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Galactic diffusion and the antiproton signal of supersymmetric dark matter

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Abstract

The leaky box model is now ruled out by measurements of a cosmic ray gradient throughout the galactic disk. It needs to be replaced by a more refined treatment which takes into account the diffusion of cosmic rays in the magnetic fields of the Galaxy. We have estimated the flux of antiprotons on the Earth in the framework of a two-zone diffusion model. Those species are created by the spallation reactions of high-energy nuclei with the interstellar gas. Another potential source of antiprotons is the annihilation of supersymmetric particles in the dark halo that surrounds our Galaxy. In this letter, we investigate both processes. Special emphasis is given to the antiproton signature of supersymmetric dark matter. The corresponding signal exceeds the conventional spallation flux below 300 MeV, a domain that will be thoroughly explored by the Antimatter Spectrometer experiment. The propagation of the antiprotons produced in the remote regions of the halo back to the Earth plays a crucial role. Depending on the energy, the leaky box estimates are wrong by a factor varying from 0.5 up to 3.

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1 Introduction

The flux of antiprotons on the Earth is about to be measured with unprecedented accuracy by the Antimatter Spectrometer experiment (AMS) [1]. A detector will be shipped in orbit on the space shuttle. Cosmic rays will be directly detected in space. Unlike in balloon-borne experiments, measurements will not be spoilt by the atmosphere. Even in the stratosphere, the column density of air is still of the order of a few g$\cdot$cm^{-2}. This value is still an order of magnitude above the average of the column density of interstellar gas toward the region of the galactic centre. The AMS mission will be mostly sensitive to the energy range extending between 100 MeV and a few GeV, in a domain so far barely explored and where previous measurements are inconsistent with one another. The proton and antiproton fluxes will give precious indications on the propagation of cosmic rays at low energy.

As detailed in section 2, antiprotons are predominantly produced by the interactions of primary cosmic rays, mostly protons, with the interstellar gas that pervades the thin matter disk of our Galaxy. Quite exciting is the possible presence of an additional antiproton flux at low energy, which would signal the presence of massive neutral particles around our Galaxy. The Milky Way is embedded inside a halo of invisible material whose nature has not yet been determined. That dark matter could be made of relics from the big-bang. In that case, supersymmetric species are a favoured option and AMS should be sensitive to the antiprotons produced by their mutual annihilations.

Our understanding of cosmic ray propagation throughout the Galaxy has recently improved. In the old leaky box scheme, the Galaxy is pictured as one single region where production, interactions and diffusion of cosmic rays take place homogeneously. Cosmic rays are stored in a vast domain, from which they escape after being confined for some time. According to the leaky box model, they are uniformly distributed. This last feature is not quite correct. Measurements of the γ-ray diffuse emission of the Galaxy actually point toward a gradient of the cosmic ray density along the galactic ridge [2]. The proton flux varies with a galactocentric radius r. Recently, the γ-ray diffuse radiation of the Perseus arm region has been accurately determined by the EGRET experiment on board the Compton Gamma Ray Observatory. The γ-ray emissivity of interstellar hydrogen atoms immersed in the cosmic radiation drops by a factor of ~ 1.7 between the solar circle ($r \sim 9$ kpc) and the Perseus arm ($r \sim 13$ kpc) [3]. The naive leaky box model needs actually to be replaced by a more refined treatment of cosmic ray propagation.

In section 3, a two-zone diffusion model is presented. Cosmic ray primaries are produced inside a thin matter disk in which they propagate and interact with the interstellar gas. Those spallations generate antiprotons, among a variety of secondary nuclei. Cosmic rays diffuse in the chaotic magnetic fields carried by the galactic stellar winds. That diffusion takes place in an extended region, which encapsulates the previous thin disk and extends a few kiloparsecs away from the galactic plane. In this letter, we focus on the antiproton flux on the Earth, which is due to the annihilation of supersymmetric particles in the galactic halo. The corresponding antiproton yield is also derived in that section, in the framework of diffusion.

Finally, in section 4, we discuss our results. Massive neutral species annihilate in remote regions of the Galaxy, and antiprotons propagate back to the solar system. Their diffusion from the outer parts of the halo all the way toward the Earth is a crucial mechanism, which cannot be accounted for by the naive leaky box model. However, the main trend is preserved: the supersymmetric antiprotons show up at low energy. Above ~ 1 GeV, they are swamped in the flux of spallation antiprotons. The strongest supersymmetric signal is generated either by a pure gaugino or a pure higgsino. The intermediate case, where the supersymmetric species is a mixture of a gaugino and a higgsino, will be barely detectable, unless the abundance of that particle in the galactic halo is larger than its cosmological average. We also compare our predictions to the leaky box estimates. A correct treatment of the cosmic ray diffusion throughout the Galaxy is important. In the leaky box model, the antiproton flux is underestimated at low energy by a factor of 2 and overestimated at high energy by a factor of ~ 3. We have also derived the confinement time of the antiprotons inside the galactic halo and disk as a function of energy. Such a result may be directly incorporated in a leaky box model to yield a not really bad estimate of the antiproton flux. We feel that it may be helpful to colleagues who would like to rapidly derive a fair value of the antiproton signal without getting into the intricacies of our more involved treatment.

2 The sources of antiprotons

Antiprotons are naturally produced by the nuclear interactions of cosmic ray particles with the interstellar medium. In order to estimate the energy spectrum of the antiprotons created during a single collision, we have used the Lund Monte Carlo simulations PHYTIA and JETSET [4]. Since both cosmic rays and the interstellar medium are mostly composed of protons, the fundamental process is the collision of a high-energy proton with a proton at rest in the interstellar medium. This reaction produces hadrons, mostly pions whose radiative decays are the principal source of the galactic diffuse gamma-ray emission. During the fragmentation process, when the inelastic collision produces coloured strings, resonances such as Λ^0, Δ^-, Δ^{--} or Σ^- are formed and subsequently decay into antiprotons. Spallation reactions also produce antineutrons, which in turn decay into antiprotons. The threshold for the antiproton production mechanism $p + p \rightarrow 3p + \overline{p}$ is 7 GeV. The energy E_p of the incoming cosmic ray proton has been varied from that threshold up to 2.7 TeV. For each value of E_p, a million events have been generated to yield the antiproton multiplicity per collision

$$Y_{\bar{p}}(E_p \rightarrow E_{\bar{p}}) \; = \; \frac{dN_{\bar{p}}}{dE_{\bar{p}}} \;\; , \tag{1}$$

in the antiproton momentum range extending from 100 MeV to 100 GeV.

One of the best motivated particle candidates for cold dark matter is provided by supersymmetry [5]. The lightest supersymmetric particle (LSP) is stable, provided R-parity is conserved. In a large region of the supersymmetric parameter space, that species is the lightest neutralino (χ), defined as the lowest-mass superposition of the gaugino ($\tilde{\gamma}, \tilde{Z}$) and the higgsino ($\tilde{H}_1, \tilde{H}_2$) fields :

$$\chi \; = \; a_1 \tilde{\gamma} + a_2 \tilde{Z} + a_3 \tilde{H}_1 + a_4 \tilde{H}_2 \;\; . \tag{2}$$

The possibility to detect the presence of neutralinos in our galactic halo has been studied extensively in many different ways [6]. Direct detection of the nuclear recoil induced by neutralino–nucleus elastic scattering is, both theoretically [7] and experimentally [8], under investigation. The indirect detection of high-energy neutrinos coming from the centre of the Earth or the Sun [9], or the indirect detection of exotic components in the primary cosmic rays, such as γ, e^+ and $\bar{p}$, have been studied in detail [10, 11]. Here we examine the latter possibility, and concentrate on the diffusion of the cosmic antiprotons $\bar{p}$ from the remote regions of their production back to the inner Galaxy and the Earth.

The differential rate (per unit volume and per second) for the production of antiprotons from χ–χ annihilations is given by

$$q_{\bar{p}}^{\rm susy}(E_{\bar{p}}) \; = \; \langle \sigma v \rangle f(E_{\bar{p}}) \left\{ \frac{\rho_\chi}{m_\chi} \right\}^2 \quad , \tag{3}$$

in which $E_{\bar{p}}$ denotes the antiproton energy, σ is the χ–χ annihilation cross section and v is the neutralino velocity in the galactic halo. The neutralino density ρ_χ varies with its position. For a single annihilation, the antiproton energy spectrum is

$$f(E_{\bar{p}}) \; \equiv \; \left\{ \frac{1}{\sigma} \right\} \left\{ \frac{d\sigma(\chi\chi \to \bar{p} + X)}{dE_{\bar{p}}} \right\} \; = \; \sum_{F,f} B_{\chi f}^{(F)} \quad \left(\frac{dN_{\bar{p}}^f}{dE_{\bar{p}}} \right) \quad , \tag{4}$$

where F describes the χ–χ annihilation final state and $B_{\chi f}^{(F)}$ is the branching ratio into the quarks or gluons f in the channel F. The differential distribution of the antiprotons generated by the hadronization of quarks (with the exception of the top quark) and of gluons is denoted by $dN_{\bar{p}}^f/dE_{\bar{p}}$ and depends on the nature of the species f. Of the various quantities that are present in Eq.(3), $\langle \sigma v \rangle$ and $f(E_{\bar{p}})$ depend on the neutralino properties. The antiproton production rate also depends on the distribution ρ_χ of the dark matter particles inside the galactic halo. At this stage, some comments are in order :

(i) The neutralino annihilation cross section $\langle \sigma v \rangle$ is evaluated as in Ref. [11], with the parameters of the minimal supersymmetric standard model (MSSM) fixed at the following values: the lightest Higgs mass is $m_h = 55$ GeV while the sfermion mass is $\tilde{m} = 500$ GeV and $\tan\beta = 8$. The χ composition parameter $P = a_1^2 + a_2^2$ is fixed, for the three different cases considered here, at the values $P = 0.01$ (higgsino), $P = 0.5$ (mixture) and $P = 0.99$ (gaugino).

(ii) For the $\bar{p}$ differential distribution $f(E_{\bar{p}})$, we have evaluated the branching ratios $B_f^{(F)}$ for all annihilation final states that may produce antiprotons, i.e. direct production of quarks and gluons, generation of quarks through the intermediate production of Higgs bosons, gauge bosons and the top quark. The distributions $dN_{\bar{p}}^f/dE_{\bar{p}}$ from the hadronization of quarks (with the exception of the top quark) and gluons have been computed by using the Monte Carlo code JETSET 7.2 [4].

(iii) The neutralino halo distribution ρ_χ is taken to be spherically symmetric. In the axisymmetric coordinate system r and z, the density profile is given by

$$\rho_\chi(r,z) \;=\; \rho_\chi(\odot) \left\{ \frac{a^2 + r_\odot^2}{a^2 + r^2 + z^2} \right\} \;, \tag{5}$$

where $a = 3.5$ kpc is the core radius of the dark matter halo. Particular care must be taken about the local neutralino density $\rho_\chi(\odot)$, which depends on the LSP properties. Actually, if the big-bang relic density $\Omega_\chi h^2$, which we evaluate following [12], is too small to account for the cosmological dark matter, the density of neutralinos in the galactic halo should be corrected by a factor of η_χ. The latter deals with the fact that the neutralino density is less than the halo density whenever $\Omega_\chi h^2$ is smaller than a minimal value of, say, $(\Omega h^2)_{min} = 0.03$, which is compatible with the observed rotation curve of the Galaxy. At cosmological distances, this ratio is given by

$$\eta_\chi \;=\; \frac{\Omega_\chi h^2}{(\Omega h^2)_{min}} \;, \tag{6}$$

whereas in the galactic halo, it may well be significantly larger. For instance, there may be segregation between neutralinos and dark baryons as a result of the dissipation of the latter. Therefore, we must keep it in mind that η_χ could be as small as its cosmological average, but it may also be way larger.

3 The diffusion model for antiprotons

Parker has studied the propagation of cosmic rays inside the Galaxy as a consequence of their scattering by the irregularities of magnetic fields. The presence of the latter is now firmly established by synchrotron radiation far above the plane of our Galaxy as mentioned by Badwar [13]. Magnetic fields are also detected in other galaxies [14]. So the cosmic ray transport in the Galaxy crucially depends on the diffusion across magnetic fields. In the following, we will assume an isotropic diffusion with an empirical value for the diffusion coefficient. Another proof of the existence of a diffusion region in our Galaxy is provided by the recent diffuse γ-ray observations, which point toward the presence of cosmic rays far above the galactic disk. As regards convection, it seems probable that cosmic rays as well as the stellar wind from disk stars contribute to push out the magnetic fields so that the region where the particles diffuse inflates at a speed of the order of a few kilometers per second [13, 15]. Because convection has been shown to be negligible [16], we will disregard it and will focus our analysis on the pure diffusion case. Thus, our Galaxy can be reasonably modelled by a thin disk of atomic and molecular hydrogen with $0 \leq r \leq R = 20$ kpc and $|z| \leq h = 100$ pc, associated to an extended region of diffusion containing irregular magnetic fields with the same radial extension and $|z| \leq L = 3$ kpc. Those various regions are superimposed to the spheroidal halo of dark matter whose density profile has already been given in relation (5). That two-zone diffusion model is in good agreement with the observed primary and secondary nuclei abundances [16]. Since their discovery by Golden in 1979 [17], cosmic antiprotons have been thoroughly studied in the framework of the leaky box model [18]. We analyse here their propagation throughout the Galaxy in the light of a two-zone diffusion model.

In a stationary regime, the propagation equation of cosmic antiprotons may be expressed as

$$\frac{\partial n_{\bar{p}}}{\partial t} = 0 = K \Delta n_{\bar{p}} - \Gamma_{\bar{p}} n_{\bar{p}} + q_{\bar{p}} \;, \tag{7}$$

where $n_{\bar{p}}(E_{\bar{p}}, r, z)$ is the density of antiprotons with energy $E_{\bar{p}}$ at location (r, z). In the right-hand side of relation (7), the first term describes the diffusion of antiprotons. The diffusion coefficient K is constant at low energies, but raises with the rigidity p of the particle beyond a rigidity of 3 GV. This behaviour can be modelled by the form

$$K = 6 \times 10^{23} \, \mathrm{m}^2 \cdot \mathrm{s}^{-1} \left(1 + \frac{p}{3 \, \mathrm{GV}}\right)^{0.6} \;. \tag{8}$$

The second term in Eq.(7) describes the destruction of antiprotons by their interactions with the interstellar medium. That destruction rate is shown to be very small but has not been neglected in what follows. The collision rate of antiprotons with the interstellar hydrogen is given by

$$\Gamma_{\bar{p}} = \sigma_{\bar{p} H} \, v_{\bar{p}} \, n_H \;, \tag{9}$$

where $\sigma_{\bar{p} H}$ is the total antiproton interaction cross section with protons, $v_{\bar{p}}$ denotes the velocity and $n_H = 1 \, \mathrm{cm}^{-3}$ is the average hydrogen density in the thin matter disk. The last term in relation (7) deals with the various sources of antiprotons. Those species are produced by the spallation of cosmic protons on the interstellar matter of the disk. The antiproton production rate involves a convolution over the incident cosmic proton energy spectrum dn_p/dE_p

$$q_{\bar{p}}^{\rm st}(E_{\bar{p}}) \; = \; \int_{E_{\bar{p}}}^{+\infty} dE_p \, \left\{ \frac{dn_p}{dE_p}(E_p) \right\} \, \Gamma_p(E_p) \, Y_{\bar{p}}(E_p \to E_{\bar{p}}) \;\; . \tag{10}$$

The collision rate Γ_p of protons with the interstellar gas is defined in just the same way as the collision rate $\Gamma_{\bar{p}}$ of antiprotons in relation (9). The antiproton differential spectrum $Y_{\bar{p}}$ produced during a single proton spallation was previously defined in Eq.(1). The supersymmetric source term (3) may also be present if antiprotons are produced by the mutual annihilation of neutralinos. This leads to an additional antiproton flux.

We have solved Eq.(7) following the analysis by Webber, Lee and Gupta [16]. At the edge of the domain where cosmic rays are confined, the particles escape freely and the diffusion becomes inefficient. Thus the density vanishes at the boundaries of the domain where cosmic rays are confined by diffusion. This provides the initial conditions for solving the diffusion equation. Then, because the problem has a cylindrical symmetry, the densities n_p and $n_{\bar{p}}$ may be expanded as series of the Bessel functions of zeroth order $J_0\left(\zeta_i x\right)$ where ζ_i is the ith zero of J_0 and where $x = r/R$. Details may be found in [16]. The cosmic ray sources are located in the thin gaseous disk and we have taken the radial distribution of supernovae remnants and pulsars measured by Lyne *et al.* [19]. As regards the spallation mechanism, suffice it to say that an effective antiproton multiplicity may be defined as

$$Y_{\bar{p}}^{\rm eff}(E_{\bar{p}}) \; = \; \int_{E_{\bar{p}}}^{+\infty} dE_p \, \left\{ \frac{\Phi_p(E_p)}{\Phi_p(E_{\bar{p}})} \right\} \, Y_{\bar{p}}(E_p \to E_{\bar{p}}) \;\; , \tag{11}$$

so that no convolution with the cosmic proton energy spectrum is needed any longer. The differential flux of protons of energy E_p is denoted here by $\Phi_p(E_p)$.

In the case of the supersymmetric antiprotons, the resolution of Eq.(7) is more involved. The supersymmetric source term $q_{\bar{p}}^{\rm susy}$ now depends on both the galactocentric radius r and on the vertical coordinate z. In the solar neighbourhood, the antiproton energy spectrum due to the mutual annihilations of exotic particles is found to be :

$$\frac{dn_{\bar{p}}}{dE_{\bar{p}}}(\odot) \; = \; \sum_{i=1}^{\infty} \left\{ \frac{4}{A_i} \right\} \left\{ J_0\left(\zeta_i \frac{R_\odot}{R}\right) \right\} \left\{ J_1^{-2}(\zeta_i) \right\} \left\{ \int_0^L \mathcal{F}_i(z) \, Q_i^{\rm susy}(z) \, dz \right\} \;\; , \tag{12}$$

where the Bessel transform $Q_i^{\rm susy}(z)$ is defined as

$$Q_i^{\rm susy}(z) \; = \; \int_0^1 x \, dx \; q_{\bar{p}}^{\rm susy}(E_{\bar{p}}, r = xR, z) J_0\left(\zeta_i \frac{R_\odot}{R}\right) \;\; . \tag{13}$$

The vertical distribution $\mathcal{F}_i(z)$ is given by

$$\mathcal{F}_i(z) \; = \; \frac{\sinh \left\{ \frac{S_i}{2} (L - z) \right\}}{\sinh \left\{ \frac{S_i}{2} L \right\}} \quad , \tag{14}$$

where the parameter S_i is equal to $2\zeta_i/R$. Finally, the coefficient A_i in relation (12) stands for

$$A_i \; = \; 2h\Gamma_{\bar{p}} \; + \; K S_i \coth \left\{ \frac{S_i}{2} L \right\} \quad , \tag{15}$$

and only depends on the antiproton energy $E_{\bar{p}}$ through the diffusion coefficient K (8) and the collision rate $\Gamma_{\bar{p}}$ (9). Expression (12) involves an integral on both the galactocentric radius r and on the height z. That integration has been performed here with the specific form (3) for the supersymmetric production rate $q_{\bar{p}}^{\rm susy}$.

4 Results and discussion

We first show, in fig. 1, the standard interstellar $\bar{p}/p$ ratio obtained in the framework of our diffusion model, as a function of energy. As there is some uncertainty in the measurement of the spectral index α of the high-energy proton spectrum, we considered the cases $\alpha = 2.65$ (dashed line), 2.70 (intermediate solid curve) and 2.75 (dotted line). The $\bar{p}/p$ ratio decreases at low energy because the low-energy antiprotons must be produced with a large backward momentum in the centre-of-mass reference frame, and so their progenitors are very high energy protons, whose density is very low. The harder the spectrum, the larger the $\bar{p}/p$ ratio. Our results are in fair agreement with the estimates of Gaisser and Schaefer [18] collected in their fig. 5. Differences arise from the improved treatment of the diffusion mechanism with respect to the phenomenological leaky box model.

The antiproton signature $\bar{p}/p$ of neutralino pair-annihilations in the halo must be compared with the standard $\bar{p}/p$ ratio discussed above. Figure 2 features this ratio for three species of neutralinos, as discussed in section 2. At low energy, the SUSY antiproton production may exceed the standard signal in the pure gaugino and higgsino cases. In the intermediate situation, it is well below the secondary antiproton flux because the neutralino relic density is $\Omega_\chi h^2 \simeq 3 \times 10^{-3}$, only a tenth of the minimal value $(\Omega h^2)_{min}$.

This is not the case for a pure gaugino or higgsino. Note that the suppression factor η_χ may be larger than 1/10 so that the dotted curve may well be shifted upward.

In the leaky box model, cosmic rays are distributed homogeneously over the entire diffusion domain where they are confined by the magnetic fields of the Galaxy. Their diffusion may be described from a phenomenological point of view by the confinement time τ, which measures the rapidity with which the particles manage to escape in the intergalactic medium. That confinement duration τ is related to the column density, i.e. the amount of matter which the cosmic rays cross during their erratic journey. Typical values of a few g·cm^{-2} are necessary to convert primary nuclei such as carbon, oxygen or nitrogen into secondaries such as boron or beryllium. This implies a confinement time in the matter disk of the Galaxy of order 10^7 years. Because the unstable isotope ^{10}Be decays with a half-life of 1.6 megayears (My), it provides a unique chronometer of the time actually spent by cosmic rays since their production. Measurements of its abundance relative to its stable partner indicate that beryllium is confined during $\sim 10^8$ years, hence the need of an extended region of diffusion which encapsulates the thin gaseous disk. In the leaky box model, the supersymmetric production rate $q_{\bar{p}}^{\rm susy}$ is averaged over the confinement region and multiplied by the time τ_g it takes for a high-energy particle to escape from that diffusion domain

$$\frac{dn_{\bar{p}}}{dE_{\bar{p}}} \; = \; \langle \sigma v \rangle f(E_{\bar{p}}) \left\{ \frac{\langle \rho_\chi^2 \rangle}{m_\chi^2} \right\} \tau_g \; . \tag{16}$$

The square of the neutralino density is easily averaged over the diffusion box. More uncertain is the determination of the confinement time of antiprotons. Previous calculations [10, 11] are based on a typical escape time τ_g of order 10^8 years. The authors nevertheless note that estimates for that value may well vary by an order of magnitude. Our two-zone diffusion model directly incorporates that escape time, which depends on the cosmic ray distribution throughout the Galaxy and on the energy through the diffusion coefficient. The escape time from the disk τ_d and from the whole Galaxy τ_g may also be derived from that model. For protons or antiprotons, the net production rate Q in the entire Galaxy may be computed. A fraction of the particles that are produced are destroyed by spallation on the interstellar gas of the disk. What remains is the escape rate $\dot{N}_{\rm esc}$, provided that steady state is achieved

$$Q \; = \; \Gamma N_d + \dot{N}_{\rm esc} \; . \tag{17}$$

The confinement time of cosmic rays in the thin gaseous disk and in the whole domain of diffusion are related to the escape rate through

$$\dot{N}_{\rm esc} \; = \; \frac{N_d}{\tau_d} \; = \; \frac{N_g}{\tau_g} \;\; , \tag{18}$$

where the total number of particles in these two regions are respectively denoted by N_d and N_g. For both protons and antiprotons, we have evaluated the various escape times in the framework of our diffusion model. We find that they are fairly similar. The solid curve in fig. 3 features the variations of the antiproton escape time τ_g as a function of kinetic energy. The dashed line stands for the escape time from the matter disk. Both escape times decrease with energy. As a matter of fact, the diffusion coefficient increases at high rigidity so that particles diffuse, and therefore escape, more easily. From 100 MeV to 1 GeV, the disk confinement duration is $\tau_d \sim 11$ My while the escape time from the Galaxy as a whole is $\tau_g \sim 180$ My, a factor of 2 above the value currently used in the previous estimates of the antiproton flux. In fig. 4, we focus on the antiproton signal of supersymmetric dark matter. For purposes of comparison, the ratio of the leaky box prediction (16) to the exact result (12) is plotted as a function of the cosmic ray kinetic energy. The solid line corresponds to an escape time τ_g of 3×10^{15} s, independent of the energy. At low energy, the leaky box model underestimates the antiproton flux by a factor of 2. On the contrary, it is too optimistic at high energy by a factor ~ 3. If in relation (16), we use the value of the escape time τ_g, which has been derived in fig. 3, the situation considerably improves as featured by the dashed curve. The leaky box model may actually be used, provided the escape times are correctly derived with a diffusion model. The excess over relation (12) is at most 30% for a kinetic energy of 1 GeV.

In this letter, we have used a two-zone diffusion model to describe the propagation of antiprotons throughout the Galaxy. We have estimated the conventional and supersymmetric antiproton yields on the Earth. As regards the neutralino pair-annihilations in the halo, a correct treatment of diffusion improves the old leaky box estimates. We have presented here three characteristic examples of neutralino composition. A more exhaustive investigation of the supersymmetric parameter space is now necessary.

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Figure Captions

Fig 1 : The $\bar{p}/p$ ratio obtained in the framework of a diffusion model is displayed as a function of energy. The sources of antiprotons are the spallation reactions of cosmic ray primaries on the interstellar gas. The spectral index of the proton flux has been varied from 2.65 (top curve) to 2.75 (bottom curve).

Fig 2 : The $\bar{p}/p$ ratio is featured as a function of energy, for various antiproton sources: standard spallations (solid line) assuming a spectral index of 2.7 for the primary proton distribution, and neutralino pair annihilations, for three different neutralino compositions (gaugino, higgsino, and a mixture).

Fig 3 : The diffusion time scales of antiprotons in the thin gaseous disk (dashed line) and in the whole Galaxy (solid line) are plotted as a function of energy. Those time scales are inferred in the framework of the diffusion model discussed in the text.

Fig 4 : The ratio of leaky box results over direct diffusion estimates are presented as a function of energy, for the antiprotons from neutralino pair annihilations. The solid line is obtained by setting in the leaky box model the antiproton escape time scale at the constant value of 3×10^{15} s. In the case featured by the dashed curve, this escape time scale has been borrowed from fig. 3.