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Antideuterons as a probe of primordial black holes

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Abstract. In most cosmological models, primordial black holes (PBH) should have formed in the early Universe. Their Hawking evaporation into particles could eventually lead to the formation of antideuterium nuclei. This paper is devoted to a first computation of this antideuteron flux. The production of these antinuclei is studied with a simple coalescence scheme, and their propagation in the Galaxy is treated with a well-constrained diffusion model. We compare the resulting primary flux to the secondary background, due to the spallation of protons on the interstellar matter. Antideuterons are shown to be a very sensitive probe for primordial black holes in our Galaxy. The next generation of experiments should allow investigators to significantly improve the current upper limit, nor even provide the first evidence of the existence of evaporating black holes.

Key words. black hole physics – cosmology: miscellaneous

1. Introduction

Very small black holes could have formed in the early Universe from initial density inhomogeneities (Hawking 1971), from phase transition (Hawking 1982), from collapse of cosmic strings (Hawking 1989) or as a result of a softening of the equation of state (Canuto 1978). It was also shown by Choptuik (Choptuik 1993) and, more recently, studied in the framework of double inflation (Kim 2000), that PBHS could even have formed by near-critical collapse in the expanding Universe.

The interest in primordial black holes has been revived in the last years for several reasons. On the one hand, new experimental data on gamma-rays (Connaughton 1998) and cosmic rays (Barrau et al. 2002) together with the construction of neutrino detectors (Bugaev & Konishchev 2001), of extremely high-energy particle observatories (Barrau 2000) and of gravitational waves interferometers (Nakamura et al. 1997) give interesting investigational means to look for indirect signatures of PBHS. On the other hand, primordial black holes have been used to derive interesting limits on the scalar fluctuation spectrum on very small scales, extremely far from the range accessible to CMB studies (Kim et al. 1999; Blais et al. 2002). It was also found that PBHS are a useful probe of the early Universe with a varying gravitational constant (Carr 2000). Finally, significant progress has been made in the understanding of the evaporation mechanism itself, both at usual energies (Parikh & Wilczek 2000) and in the near-Planckian tail of the spectrum (Barrau & Alexeyev 2001; Alexeyev et al. 2001; Alexeyev et al. 2002).

For the time being there is no evidence in experimental data in favour of the existence of PBHS in our Universe. Only upper limits on their number density or on their explosion rate have been obtained (Barrau et al. 2002; MacGibbon & Carr 1991). As the spectra of gamma-rays, antiprotons and positrons can be well explained without any new physics input (e.g. PBHS or annihilating supersymmetric particles) there is no real hope for any detection in the forthcoming years using those cosmic-rays. The situation is very different with antideuterons which could be a powerful probe used to search for exotic objects, as the background is extremely low below a few GeV (Chardonnet et al. 1997; Donato et al. 2000). Such light antinuclei could be the only way to find PBHS or to improve the current limits. This paper is organized along the same guidelines as our previous study on PBH antiprotons (Barrau et al. 2002), to which the reader is referred for a full description of the source and propagation model used. The main difference is the necessity to consider a coalescence scheme for the antideuteron production. We compute the expected flux of antideuterons for a given distribution of PBHS in our Galaxy, propagate the resulting spectra in a refined astrophysical model whose parameters are strongly constrained and, finally, give the possible experimental detection opportunities with the next generation of experiments as a function of the uncertainties on the model.

2. Antideuterons emission

2.1. Hawking process and subsequent fragmentation

The Hawking black hole evaporation process can be intuitively understood as a quantum creation of particles from the

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vacuum by an external field. The basic characteristics can be easily seen through a simplified model (see Frolov & Novikov 1998 for more details) which allowed Schwinger to derive, in 1951, the rate of particle production by a uniform electric field and remains correct, at the intuitive level, for black hole evaporation. If we focus on a static gravitational field, it should be taken into account that the energy of a particle can be written as $E = -p_\mu \xi^\mu$, where p^μ is the four-momentum and ξ^μ is the Killing vector. The momentum being a future-directed timelike vector, the energy E is always positive in the regions where the Killing vector is also future-directed and timelike. If both particles were created in such a region, their total energy would not vanish and the process would, therefore, be forbidden by conservation of energy. As a result, a static gravitational field can create particles only in a region where the Killing vector is spacelike. Such a region lies inside the Killing horizon, i.e. the $\xi^2 = 0$ surface, which is the event horizon in a static spacetime. This basic argument shows that particle creation by a gravitational field in a static spacetime (this is also true in a stationary case) is possible only if it contains a black hole. Although very similar to the effect of particle creation by an electric field, the Hawking process has a fundamental difference: since the states of negative energy are confined inside the hole, only one of the created particles can appear outside and reach infinity.

The accurate emission process, which mimics a Planck law, was derived by Hawking, using the usual quantum mechanical wave equation for a collapsing object with a postcollapse classical curved metric instead of a precollapse Minkowski one (Hawking 1975). He found that the emission spectrum for particles of energy Q per unit of time t is, for each degree of freedom:

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

where contributions of angular velocity and electric potential have been neglected since the black hole discharges and finishes its rotation much faster than it evaporates (MacGibbon & Webber 1975; Page 1977). κ is the surface gravity, s is the spin of the emitted species and Γ_s is the absorption probability. If we introduce the Hawking temperature (one of the rare physical formulæ using all the fundamental constants) defined by

$$T = \frac{hc^3}{16\pi kGM} \approx \frac{10^{13}\mathrm{g}}{M}\,\mathrm{GeV} \tag{2}$$

the argument of the exponent becomes simply a function of Q/kT. Although the absorption probability is often approximated by its relativistic limit

$$\lim_{Q\to\infty} \Gamma_\mathrm{s} = \frac{108\pi^2 G^2 M^2 Q^2}{h^2 c^6} \tag{3}$$

we took into account in this work its real expression for non-relativistic particles:

$$\Gamma_\mathrm{s} = \frac{4\pi\sigma_\mathrm{s}(Q, M, \mu)}{h^2 c^2}(Q^2 - \mu^2) \tag{4}$$

where σ_s is the absorption cross-section computed numerically (Page 1976) and μ the rest mass of the emitted particle. Even if this mass effect is partially compensated by the pseudo-oscillating behaviour of the cross-section and remains at the level of a correction, we found some substantial discrepancies between the geometric limit and the numerical calculation which justifies this technical complication.

As was shown by MacGibbon and Webber (MacGibbon & Webber 1990), when the black hole temperature is greater than the quantum chromodynamics confinement scale Λ_QCD, quark and gluon jets are emitted instead of composite hadrons. To evaluate the number of emitted antinucleons $\bar{N}$, one therefore needs to perform the following convolution:

$$\frac{\mathrm{d}^2 N_{\bar{N}}}{\mathrm{d}E\mathrm{d}t} = \sum_j \int_{Q=E}^{\infty} \alpha_j \frac{\Gamma_{\mathrm{s}_j}(Q,T)}{h}\left(\mathrm{e}^{\frac{Q}{kT}} - (-1)^{2s_j}\right)^{-1} \times \frac{\mathrm{d}g_{j\bar{N}}(Q,E)}{\mathrm{d}E}\mathrm{d}Q \tag{5}$$

where α_j is the number of degrees of freedom, E is the antinucleon energy and $\mathrm{d}g_{j\bar{N}}(Q,E)/\mathrm{d}E$ is the normalized differential fragmentation function, i.e. the number of antinucleons between E and $E + \mathrm{d}E$ created by a parton jet of type j and energy Q. The fragmentation functions have been evaluated with the high-energy physics frequently-used event generator PYTHIA/JETSET (Tjöstrand 1994). This program is based on the so-called string fragmentation model (developed by the Lund group) which is an explicit and detailed framework where the long-range confinement forces are allowed to distribute the energies and flavours of a parton configuration among a collection of primary hadrons. It has received many improvements related, e.g., to parton showers, hard processes, Higgs mechanisms and it is now in excellent agreement with experimental data.

2.2. Coalescence scheme

In the context of proton-nucleus collisions it was suggested that, independently of the details of the deuteron formation mechanism, the momentum distribution of deuterons should be proportional to the product of the proton and neutron momentum distributions (see Csernai & Kapusta 1986 for a review). This was based on phase space considerations alone: the deuteron density in momentum space is proportional to the product of the proton density and the probability of finding a neutron within a small sphere of radius p_0 around the proton momentum. Thus:

$$\gamma\frac{\mathrm{d}^3 N_d}{\mathrm{d}k_d^3} = \frac{4\pi}{3}p_0^3\left(\gamma\frac{\mathrm{d}^3 N_p}{\mathrm{d}k_p^3}\right)\left(\gamma\frac{\mathrm{d}^3 N_n}{\mathrm{d}k_n^3}\right) \tag{6}$$

where p_0 is the coalescence momentum which must be determined from experiments. The very same arguments can be used for antideuterons resulting from an antiproton and antineutron momentum distribution. In our case, the coalescence scheme has to be implemented directly within the PBH jets as no nuclear collision is involved. We defined the following procedure:
- for each hadronic jet resulting from a parton emitted by a PBH, we search for antiprotons;
- if an antiproton is found within the jet, we search for antineutrons;

- if an antineutron is also found within the same jet, we compare their momenta;
- if the difference of the antiproton and antineutron momenta is smaller than the coalescence momentum p_0, we consider that an antideuteron should be formed.
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. Figure 1 gives the differential spectrum of antiprotons resulting from 1.9×10^8 $\bar{u}$ quark jets generated at 100, 75, 50, 25 GeV and the subsequent distribution of antideuterons with p_0 = 160 MeV. The ratio between the antideuteron and antiproton spectra is of the order of a few times 10^{-5}, which reflects the mean amplitude of the cosmic antideuteron flux from PBHs, given in Sect. 4 of this article, with respect to the one given for antiprotons in Barrau et al. (2002). This value is not surprising at it is in reasonable agreement with:
- the Serpukhov experimental ratio of the $\bar{p}$ to $\bar{D}$ production cross-sections for proton-proton interactions measured at $\sqrt{s}$ = 11.5 GeV (between 1.9×10^{-5} and 3.5×10^{-5} depending on the transverse momentum) as given in Abranov et al. (1987) and for proton-aluminium interactions measured at the same energy (7×10^{-5} for a center of mass transverse momentum around 270 MeV) as given in Binon et al. (1969);
- the CERN-ISR experimental ratio of the $\bar{p}$ to $\bar{D}$ production cross-sections for proton-proton interactions measured at $\sqrt{s}$ = 53 GeV (between 10^{-4} and 3.4×10^{-4}) as given in Alper et al. (1973) and Gibson et al. (1978);
- the theoretical cosmic secondary $\bar{p}$ to $\bar{D}$ ratio (around 10^{-5}) as given in Chardonnet et al. (1997);
- the theoretical cosmic primary $\bar{p}$ to $\bar{D}$ ratio from neutralinos (around a few times 10^{-4}) as given in Donato et al. (2000);
- the simulated ratio of $\bar{p}$ to $\bar{D}$ fluxes created within the Earth's atmosphere (around 10^{-5}) as evaluated with the program (Derome et al. 2000) that was used to explain AMS experimental data (Derome, private communication).

Although the orders of magnitude are correct, large discrepancies between these theoretical and experimental results can be noticed. This is taken into account in this work by allowing the coalescence momentum to vary between 60 MeV and 285 MeV, numbers than can be considered as "extreme" possible values.

The flux of emitted antideuterons should now be written as:

$$\frac{\mathrm{d}^2N_{\bar{D}}}{\mathrm{d}E\mathrm{d}t}=\sum_j\int_{Q=E}^{\infty}\alpha_j\frac{\Gamma_{s_j}(Q,T)}{h}\left(\mathrm{e}^{\frac{Q}{kT}}-(-1)^{2s_j}\right)^{-1}\times\frac{\mathrm{d}g_{j\bar{D}}(Q,E,p_0)}{\mathrm{d}E}\mathrm{d}Q \tag{7}$$

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. As the mean number of produced antideuterons per jet is extremely low, millions of events were generated for each energy and each partonic degree of freedom. Some interpolations are also required to avoid a diverging computing time: the associated uncertainties have been found to be negligible.

2.3. Convolution with the mass spectrum

The above expression gives the antideuteron flux due to a single black hole of temperature T. As PBHs of different temperatures (or masses) should be present, this flux must be integrated over the full mass spectrum of PBHs:

$$q^{\mathrm{prim}}(r,z,E)=\int\frac{\mathrm{d}^2N_{\bar{D}}(M,E)}{\mathrm{d}E\,\mathrm{d}t}\cdot\frac{\mathrm{d}^2n(r,z)}{\mathrm{d}M\,\mathrm{d}V}\mathrm{d}M$$

with

$$\frac{\mathrm{d}n}{\mathrm{d}M}\propto M^2 \text{ for } M<M_*$$

$$\frac{\mathrm{d}n}{\mathrm{d}M}\propto M^{-5/2} \text{ for } M>M_*$$

where $M_*\approx5\times10^{14}$ g is the initial mass of a PBH expiring nowadays. As explained in (Barrau et al. 2002), the shape below M_* does not depend on any assumption about the initial mass spectrum whereas the shape above M_* relies on the assumption of a scale-invariant power spectrum. The resulting distribution is, then, normalized to the local PBH density $\rho_\odot$. The spatial dependence of this source term is given in Eq. (11).

3. Propagation and source distribution

The propagation of the antideuterons produced by PBHs in the Galaxy has been studied in the two zone diffusion model described in Donato et al. (2001).
In this model, the geometry of the Milky Way is a cylindrical box whose radial extension is R = 20 kpc from the galactic center, with a disk whose thickness is $2h$ = 200 pc and a diffusion halo whose extent is still subject to large uncertainties.
The five parameters used in this model are: K_0, δ (describing the diffusion coefficient $K(E)=K_0\beta R^\delta$), the halo half height L, the convective velocity V_c and the Alfvén velocity V_a. They are varied within a given range determined by an exhaustive and systematic study of cosmic ray nuclei data (Maurin et al. 2001, 2002). The same parameters as employed to study the antiproton flux (Barrau et al. 2002) are used again in this analysis.
The antideuterons density produced by evaporating PBHs per energy bin $\psi_{\bar{D}}$ obeys the following diffusion equation:

$$\left\{V_\mathrm{c}\frac{\partial}{\partial z}-K\left(\frac{\partial^2}{\partial z^2}\left(r\frac{\partial}{\partial z}\right)\right)\right\}\psi_{\bar{D}}(r,z,E)+2h\delta(z)\Gamma_{\bar{D}}\psi_{\bar{D}}(r,0,E)=q^{\mathrm{prim}}(r,z,E) \tag{8}$$

where $q^{\mathrm{prim}}(r,z,E)$ corresponds to the source term discussed at the end of this section.
The total collision rate is given by $\Gamma_{\bar{D}}=n_H\sigma_{\bar{D}H}v_{\bar{D}}$ where $\sigma_{\bar{D}H}$ is the total antideuteron cross-section with protons (Groom et al. 2000). The hydrogen density, assumed to be constant all over the disk, has been fixed to n_H = 1 cm^{-3}.

Performing Bessel transforms, all the quantities can be expanded over the orthogonal set of Bessel functions of zeroth order:

$$\psi_{\bar{D}}=\sum_{i=1}^{\infty}N_i^{\bar{D},\mathrm{prim}}J_0(\zeta_i(x)) \tag{9}$$

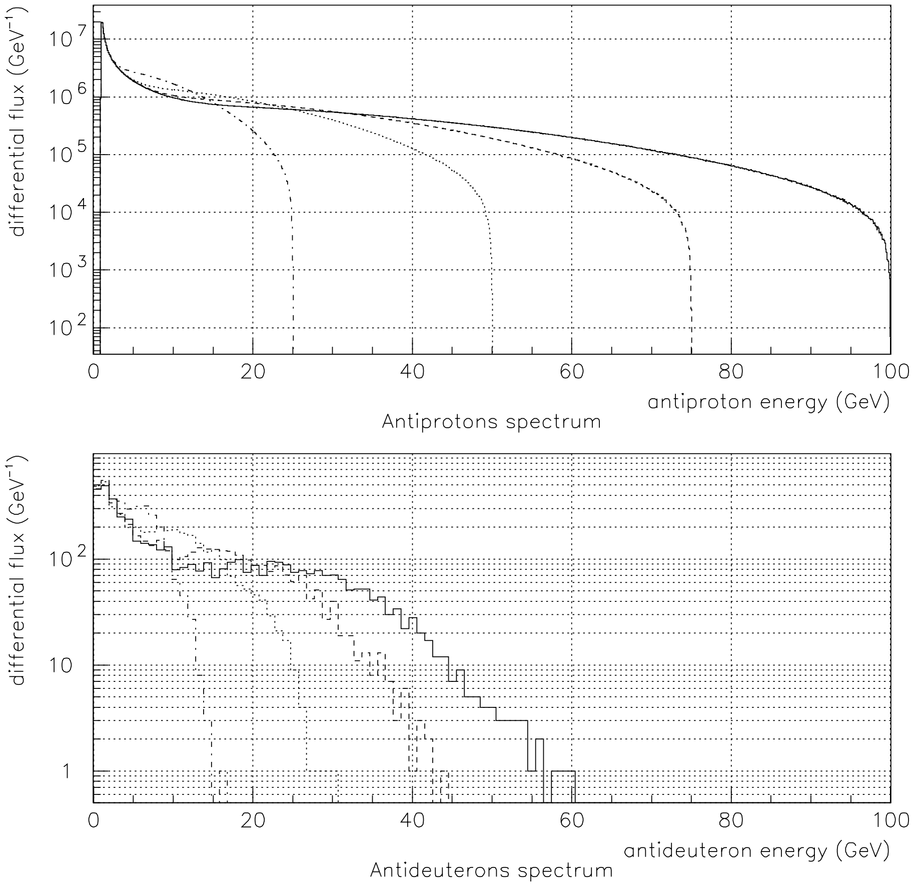

Fig. 1. Upper plot: antiproton differential spectrum obtained with 1.9×10^8 $\bar{u}$ quark jets generated by PYTHIA at 100, 75, 50, 25 GeV. Lower plot: antideuteron spectrum obtained in the same conditions with a coalescence momentum $p_0 = 160$ MeV.

and the solution of the Eq. (8) for antideuterons can be written as:

$$N_i^{\bar{D},\mathrm{prim}}(0) = \exp\left(\frac{-V_\mathrm{c} L}{2K}\right) \frac{y_i(L)}{A_i \sinh(S_i L/2)} \qquad (10)$$

where

$$\begin{cases} y_i(L) = 2\int_0^L \exp\left(\frac{V_\mathrm{c}}{2K}(L-z')\right)\sinh\left(\frac{S_i}{2}(L-z')\right) q_i^{\mathrm{prim}}(z')\mathrm{d}z' \\ S_i \equiv \left\{\dfrac{V_\mathrm{c}^2}{K^2} + 4\dfrac{\zeta_i^2}{R^2}\right\}^{1/2} \\ A_i \equiv 2h\,\Gamma_{\bar{D}}^{ine} + V_\mathrm{c} + K S_i \coth\left\{\dfrac{S_i L}{2}\right\}. \end{cases}$$

Energy changes (predominantly ionization losses, adiabatic losses and diffusive reacceleration) are taken into account via a second order differential equation for $N_i^{\bar{D},\mathrm{prim}}$ (see, e.g. Eq. (9) in Barrau et al. 2002, or Sects. 3.6.1, 3.6.2 and 3.6.3 in Maurin et al. 2001 for further details). At variance with antiproton studies, in a first approximation, we discarded the so-called tertiary term (corresponding to nonannihilating inelastic reaction, as given in Sect. 4 from Donato et al. (2000) which should be unimportant at the considered energies since the binding energy of this nucleus is of about 2 MeV.

The spatial distribution of PBH is a priori unknown. However, as these objects should have formed in the very early stages of the history of the Universe, it seems reasonable to assume that their distribution should be rather homogeneous. When the cosmic structures have formed, they should have followed the cold dark matter particles and we assume that they currently have the same distribution. As a consequence, the following profile for the PBHs distribution has been used (normalized to the local density):

$$f(r,z) = \frac{R_\mathrm{c}^2 + R_\odot^2}{R_\mathrm{c}^2 + r^2 + z^2} \qquad (11)$$

where the core radius R_c has been fixed to 3.5 kpc and $R_\odot = 8$ kpc. This profile corresponds to the isothermal case with a spherical symmetry, the uncertainties on R_c and the consequences of a possible flatness have been shown to be irrelevant in (Barrau et al. 2002).

4. Top of the atmosphere spectrum and experimental detection

The flux is then solar modulated in the force field approximation with $\Phi = 500$ MV – corresponding to the solar minimum – and shown in Fig. 2 for a reasonable ($p_0 = 160$ MeV/c, $L = 3$ kpc) set of parameters at the top of atmosphere (TOA). The lower curve is the antideuteron background due to interactions of cosmic rays on the interstellar medium as given in (Donato et al. 2000) whereas the upper curve is due to evaporating PBHs with a local density of 10^{-33} g cm^{-3} (allowed by the currently available upper limits, Barrau et al. 2002).

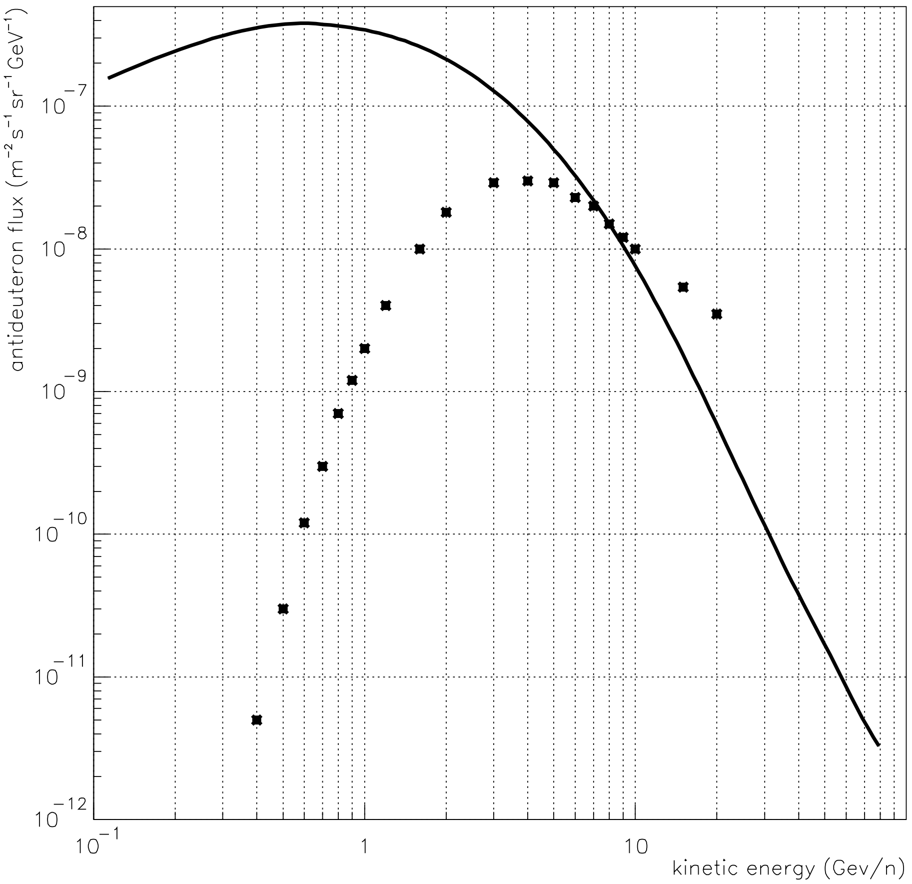

Fig. 2. TOA antideuteron flux at solar minimum. The upper curve (left part) is from a PBH distribution with a local density of 10^{-33} g cm^{-3} and the lower curve (taken from Donato et al. 2000) is from secondary processes.

Secondaries have been obtained in a two-zone diffusion model, with some simplifications: no convection and no energy losses have been included. However, as in the case of antiprotons, their effect should be marginal, while they are very important for primary fluxes, and the conclusions of the present analysis should not be substantially modified. To see all the computation steps, we refer the interested reader to Donato et al. (2000): the procedure is basically the same as in this work, except for the production cross-sections that are simply deduced from the antiproton production cross-sections within a coalescence model with a fixed momentum (taken as 58 MeV, which corresponds to 116 MeV in our notation) instead of being computed by a Monte-Carlo method. The fundamental point is that this background becomes extremely small below a few GeV/n for kinematical reasons: the threshold for an antideuteron production is $E = 17\,m_{\rm p}$ (total energy) in the laboratory, 2.4 times higher than for antiproton production. The center of mass is, therefore, moving fast and it is very unlikely to produce an antideuteron at rest in the laboratory. It should be noted that the secondary antideuteron background is only presented here to give a crude estimate of the expected "physical" background. In a forthcoming paper, we expect to study this secondary flux in much more detail, taking special care in the treatment of diffusion and the cross-sections.

The number of events expected in the AMS experiment (Barrau 2001) onboard the International Space Station can be estimated, following Donato et al. (2000). Taking into account the geomagnetic rigidity cut-off below which the cosmic-ray flux is suppressed (as a function of the orbit parameters), the acceptance of the detector and convoluting with the TOA spectrum, we obtain 7 events in three years between 500 MeV/n and 2.7 GeV/n for the previously-given PBH density and the previously-given typical astrophysical and nuclear parameters. This is a quite low value which would be difficult to measure due to the possible mis-reconstruction of $\bar{p}$ or D events. Nevertheless, it should be emphasized that the situation is very different to that of antiprotons, as the limit here is not due to the unavoidable physical background but just to the instrument capability. Many uncertainties are still unremoved and can affect the primary flux more significantly than the secondary one.

In order to be more quantitative, we performed a multi-variable analysis. Our model has a large set of free parameters: the astrophysical quantities used for propagation $(K_0, \delta, L, V_{\rm c}, V_{\rm a})$, the local density $\rho_\odot$ of PBHs and the nuclear coalescence momentum p_0 for the formation of antideuterons. To evaluate the possible detection of a signal we chose the following strategy: as the main uncertainty from astrophysical processes comes from the halo thickness L, the other parameters were fixed to the value giving the smallest flux. This sub-set of parameters depends slightly on L and was varied as a function of L to ensure that whatever the thickness chosen the real minimum is reached. All the results are therefore

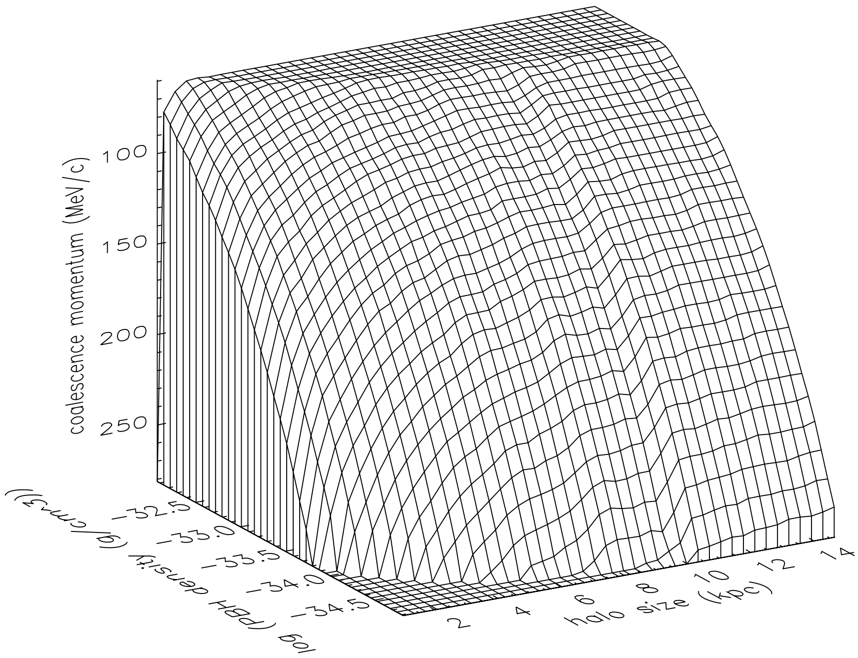

Fig. 3. Parameter space (halo thickness L: 1–15 kpc; coalescence momentum p_0: 60–285 MeV/c; PBH density $\rho_\odot$: 10^{-35}–10^{-31} g cm^{-3}) within the AMS sensitivity (3 years of data). The allowed region lies below the surface.

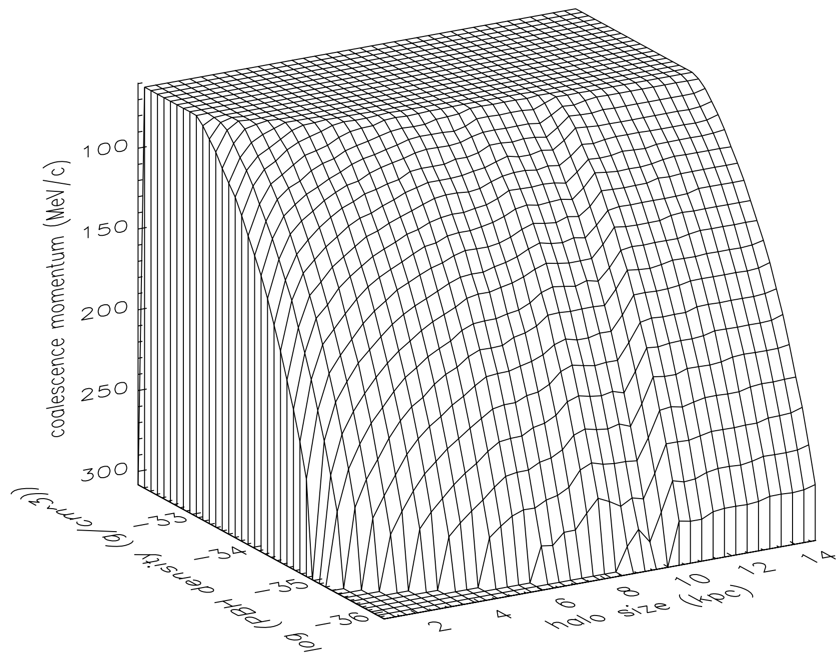

Fig. 4. Parameter space (halo thickness L: 1–15 kpc; coalescence momentum p_0: 60–285 MeV/c; PBH density $\rho_\odot$: 10^{-35}–10^{-31} g cm^{-3}) within the GAPS sensitivity (3 years of data taking). The allowed region lies below the surface.

conservative. The remaining variables $\rho_\odot$, L and p_0 are then varied within their allowed physical ranges: L between 1 and 15 kpc (see Barrau et al. 2002 for the details), p_0 between 60 and 280 MeV/c (depending on the experiments) and $\rho_\odot$ on the largest scale matching the related experimental sensitivity. Two experiments were investigated: the large spectrometer AMS (Barrau 2001) which will take data over 3 years from 2005 and the GAPS project (Mori et al. 2002), based on a clever design using X-ray desexcitation of exotic atoms. The allowed parameter space is given in Figs. 3 and 4: the values of L, p_0 and $\rho_\odot$ that can be explored by the considered experiment, without taking into account possible mis-reconstructions, are located below the surface. The sensitivity of AMS was taken to be 5.7×10^{-8} m^{-2} sr^{-1} GeV/n^{-1}s^{-1} between 500 MeV/n and 2.7 GeV/n for three years of observations whereas the one of GAPS was chosen as 2.6×10^{-9} m^{-2} sr^{-1} GeV/n^{-1}s^{-1} between 0.1 GeV/n and 0.4 GeV/n for the same duration (Mori et al. 2002). To make the results easier to read, Figs. 5 and 6

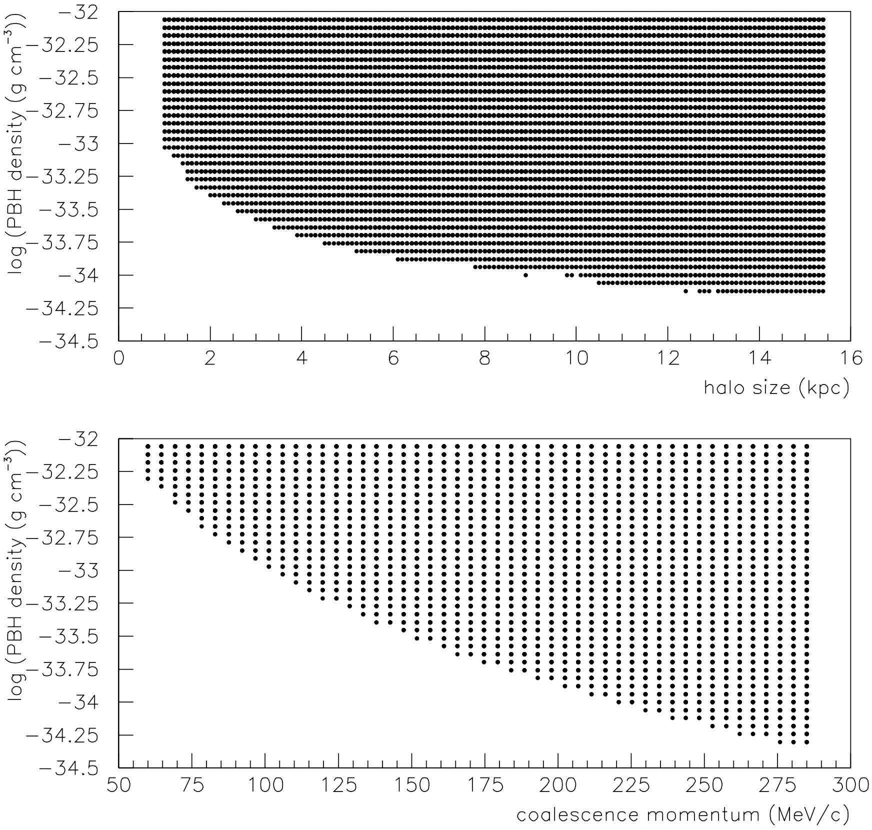

Fig. 5. Upper plot: parameter space (PBH density vs. halo thickness) within the AMS sensitivity for a fixed value of the coalescence momentum p_0 = 160 MeV/c. Lower plot: parameter space (PBH density vs. coalescence momentum) for a fixed value of the halo thickness L = 3 kpc.

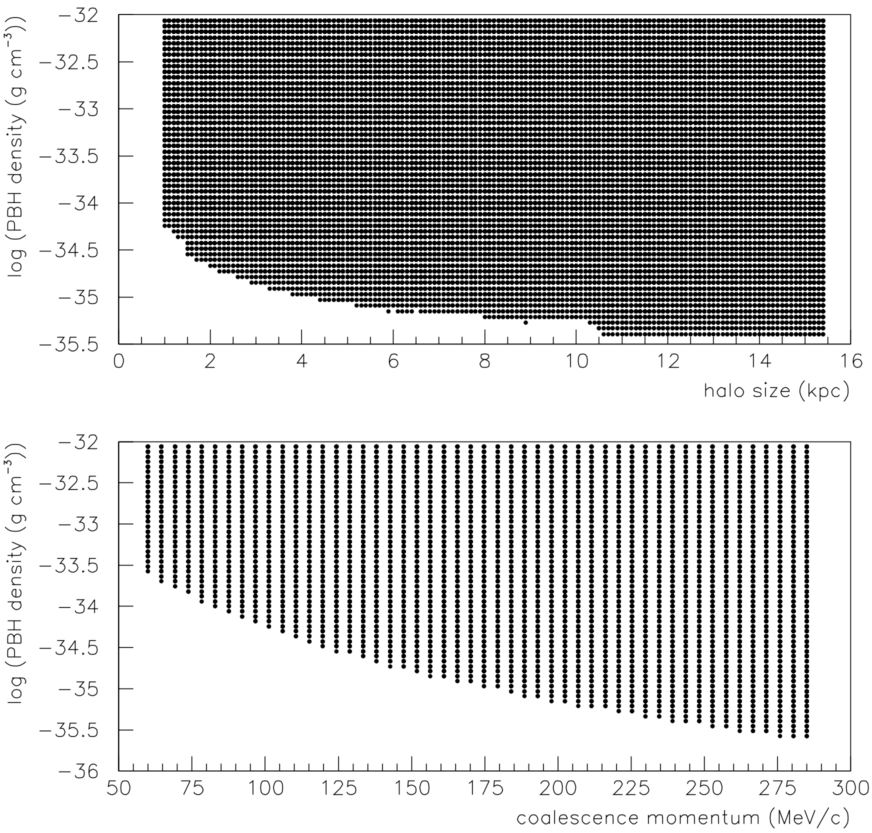

Fig. 6. Upper plot: parameter space (PBH density vs. halo thickness) within the GAPS sensitivity for a fixed value of the coalescence momentum p_0 = 160 MeV/c. Lower plot: parameter space (PBH density vs. coalescence momentum) for a fixed value of the halo thickness L = 3 kpc.

give the accessible densities of PBHs for AMS and GAPS with a fixed L (at the more reasonable value around 3 kpc) or a fixed p_0 (at the more favoured value around 160 MeV/c). As expected, the primary flux is increasing linearly with the PBH density (at variance with the search for supersymmetric particles related to the square of $\rho_\odot$, as a collision is involved), linearly with the magnetic halo thickness (as the core radius R_c is of the same order as L) and with the third power of the coalescence momentum (as the probability to create an antideuteron is related to a volume element in this space). The smallest detectable density of PBHs for the employed astrophysical and nuclear parameters is $\rho_\odot \approx 10^{-33.60} \approx 2.6 \times 10^{-34}$ g cm^{-3} for AMS and $\rho_\odot \approx 10^{-34.86} \approx 1.4 \times 10^{-35}$ g cm^{-3} for GAPS. It is much less than the best upper limit available nowadays $\rho_\odot < 1.7 \times 10^{-33}$ g cm^{-3} and it should open an interesting window for discovery in the forthcoming years. If no antideuteron is found, the upper limits will be significantly decreased, allowing stringent constraints on the spectrum of fluctuations in the Universe on very small scales. It should also be mentioned that, in spite of its much smaller acceptance, the PAMELA experiment (Adriani et al. 2002) could supply interesting additional information thanks to its very low energy threshold, around 50 MeV/n.

5. Discussion

As recently pointed out in Donato et al. (2000), antideuterons seem to be a more promising probe to look for exotic sources than antiprotons. In this preliminary study, we show that this should also be the case for PBHs, so that antideuterons may be the only probe to look for such objects. They should allow a great improvement in sensitivity during the forthcoming years: a factor 6 better than the current upper limit for AMS and a factor of 40 for GAPS.

Among the possible uncertainties mentioned in Barrau et al. (2002), the most important one was, by far, the possible existence of a QCD halo around PBHs (Heckler 1997). The latest studies seem to show that this effect should be much weaker (Mac Gibbon et al., in preparation) than expected in Cline et al. (1999). The results given in this work should, therefore, be reliable from this point of view.

Nevertheless, two points could make this picture a bit less exciting and deserve detailed studies. The first one is related to secondary antideuterons: the cross-sections used in this work could be slightly underestimated and some other processes could have to be taken into account (Protassov et al., in preparation). This could increase the background which should be considered with the same propagation model. The second one is that the signal is extremely close to the one obtained with the annihilation of supersymmetric particles as the shape of the spectrum is mostly due to fragmentation processes. In the case of detection, it would be very difficult to distinguish between the two possible phenomena, unless collider data or indirect or direct neutralino dark matter searches have given enough information to fix the supersymmetric parameters.

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