data can be reproduced without any new physics input. Taking into account the statistical significance of the astrophysical uncertainties, an upper limit on $\rho_{\odot}^{PBH}$ can be obtained[13] as a function of the diffusion halo thickness L. For a "reasonable" value of this parameter around 3 kpc, the upper limit is $\rho_{\odot}^{PBH} < 5.3 \times 10^{-33}$ g cm^{-3} which translates into $\Omega_{PBH} \leq 10^{-8}\,\Omega_M \sim 4 \times 10^{-9}$ assuming that PBHs cluster as dark matter.

4.2 A new window for detection : antideuterons

To go beyond an upper limit and try to detect PBHs is seems very interesting to look for antideuterons. Below a few GeV, there is nearly no background for kinematical reasons[9] and the possible signal due to PBHs evaporation could be easy to detect. We have evaluated the possible range of detection for the AMS experiment[14]. It is shown on Fig. 3 as a function of the three unknown parameters[15]: L, p_0 and $\rho_{\odot}^{PBH}$. The sensitivity of the experiment should allow, for averaged parameters, an improvement in the current best upper limit by a factor of six, if not a positive detection.

A complete study of the uncertainties due to the PBHs halo profile, to the possible photosphere near the event horizon, to the finite reheating temperature, to nuclear process and experimental measurements can be found in Barrau *et al.*[13 14].

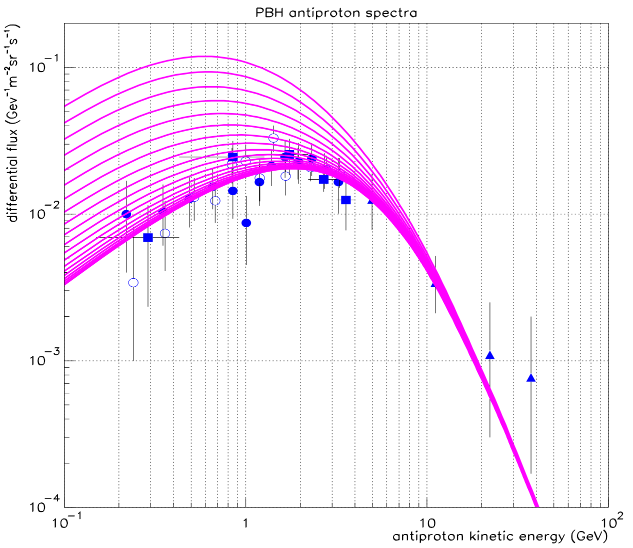

Figure 2: Experimental data from BESS95 (filled circles), BESS98 (circles), CAPRICE (triangles) and AMS (squares) superimposed with mean theoretical PBH spectra for $\rho_{\odot}^{PBH}$ between $5 \cdot 10^{-35}$ g.cm^{-3} (lower curve) and 10^{-32} g cm^{-3} (upper curves).

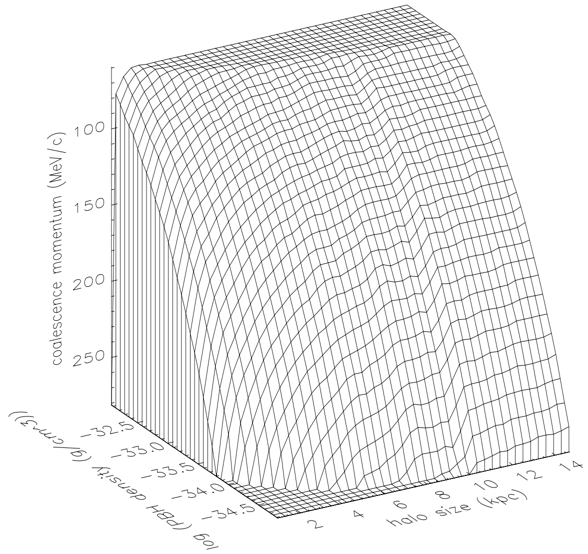

Figure 3: Parameter space (halo thickness L : 1-15 kpc ; coalescence momentum p_0 : 60-285 MeV/c; PBH density $\rho_{\odot}$: $10^{-35} - 10^{-31}$g.cm^{-3}) within the AMS sensitivity (3 years of data taking). The allowed region lies below the surface.

5 Conclusion

Primordial black holes have been used to derive interesting limits on the scalar fluctuations spectrum on very small scales studies [16] [17]. It was also found that PBHs are a great probe of the early Universe with a varying gravitational constant [18]. Significant progress has been made in the understanding of the evaporation mechanism itself, both at usual energies [19] and in the near-planckian tail of the spectrum [20] [21]. Looking for PBHs or improving the current upper limit is therefore a great challenge for the forthcoming years.

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