Transport of exotic anti-nuclei: II-$\bar{p}$ and $\bar{d}$ astrophysical uncertainties

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Abstract
We use a 1D propagation model to study the dependence of the $\bar{p}$ and $\bar{d}$ exotic fluxes on the transport parameters. The simple analytical solutions allow us i) to clarify the origin of the astrophysical uncertainties, and ii) to compare two models used for signal predictions, namely the constant and the linear Galactic wind models. We also study how these uncertainties should be reduced using forthcoming nuclear cosmic ray data. We confirm that the degeneracy of the transport parameters for a given propagation model leads to very different fluxes for primary antinuclei ($\sim 10^2$). However, we show that with forthcoming data, these uncertainties could be greatly reduced ($\sim 2$). As the precision will increase, the astrophysical uncertainty could then be dominated by our ignorance of the correct spatial dependence for some of the transport parameters: for instance, the constant and the linear wind models do not predict the same amount of exotic $\bar{p}$ at low energy.

Key words: Cosmic Rays, Diffusion equation, Anti-nuclei, Dark matter, Indirect detection
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1. Introduction
Positron, anti-proton and anti-deuteron fluxes are among the primary targets of ongoing (BESS, PAMELA) and forthcoming experiments (AMS, GAPS), seeking for indirect hints at dark matter candidates. These particles, unlike $\gamma$-rays, are very sensitive to the random magnetic fields pervading the Galaxy, and their transport is diffusive in nature.

Several propagation models (e.g., DARKSUSY—Gondolo et al. 2004; GALPROP—Moskalenko et al. 2005; or Donato et al. 2001) are being used to calculate the standard background fluxes as well as possible exotic contributions from new particles filling the dark matter halo. These calculations aim to uncover excesses over the background, or to put some constraints on parameters of new physics if none is observed. In this context, it is crucial to understand the uncertainties associated with the background and the hypothetical signal. Throughout this paper, we focus on astrophysical uncertainties only. To estimate them, we assume that the source spectrum and spatial distribution of the exotic matter are fixed, leaving the propagation coefficients as the only free parameters of flux calculations.

Whatever the propagation model, the exotic fluxes (and astrophysical uncertainties) depend on the associated transport coefficients (and their uncertainties). The usual way to derive all these quantities is as follows:
1. Transport parameters are determined using secondary to primary ratios, usually B/C, i.e. from standard GCRs whose sources are located in the disk of the Galaxy. A numerical study is generally required to extract (a) the parameters yielding the best fit to data; (b) uncertainties on these parameters.
2. These parameters are then used to calculate (a) $e^+$, $\bar{p}$, and $\bar{d}$ secondary fluxes (background), whose sources are also in the Galactic disk; (b) $e^+$, $\bar{p}$, and $\bar{d}$ exotic fluxes, whose sources are now located in the diffusive halo of the Galaxy. Transport coefficients from the best fit give the most likely $e^+$ (or $\bar{p}$ $\bar{d}$) fluxes, whereas the range of allowed transport parameters determine their uncertainties (for the chosen modelling).

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\textsuperscript{1} Below, we use indifferently 'exotic' or 'primary' fluxes.
A thorough study along the lines sketched above has been performed in the framework of the 2D constant wind diffusion model (Maurin et al., 2001; Donato et al., 2001; Barrau et al., 2005). With respect to item (1), Maurin et al. (2001) found that the set of allowed propagation parameters is strongly degenerated. As regards (2a), Donato et al. (2001) found that this degeneracy has almost no consequence on the secondary $\bar{\Phi}$ or $\bar{d}$ fluxes (uncertainties are of about 25% at most)—which is expected for any modelling, as long as the propagation parameters are adjusted from B/C data. Finally, related to (2b), Barrau et al. (2005) showed that this degeneracy leads to an uncertainty on exotic $\bar{\Phi}$ fluxes of about two orders of magnitude at low energy. The purpose of this paper is partly to explicit with simple calculations the above result, then to extend the analysis to different propagation models.

The outline of the paper is the following: in Sec. 2, we start with a description of the 1D modelling used throughout the paper. Section 3 deals with astrophysical uncertainties of $\bar{\Phi}$ and $\bar{d}$ primary exotic fluxes. The analysis is performed for the case of pure diffusion (§3.1), then for the case of diffusion/convection models (§3.2). The predictions for the constant and the linear wind models are compared in Sec. 4, using the best-fit values of the transport parameters provided in the literature. Finally, in Sec. 5, we focus on the constant wind model and estimate by how much the existing uncertainties on the $\bar{\Phi}$ and $\bar{d}$ exotic fluxes could be reduced with better data.

2. 1D diffusion models

Diffusion models in which the density is assumed to depend only on the z-coordinate (1D models) provide a simple but useful description of the propagation of cosmic ray nuclei (Jones, 1979; Jones et al., 2001).

Regarding exotic sources, we showed in the companion paper (Maurin et al., 2006) that analytical 1D–models provide a fair description of the $\bar{\Phi}$ primary fluxes, compared to that calculated from a full 2D–model taking into account energy gain and losses. The main reason is that the energy redistribution terms are restricted to the thin disk. However, exotic sources of $\bar{\Phi}$ are located in the extended diffusive halo of the Galaxy, and the $\bar{\Phi}$ reaching us rarely cross the disk on average.

Thus, if we discard energy gains and losses and use a 1D geometry, the $\bar{\Phi}$ and $\bar{d}$ flux calculations will still be satisfactory for a gross estimate (compared with full 2D calculation), but now the advantage is that we deal with simple analytical solutions (see App. B and C). These solutions allow us to put to the fore the key parameters driving exotic anti-nuclei uncertainties, as well as a their quick estimates.

2.1. Short description

We consider an infinite plane whose density and source distribution do not depend on $r$ (see Fig. 1). The thin-disk approximation is used ($h \ll L$). The diffusion/convection transport equation (without energy redistributions) for a constant source term $q_{\text{Dark}}(E)$ reads

$$-\frac{d}{dz} \left[ K(z) \frac{dN}{dz} \right] + \frac{d}{dz} \left[ V_{\text{gal}}(z) N \right] + 2h \Gamma \delta(z) N = q_{\text{Dark}}(E) \tag{1}$$

The spatial and energy dependence of the diffusion coefficient are assumed to be independent: $K(z, E) = \beta K_0(z) R^\delta$ ($R$ is the rigidity, $\beta = v/c$).

Discussions in the paper will refer to the four propagation parameters of the model: i) the halo size of the Galaxy $L$, ii) the diffusion coefficient normalization $K_0(z)$, iii) the diffusion slope $\delta$, and iv) the value of the Galactic wind $V_{\text{gal}}(z)$. Many propagation models are equivalent to a Leaky Box Model (LBM), as long as stable species originating from the disk are considered (Jones, 1970). Hence, transport parameters of 1D–models can be easily inferred (step 1 described in Sec. 1) from the mean grammage $\langle \chi \rangle_{LB} = \lambda_{esc}(E)$ of the LBM: the details of this equivalence as well as specific relationships are reminded in App. A: mean grammage in various 1D configurations are given in App. B. Step (2) of the analysis, i.e. estimating uncertainties on exotic fluxes, is then straightforward using 1D formulae derived in App. C.

For the sake of simplicity, spallative destruction of exotic species in the disk is neglected throughout the paper. It is checked in App. D, for the constant wind model, that this leaves the conclusions unchanged. This is understood as the bulk of exotic $\bar{\Phi}$ reaching us are mostly those created in the halo: on average, their disk crossings are too rare to yield a sizeable effect on the low energy spectrum (energy redistribution are neglected for the same reason).

2.2. Type I and Type II uncertainties

Two types of uncertainties are identified and discussed in this paper: 

Type I (parameter uncertainty) corresponds to uncertainties related to the degeneracy of transport parameters for a given propagation model (i.e. departure from best fit). Type II (modelling uncertainty) corresponds to the different predictions of primary fluxes between different propagation models whose respective transport parameters give the same standard fluxes.

We focus on the following configurations: pure diffusion (with one diffusion coefficient) and constant or linear wind model.

![Fig. 1. Upper half-plane of the 1D infinite disk along r (half-thickness h). Cosmic rays diffuse in the disk and in the halo, with a diffusion coefficient $K(z, E)$.](image_url)
3. Degeneracy in the transport parameters

The diffusion coefficient is assumed independent of the spatial coordinates, so that $K_0(z) \equiv K_0$.

### 3.1. Pure diffusion

#### 3.1.1. Degeneracy of parameters for standard sources

In the thin disk model, the transport equation reads:

$$-KN'' + n\sigma 2h\delta(z) \times N = 2h\delta(z)q.$$  

For $z = 0$, the solution is

$$N(0) = \frac{2hq}{2K/L + n\sigma}.$$  

Inserted in Eq. (A.6), this gives for the mean grammage

$$\langle x \rangle^{\text{pure-DM}} = \frac{\mu v L}{2K},$$  

where $\mu \equiv 2h\bar{m}$ is the surface mass density in the disk, $L$ the halo size, $K$ the diffusion coefficient and $v$ the velocity of the nucleus.

As the mean grammage in the LB model is given by

$$\langle x \rangle^{\text{LB}} = \lambda_{\text{esc}}(E),$$

the diffusion coefficient is inferred from Eq. (A.7) — i.e. $\langle x \rangle^{\text{pure-DM}} = \langle x \rangle^{\text{LB}}$ — and Eq. (2):

$$K(E) = \frac{\mu v L}{2\lambda_{\text{esc}}(E)}.$$  

Both the diffusion model and the leaky box model lead to the same B/C ratio as long as Eq. (3) holds. Consequently, both models lead to the same standard secondary fluxes for $\overline{\sigma}$ and $\overline{\tau}$.

#### 3.1.2. Lifting the degeneracy: uncertainties for primary $\overline{\sigma}$ and $\overline{\tau}$ in the halo

In contrast, exotic sources are located in the whole diffusive halo, which lifts the above mentioned degeneracy. The equation (no spillallations) now reads

$$-KN'' = q_{\text{Dark}},$$

whose solution is given by Eq. (C.8)

$$N^{\text{pure-DM}}(z = 0) = \frac{q_{\text{Dark}} L^2}{2K} = \frac{q_{\text{Dark}} \lambda_{\text{esc}} L}{\mu v}.$$  

For a given value of $\lambda_{\text{esc}}$, i.e. a given B/C ratio, the primary flux depends linearly$^2$ on $L$. If a very conservative range, $1 - 15$ kpc, is assumed for $L$ (as taken for example in Maurin et al. 2001), then the primary flux is uncertain by a factor of 15.

### 3.2. Adding a constant wind $V_{\text{gal}} = V_c$

Keeping the same spatial dependence for the diffusion coefficient, a constant wind directed outward the Galaxy is now added (pure diffusion recovered when $V_c \rightarrow 0$).

One of the main appeal for adding a constant wind comes from the measured form of $\lambda_{\text{esc}}(E)$. A fit to the B/C data in the Leaky Box Model—including all ingredients, i.e. energy losses, etc.—gives (see, e.g., Webber et al. 1998)

$$\lambda_{\text{esc}}(R) = \begin{cases} 
\beta \times 15.61 \text{ g cm}^{-2} & \text{if } R < 3.6 \text{ GV;} \\
\beta (R/3.6)^{-0.7} \times 15.61 \text{ g cm}^{-2} & \text{otherwise.}
\end{cases}$$  

(5)

Such a form naturally arises in diffusion/convexion models (compare $\langle x \rangle^{\text{LB}}$ and $\lambda_{\text{esc}}(E)$ at low energy). This remarkable result was first pointed out by Jones (1979): the phenomenological quantity $\lambda_{\text{esc}}(E)$, taken from the LBM, hints at a dual transport in propagation models (see also Jones et al. 2001 for other interpretations). Beyond a few GV, the shape of $\lambda_{\text{esc}}$ shows that diffusion always prevails so that conclusions of Sec. 3.1 still hold at high energy.

The mean grammage is obtained from Eq. (B.8)

$$\langle x \rangle^{\text{LB}} = \frac{\mu v}{2V_c} \left[ 1 - e^{-\frac{V_c L}{\lambda_{\text{esc}}(E)}} \right].$$  

(6)

This formula has two asymptotic behaviours with energy ($K(E)$ depends on energy): i) a diffusion-dominated regime if $V_c L/K \ll 1$ (reached at high energy) and ii) a convection-dominated regime if $V_c L/K \gg 1$ (low energy). The limiting cases are

$$\langle x \rangle^{\text{LB}} \rightarrow \frac{\mu v L}{2K} \text{ and } \langle x \rangle^{\text{LB}} \rightarrow \frac{\mu v}{2V_c}.$$  

(7)

At high energy, the same interplay between the propagation parameters applies as in Sec. 3.1. At low energy, an upper limit for the wind velocity is found when the convection-dominated regime is reached: equating rhs of Eq. (7) and first line of Eq. (5), with a standard value $\mu = 2.4 \times 10^{-3} \text{ g cm}^{-2}$ gives,

$$V_c \sim 20 \text{ km s}^{-1}.$$  

(8)

Equation (C.8) gives the flux for exotic sources in the galactic halo (as before, spallations neglected):

$$N^{\text{LB}}_{(\bar{p}, d)}(z = 0) = \frac{q_{\text{Dark}} K}{V_c^2} \left[ 1 - e^{-\frac{V_c L}{K}} \left( 1 + \frac{V_c L}{K} \right) \right].$$  

(9)

which asymptotic forms read

$$N^{\text{LB}}_{(\bar{p}, d)} \rightarrow \frac{q_{\text{Dark}} L^2}{2K} \text{ and } N^{\text{LB}}_{(\bar{p}, d)} \rightarrow \frac{q_{\text{Dark}} K}{V_c^2}.$$  

(10)

Equation (6) gives $V_c L/K$ as a function of $\lambda_{\text{esc}}$, provided that $V_c < \mu v/2\lambda_{\text{esc}}$ ($\sim 20 \text{ km s}^{-1}$). Equation (9) is rewritten

$$N^{\text{LB}}_{(\bar{p}, d)}(0) = \frac{4q_{\text{Dark}}^2 \lambda_{\text{esc}} K}{\mu^2 v^2} \left[ 1 - e^{-\frac{V_c L}{K}} \left( 1 + \frac{V_c L}{K} \right) \right].$$  

(11)

For a fixed value of $\lambda_{\text{esc}}$, the exotic flux depends linearly on $K$ and only weakly on the combination $V_c L/K$. This gives an overall uncertainty similar to the asymptotic case.
3.3. Linear wind \( V_{\text{real}}(z) = V_i \times z \)

A linear wind \( V_{\text{real}}(z) = V_i \times z \) is now considered ([\( V_i = \text{km s}^{-1} \text{ kpc}^{-1} \)]). The mean grammage is obtained from Eq. (B.9)

\[
\langle x \rangle^{V_i} = \frac{\mu \nu \sqrt{\pi} \text{ erf} \left( \sqrt{\frac{V_i}{2K}} L \right)}{4K \sqrt{\frac{V_i}{2K}}} \tag{12}
\]

and the primary flux is given by Eq. (C.7)

\[
N_{(\bar{\nu}, \bar{d})}^{V_i}(0) = \frac{q}{V_i} \left( 1 - e^{-\frac{\bar{V}_L^2}{2\pi}} \right). \tag{13}
\]

The corresponding limiting cases are

\[
\langle x \rangle^{V_i} \xrightarrow{\nu \Rightarrow K} \frac{\mu \nu L}{2K}, \quad \text{and} \quad \langle x \rangle^{V_i} \xrightarrow{\nu \Rightarrow K} \frac{\mu \nu \sqrt{\pi}}{\sqrt{8K} V_i}, \tag{14}
\]

and

\[
N_{(\bar{\nu}, \bar{d})}^{V_i} \xrightarrow{\nu \Rightarrow K} \frac{q L^2}{2K}, \quad \text{and} \quad N_{(\bar{\nu}, \bar{d})}^{V_i} \xrightarrow{\nu \Rightarrow K} \frac{q}{V_i}. \tag{15}
\]

At low energy, we proceed as in the previous section (at high energy, the pure diffusive transport is recovered). It is first assumed that the convective transport regime \( V_i \gg K / L^2 \) holds and that the mean grammage is perfectly determined from hypothetically perfect data. The mean grammage \( V_i \) through right-hand side Eq. (14). This time, the degeneracy on \( K_0 / L \) leads to no uncertainty on the exotic flux, at variance with the former case:

\[
N_{(\bar{\nu}, \bar{d})}^{V_i} \approx \frac{q}{V_i} \quad \text{compared to} \quad N_{(\bar{\nu}, \bar{d})}^{V_c} \approx \frac{qK}{V_c^2}. \tag{15}
\]

This simply pertains to the absence of the factor \( L \) or \( K \) in the left-hand side formula.

As in Sec. 5.1, we can derive estimates of the range span by \( V_i \) from real data. At low energy, one should obtain from Eqs. (5) and (14) the relation

\[
15.61 \, \text{g cm}^{-2} = \frac{\mu c \sqrt{\pi}}{\sqrt{8K} V_i}. \tag{16}
\]

From the range of variation of the LB model (i.e. \( \delta = 0.3 - 0.7 \)) using \( \mu = 2.4 \times 10^{-3} \) g cm\(^{-2} \), we get

\[
V_i \sim 8 - 30 \, \text{km s}^{-1} \text{ kpc}^{-1}. \tag{17}
\]

This value is not too sensitive to the uncertainty in \( L \) because the latter translates in \( V_i \) through \( \sqrt{K} \) in the mean-grammage formula above. This is compatible with results gathered in Tab. 2 of Lionetto et al. (2005) (for \( \delta = 0.3 \)). The “parameter” uncertainties (Type I) for this model are moderate (a factor of 3 here) and smaller than at high energy: it was the reverse for the constant wind model.

4. Difference between models: constant vs linear wind

The constant wind and the linear wind models are both used to exclude (or fit) parameters of new physics (Donato et al., 2004; Lionetto et al., 2005). It is thus of paramount importance to check if they predict the same amount of exotic \( \bar{\nu} \) and \( \bar{d} \).

This difference exists only at low energy when the two models differ from pure diffusion. Taking the ratio of the primary flux formula of the linear-wind model Eq. (13) to that of the constant-wind model Eq. (9) leads to

\[
\frac{N_{(\bar{\nu}, \bar{d})}^{V_i}}{N_{(\bar{\nu}, \bar{d})}^{V_c}} = \frac{V_i^2}{K_c V_i} \times \frac{1 - e^{-\frac{\bar{V}_L^2}{2K_i}}}{1 - e^{-\frac{\bar{V}_L^2}{2K_c}} \left( 1 + \frac{V_i}{V_c} \right)}, \tag{18}
\]

where \( K_i \) and \( K_c \) are the value of the diffusion coefficients found respectively in the linear and constant wind model.

As a new exotic component is usually sought at low energy, we only calculate this quantity for a kinetic energy \( E_k \sim 600 \, \text{MeV (IS)} \), corresponding roughly to \( R \sim 1 \, \text{GV} \), so that \( K(1 \, \text{GV}) \sim K_0 \).

The diffusion coefficient \( K \) should be constrained to be the same in both models (high energy constraint). Table 2 of Lionetto et al. (2005) gives \( K_0 = 2.5 \times 10^{28} \, \text{cm}^2 \, \text{s}^{-1} \), \( L = 4 \, \text{km} \) and \( V_i = 6 \, \text{km s}^{-1} \) kpc\(^{-1} \) (for \( \delta = 0.55 \)) whereas for the constant wind model, Tab. II of Barrau et al. (2005) gives \( K_0 = 1.35 \times 10^{28} \, \text{cm}^2 \, \text{s}^{-1} \), \( L = 4 \, \text{km} \) and \( V_c = 12 \, \text{km s}^{-1} \) (for \( \delta = 0.7 \)). Note that both best fits correspond to \( L = 4 \, \text{kpc} \) (although it could be only a coincidence).

This minimizes the difference that is observed between the two calculations as different \( L \) give different primary fluxes (see Sec.3.1.2). Plugging these parameters in the previous formula gives

\[
\frac{N_{(\bar{\nu}, \bar{d})}^{V_i}}{N_{(\bar{\nu}, \bar{d})}^{V_c}} \sim 1.3. \tag{19}
\]

This is not striking a difference, but this figure is expected to increase at lower energy. Moreover, it would also be larger would the best-fit value for \( L \) in the two models be different.

In any case, we remind that in any models, the transport parameters are more or less degenerate, providing the right amount of B/C. However, as explained in a previous section, this degeneracy is broken for (exotic) sources in the Galactic halo. The way it is broken depends on the vertical dependence of the transport parameters. Hence, different models are expected to lead to different predictions for the exotic flux. This issue deserves a dedicated study, which goes beyond the scope of this first simple discussion.

5. Reducing uncertainties

5.1. Impact of the inaccuracy of B/C data

So far, we discussed the hypothetical case of ideal data to estimate the degeneracy in the transport parameters. Using real ones, a greater degeneracy is generally obtained, enhancing the uncertainties on the exotic fluxes.

In LB models, the acceptable range of parameters found in the literature providing a good fit to B/C is \( \delta = 0.3 - 0.7 \). This value of the spectral index in \( \lambda_{\text{esc}}(R) \) [see Eq. (5)]
read from Fig. 2, reaching a maximum at low energy and decreasing at high energy. For comparison purpose, uncertainties from the 2D modelling are also displayed (using the same propagation parameters; see details about the 2D—model in the companion paper). For standard dark matter profiles, the two approaches are in fair agreement\(^4\). The various numbers found strengthen the use of the 1D—model for qualitative estimates of uncertainties.

5.2. How to decrease the astrophysical uncertainties?

The above result is a further support to our approach. It is thus tempting to pursue along this line and estimate how the uncertainties could be decreased with better data.

5.2.1. Sensitivity to the diffusion slope \(\delta\)

The uncertainty on the value of \(\delta\) greatly enlarges uncertainties on exotic fluxes at low energy. Castellina and Donato (2005) showed that the ongoing CREAM experiment (Seo et al., 2004) should pinpoint \(\delta\) with a precision of \(10 - 15\%\). Reading the corresponding intervals span by the transport parameters from Figs. 7 and 8 of Maurin et al. (2001), a simple calculation—analog to what is done in the previous subsection—shows that the uncertainty at low energy is decreased from the previous value of \(\sim 100\) down to \(\sim 10\). The latter value is in agreement with the estimate for fixed \(\delta\), meaning that the only remaining uncertainty comes now from the \(K_0/L\) degeneracy. The PAMELA experiment (Picozza et al., 2006), which was successfully launched in June 2006, or AMS on ISSA could as well help determining with a very good precision this parameter \(\delta\).

5.2.2. Radioactive nuclei

It is well known that radioactive nuclei, e.g. the \(^{10}\text{Be}/^{9}\text{Be}\) ratio lifts the \(K/L\) degeneracy. To complete the exercise, let us investigate to which precision \(L\) could be obtained. To date, the best data come from \(\text{ACE}\) (Yanasak et al., 2001): they correspond to a few energy points only—as it is the case for almost all radioactive data. We use the \(^{10}\text{Be}/^{9}\text{Be}\) ratio, as heavier isotopes (such as the \(^{26}\text{Al}/^{27}\text{Al}\) ratio) suffer larger experimental uncertainties.

Some quick procedure was exposed in Jones (1979) to extract the value of \(K_0\) (or \(L\)) and its uncertainties from the data. In our case, as we are only interested in the ratio of extreme values, i.e. \(L^{\max}/L^{\min}\), the discussion is even simpler. What is demanded is that

\[
\left(\frac{^{10}\text{Be}}{^{9}\text{Be}}\right)_{\text{ACE}} = \left(\frac{^{10}\text{Be}}{^{9}\text{Be}}\right)_{1\text{D—model}}
\]

Expressions for the radioactive species \(^{10}\text{Be}\) and the stable isotope \(^{9}\text{Be}\) remain to be determined in the 1D framework. For \(^{10}\text{Be}\), as the decay time \(\gamma\tau_0\) is generally much smaller

\begin{table}[h]
\centering
\begin{tabular}{llll}
Set & \(\delta\) & \(K_0\ (\text{kpc}^2\ \text{Myr}^{-1})\) & \(L\ (\text{kpc})\) & \(V_c\ (\text{km s}^{-1})\) \\
\hline
\text{max} & 0.46 & 0.0765 & 15 & 5 \\
\text{best} & 0.7 & 0.0112 & 4 & 12 \\
\text{min} & 0.85 & 0.0016 & 1 & 13.5 \\
\end{tabular}
\caption{Propagation parameters consistent with B/C data (Maurin et al., 2001). The set labelled best corresponds to the best fit to B/C data, while those labelled min and max correspond to sets which give minimum and maximum exotic fluxes (Donato et al., 2004).}
\end{table}

\(^3\) We underline that this is in fair agreement with the results obtained i) in a semi-analytical similar—albeit more complicated—study within a 2D propagation model or ii) using the full propagation scheme in this same 2D model (see respectively Sec. III.C and Sec. IV in (Donato et al., 2004)).

\(^4\) The minimum in the curves appear because propagation models were demanded to fit the 10 GeV/n B/C data point.
than the convective, spallative or escape time, the equation to solve in the 1D–model is simply
\[-K \frac{d^2 N}{dz^2} + \gamma \tau_0 N = 2h \eta \sec \delta(z)\]
whose solution is
\[N_{rad}(z) = \frac{hq}{\sqrt{K \gamma \tau_0}} \tanh \left( L \sqrt{\frac{\gamma \tau_0}{K}} \right) \approx \frac{hq}{\sqrt{K \gamma \tau_0}}, \quad (16)\]
where the approximation comes from \(L \sqrt{\gamma \tau_0/K} \gtrsim 10\), so that \(\tanh(\ldots) \approx 1\).

For the associated stable isotope, the solution can be found in the Appendices. However, it is not even needed: \(^9\)Be is a stable secondary nuclei having the same propagation history as boron. Demanding that a model fits B/C— which is a pre-requisite at this stage—automatically ensures the constancy of the \(^9\)Be flux. It means that
\[
\left\{ \frac{^{10}\text{Be}/^{9}\text{Be}}{^{10}\text{Be}/^{9}\text{Be}} \right\}_{ACE}^{\text{max/min}} \approx \left\{ \frac{^{10}\text{Be}}{^{9}\text{Be}} \right\}_{1D}^{\text{max/min}}.
\]

Expressing \(K = K_0 \beta R^4\) and getting the constant ratio \(K_0/L\) (fitting B/C) to appear in Eq. (16), we obtain
\[
\left\{ \frac{^{10}\text{Be}}{^{9}\text{Be}} \right\}_{1D}^{\text{max/min}} \approx \sqrt{\frac{L_{\text{max}}}{L_{\text{min}}}}.
\]

Using now for the \(^{10}\text{Be}\) data the 3 – \(\sigma\) error bars given in Yanasak et al. (2001) results in
\[
\frac{L_{\text{max}}}{L_{\text{min}}} = \left( \frac{0.120 + 3 \times 0.008}{0.120 - 3 \times 0.008} \right)^2 = 2.25.
\]

Hence an uncertainty of about a factor two in \(L\) (or equivalently in \(K_0\)), and the same uncertainty in the exotic spectra.

However, it should be kept in mind that such a small uncertainty is correct as long as \(\delta\) is known. For instance, Donato et al. (2002), using their derived range of allowed values for \(\delta\), found that the use of radioactive data could not lift the \(K_0/L\) degeneracy (although it slightly reduces it). Moreover, there could be other issues with radioactive data, as for example the effect of specific local features in the solar neighbourhood (see, e.g., Donato et al., 2002), which could affect the determination of the transport parameters.

This exercise has been conducted using existing ACE data. Future instruments, such as AMS have the capability to achieve better performances.

### 5.2.3. Summary for the constant wind model

Table 2 summarizes the qualitative results derived in this section. Determining the slope of the diffusion coefficient from B/C data should be the primary concern, whereas radioactive nuclei ultimately lift the remaining degeneracies.

We also remind that, although it was not explicitly stated all along, all the reasonings do hold for exotic anti-protons as well as for exotic anti-deuterons.

| Mean grammage \((x)/(\mu\nu)\) | Exotic \(\bar{p}/\bar{d}\) |
|--------------------------------|-----------------|
| \(N_{(\bar{p}, \bar{d})}(z = 0)/q_{\text{Dark}}\) |
| \[
\frac{1}{2V_c} \left[ 1 - e^{-\frac{V_c}{V_{c}}} \right] \quad \frac{K}{V_{c}} \left[ 1 - e^{-\frac{V_c}{V_{c}}} \left( 1 + \frac{V_c}{K} \right) \right]
\]
| \[
\begin{array}{c|c|c|c}
V_c & L/K & \Delta K_0/K_0 & \Delta L/L \\
\hline
\text{Low E} & V_c < L & 100 & 10 \\
\text{High E} & V_c > L & 100 & 10 \\
\end{array}
\]
| changed whether radioactive nuclei are considered or not. |

† Astrophysical uncertainty should vanish using new radioactive data.

Table 2

Summary of results derived in Secs. 3.1 and 3.2. The first row corresponds to (1) left column: formula for the grammage fitted from B/C data and (2) right column: the primary flux when spallative destruction is discarded. After the second row, each column (1 and 2) is further subdivided in two parts corresponding to the asymptotic behavior i) at low energy (left; convection-dominated) and ii) at high energy (right; diffusion-dominated). Note that the convection-dominated regime is not necessarily reached. In the subsequent rows, col. (1) corresponds to the degeneracies (derived from the above formulae) in the transport parameters and col. (2) to the uncertainties associated with these degeneracies. The same structure (further separation into low and high energy) is kept as for the upper half of the table. For example, for current B/C data at high energy, the degeneracy is \(\mu \cdot L/K_0\), leading to a relative uncertainty of \(\Delta L/L\) for exotic species.

### 6. Summary and conclusions

We used 1D–propagation models to study astrophysical uncertainties on exotic \(\bar{p}\) and \(\bar{d}\) fluxes (e.g. from annihilation of dark matter in the Galactic halo). We started with a detailed analysis of the constant wind diffusion model to recall and understand the origin and key parameters of the uncertainties for exotic fluxes.

We then stressed the origin of uncertainties for the transport parameters in the constant and linear wind models, and their differences at low energy, emphasizing on how crucial the determination of the diffusion slope \(\delta\) was. We showed that the present astrophysical uncertainties of \(O(100)\) could be severely reduced with a good determination of \(\delta\).

We finally showed that even if the internal degeneracies of
a given model are reduced, the differences between different mouldings (e.g. assuming different spatial dependences of some of the transport coefficients) could be important. For the constant and the linear wind model, a lower limit of 30% was derived. These differences between models are bound to become a more serious matter in the near future.

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Appendix A. Reminder of the equivalence between Leaky Box and diffusion models

The link between diffusion models and Leaky Box Models is established through the weighted-slab formalism. The weighted-slab decomposition is only approximate when energy losses are taken into account (Lezniak, 1979; Jones, 1991). But, in this paper, this is not an issue as they are neglected for all 1D models.

A.1. The weighted-slab formalism in brief

The ansatz is to rewrite the differential density \( N(x) \) of any transport equation (e.g. Eq. 1) as \( N(x) = \int_0^\infty \tilde{N}(x)G(x,r)dx \) (where \( x \) is the grammage crossed by a CR in g cm\(^{-2}\)). Demanding \( \tilde{N}(x) \) to follow the slab equation, one is left with an equation on \( G(x,r) \). The slab equation is common to all models (LB, 1D and 2D–diffusion models, etc.) and describes the nuclear aspects of propagation. The remaining equation only depends on the transport properties and on the choice of the geometry, both assumed to be independent of the species (see Sec. 2 of Maurin et al. 2001, for a longer albeit succinct summary; or Berezinskii et al. 1990, p. 45 for a more complete treatment). The exercise is easily done on the leaky box equation (no spatial dependence) governing the evolution of the nucleus \( j \) (source term \( q^j \) plus secondary contributions from all heavier nuclei \( k \))

\[
\frac{\tilde{N}}{\lambda_{esc}(E)} + \frac{\sigma^j}{m} \tilde{N} = q^j + \sum_{k>j} \frac{g^j}{m} \tilde{N}^k . \tag{A.1}
\]

Using the ansatz and inserting the slab equations

\[
\frac{dN^j(x)}{dx} + \frac{\sigma^j}{m} N^j(x) = q^j + \sum_{k=j+1}^{\text{max}} \frac{\sigma^{kj}}{m} N^k(x) . \tag{A.2}
\]

leads to an equation for \( G(x) \) whose solution is given by

\[
G_{LB}(x) = \frac{1}{\lambda_{esc}} \exp \left( \frac{-x}{\lambda_{esc}} \right) . \tag{A.3}
\]

Different propagation models can be compared through their path length distributions at the location where CR measurements are made, i.e. \( r_\odot \). Thus, a diffusion models (DM) will be locally equivalent to a LBM if

\[
G_{DM}(x, r_\odot) = G_{LB}(x) . \tag{A.4}
\]

We remind that for a LBM all locations come to the same thing since all quantities are spatially averaged.

A.2. PLD and mean grammage \( \langle x \rangle \)

A useful quantity is the mean grammage crossed by CRs, defined as

\[
\langle x \rangle(r) = \frac{\int_0^\infty xG(x,r)dx}{\int_0^\infty G(x,r)dx} . \tag{A.5}
\]

An alternative expression is provided by

\[
\langle x \rangle(r) = -\langle x \rangle \left. \frac{d}{d\sigma_p} \ln N^p(r) \right|_{\sigma_p=0} , \tag{A.6}
\]

where \( N^p(r) \) is the solution for a primary species (see Berezinskii et al. 1990). The advantage of this second formulation is that there is no need to know the PLD, \( G(x,r) \), to evaluate the mean grammage. Indeed, the former quantity can be trickier than \( N^p(r) \) to derive (as an illustration, PLDs for several modelling can be found, e.g., in Owens (1976)).

The mean grammage is only the first moment of the distribution \( G(x,r) \): only the latter contains the full information on the transport for the studied model. However, for two propagation models to be equivalent, we will use a weaker version of Eq. (A.4), only demanding the equivalence of the first moments

\[
\langle x \rangle_{DM}(r_\odot) = \langle x \rangle_{LB} \equiv \lambda_{esc}(E) . \tag{A.7}
\]

The last equality comes from Eq. (A.3) plugged into Eq. (A.5). We remind that all the above quantities depend on the energy. Note also that this relation does imply equivalence of PLDs for many cases especially if the thin-disk approximation is assumed (see App. A.2).

Appendix B. Mean grammage \( \langle x \rangle \) in two modellings

The diffusion coefficient \( K \) is the same in the disk and in the halo (see Fig. 1). The galactic wind is taken either as

\[\text{Contrary to an erroneous calculation in the previous versions of this paper, in the thin disk limit, setting two distinct diffusion coefficients for the disk and for the halo is strictly equivalent to have only one diffusion coefficient for the two zones. Indeed, in the thin disk approximation, the time spent in the disk tends to zero, while the number of crossing (hence the grammage) is kept constant: only the diffusion coefficient in the halo plays a role. This result is of course known for almost as long as diffusion models exist. The trivial mistake we made (shame on us... and oh, yes, a referee to point out the mistake would have been just the right thing to have, but as referring goes, you know...) was connected to a wrong implementation of the continuity condition at the crossing of the zones. A very small part of the paper was affected by this mistake, and the only one plain wrong conclusion is now removed.} \]
a constant $V_{\text{gal}}(z) = V_c$ or as a linear term $V_{\text{gal}}(z) = V_l \times z$. The transport equation reads:

$$-KN'' + (V_{\text{gal}}N)' + 2h\delta(z) n v \sigma \times N = 2hq\delta(z). \ (B.1)$$

The quantity $\sigma v$ is the total destruction rate of the antinucleus under study with the interstellar gas, whose density is $n$.

B.1. Solutions

For our purpose, it is sufficient to extract solutions for primary standard species, that lead straightforwardly to the mean grammage $(x)$.

B.1.1. Constant wind $V_{\text{gal}}(z) = V_c$

We start with the equation in the galactic halo, i.e.

$$-KN'' + V_c N' = 0 \ \rightarrow \ \ N = Ae^{V_c z/K} + B.$$ 

Implementing the boundary condition $N(z = L) = 0$ determines one of the two constants of the solution in the halo:

$$N = A \left( e^{V_c z/K} - e^{V_c L/K} \right).$$

We integrate over the thin-disk (see e.g. (Jones et al., 2001)), i.e. $\lim_{\epsilon \to 0} \int x_\epsilon^{x_+} (\text{Eq. B.1}) dz$, taking care of the discontinuity induced by the wind during the disk crossing:

$$-2KN'(0) + 2V_c N(0) + 2hv\sigma N(0) = 2hq.$$ 

The solution for the halo $N$ above is plugged into this equation. It is convenient for the following to write the solution as:

$$N(z) = N(0) \times \frac{1 - e^{-V_c(L - z)}}{1 - e^{-V_c L}} \ (B.2)$$

with

$$N(0) = \frac{2hq}{2V_c/(1 - e^{-V_c L/K}) + 2h\nu \sigma} \ (B.3).$$

B.1.2. Linear wind $V_{\text{gal}}(z) = V_l \times z$

The parameter $V_l$ has the dimension of the inverse of a time. As above, we start by solving this equation in the halo, where it reduces to

$$-KN'' + V_l z N' + V_l N = 0.$$ 

This equation is not hermitian and it is more convenient to use new variables $n$ and $y$ defined as

$$n(y) = N(y) e^{y^2} \quad \text{and} \quad y \equiv \sqrt{2} \nu z$$

where

$$\nu \equiv \sqrt{\frac{V_l}{2K}}. \ (B.4)$$

The diffusion equation then reads

$$n''(y) - n(y) \left( \frac{1}{2} + \frac{y^2}{4} \right) = 0.$$ 

The general solution of this equation is given in Gradsteyn and Ryzhik (1994) (p. 1067, Eq. 9.255). Rewritten using $z$ gives

$$N(z) = Ae^{(\nu z)^2} + Be^{(\nu z)^2} \text{erf}(\nu z).$$

The constants of integration $A$ and $B$ are determined as usual. First, the condition $N(z = L) = 0$ yields

$$A = -B \times \text{erf}(\nu L).$$

Second, integration of Eq. (B.1) over the thin disk yields

$$-2KN'(0) + 2\nu L N(0) = 2hq,$$

which determines $A$ and gives the final expression

$$N(z) = N(0) \times e^{(\nu z)^2} \left( \frac{\text{erf}(\nu L) - \text{erf}(\nu z)}{\text{erf}(\nu L)} \right) \ (B.5)$$

with

$$N(0) = \frac{2hq}{\sqrt{\pi} \text{erf}(\nu L) + 2h\nu \sigma} \ (B.6).$$

where $\nu$ is defined in Eq. (B.4).

B.2. Mean-grammage $(x)$ at $z = 0$

Two approaches can be used to derive the mean grammage. The first one is depicted in App. A. The second one is based on the fact that, in the thin disk approximation, all solutions for $z = 0$ can be recast to look formally as to a Leaky Box solution (see Jones et al. 2001):

$$N(0)^{1D\text{-model}} = \frac{2hq/\mu \nu}{1/(x)^{1D\text{-model}} + \sigma/\bar{m}} \ (B.7).$$

In that case, demanding an equivalence between the mean grammages of different models (as in App.A.2) is one and the same to demanding the equivalence between path length distributions. The corresponding mean-grammages are directly obtained from Eqs. (B.3) and (B.6). Using the relation $\mu \equiv 2h\nu \bar{m}$ ($\bar{m}$ is the mean mass of the interstellar medium and $\mu$ is the surface mass density of the gas in the disk),

- Constant galactic wind $V_{\text{gal}}(z) = V_c$

$$\langle x \rangle^V_c = \frac{\mu \nu}{2V_c} \times \left( 1 - e^{-V_c L/K} \right). \ (B.8)$$

- Linear galactic wind $V_{\text{gal}}(z) = V_l \times z$

$$\langle x \rangle^V_l = \frac{\mu \nu \times \sqrt{\pi} \text{erf} \left( L \sqrt{V_l/(2K)} \right)}{4K \sqrt{V_l/(2K)}} \ (B.9).$$

Note that both formulae reach the limit of pure diffusive transport for vanishing (compared to the diffusion coefficient) values of the wind:

$$\langle x \rangle^{\text{pure-diffusion}} = \frac{L \mu \nu}{2K}. \ (B.10)$$

Appendix C. $\overline{\sigma}$ and $\overline{\mathcal{A}}$ fluxes from sources in the diffusive halo

We now use a constant source term in the Galaxy:

$$KN'' + (V_{\text{gal}}N)' + n\delta(z) v \sigma \times N = q. \ (C.1)$$

\footnote{The function $\text{erf}$ is defined as $\text{erf}(z) \equiv \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} \, dt.$}
C.1. Constant wind \( V_{\text{gal}}(z) = V_c \)

We proceed as for the standard source case. In the halo, the transport equation reads

\[
-KN'' + V_c N' = q.
\]

Using the boundary condition \( N(z = L) = 0 \), gives

\[
N(z) = A \times \left( 1 - e^{-\frac{V_c}{K}(L-z)} \right) + \frac{q}{V_c}(z - L). \tag{C.1}
\]

Integration on the thin-disk gives the relation

\[
-2KN'(0) + 2V_c N(0) + 2hnu\sigma N(0) = 0,
\]

so that the final solution is

\[
N(z) = \frac{qL}{V_c} \left\{ \left( 1 + \frac{\alpha + \xi}{\alpha} \right) \left( 1 - e^{-\frac{V_c}{K}(L-z)} \right) + \frac{z}{L} - 1 \right\} \tag{C.2}
\]

\[
N(0) = \frac{qL}{V_c} \left\{ \frac{1}{\alpha + \xi} \left( 1 - e^{-\frac{V_c}{K}z} \right) \right\}
\]

where

\[
\alpha = \frac{V_c L}{K} \quad \text{and} \quad \xi \equiv \frac{hnu\sigma L}{K}. \tag{C.3}
\]

C.2. Linear wind \( V_{\text{gal}}(z) = V_l \times z \)

In the halo, the equation is

\[
-KN'' + V_l z N' + V_l N = q.
\]

Using \( \nu \equiv \sqrt{V_l/(2K)} \) and following closely the derivation of Sec. B.1.2, we find the solution

\[
N(z) = A e^{(\nu z)^2} + B e^{(\nu z)^2} \operatorname{erf}(\nu z) + \frac{q}{V_l}. \tag{C.4}
\]

The condition \( N(z = L) = 0 \) yields

\[
A = -B \times \operatorname{erf}(\nu L) - \frac{q}{V_l} e^{-(\nu L)^2}.
\]

Integration of Eq. (C.1) over the thin-disk yields

\[
-2KN'(0) + 2hnu\sigma N(0) = 0,
\]

which determines \( A \) and gives the final expression

\[
N(z) = \frac{q}{V_l} \left\{ 1 - e^{-(\nu L)^2} \left[ 1 - \frac{\operatorname{erf}(\nu z) - \operatorname{erf}(\nu L)}{2\nu L + \operatorname{erf}(\nu L)} \right] \right\} \tag{C.5}
\]

\[
N(0) = \frac{q}{V_l} \left\{ 1 - e^{-(\nu L)^2} \left[ 1 + \frac{\xi}{2
\nu L + \xi \operatorname{erf}(\nu L)} \right] \right\}
\]

where

\[
\nu \equiv \sqrt{\frac{V_l}{2K}} \quad \text{and} \quad \xi \equiv \frac{hnu\sigma L}{K}. \tag{C.6}
\]
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