# The Flux of Cosmic-ray Deuterons in Simplified Propagation Models

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## Abstract

One of the key questions in cosmic-ray astrophysics is the nature of physical processes relevant to propagation in the Galaxy. While the fundamentals of cosmic-ray propagation are thought to be understood, no single quantitative model can yet account for the spectra of all secondary components. A critical examination of the production and propagation of all secondary particles is therefore imperative. In this paper we use the simplified propagation models of Standard Leaky Box, Galactic wind at constant speed, and stochastic reacceleration to calculate the expected flux of cosmic-ray deuterons in the interstellar medium. By enumerating and examining the uncertainties in the calculations we obtain estimates for the prediction of the three models.

## 1. Introduction

The cosmic-ray spectra observed at earth are quantitatively different from the source spectra of cosmic-ray particles. The propagation process generally steepens the spectra in a model-dependent way, and any inference about the sources and the acceleration mechanism of cosmic-ray particles is contingent upon the ascribed propagation model for which a detailed and consistent canonical form has not yet been established. Propagation also affects the composition of cosmic rays. The drifting particles encounter and interact with the nuclei of the interstellar medium, and they alter the abundance of some elements (Primary Elements) and produce elements that are essentially absent in the sources (Secondary Elements). The most important parameter that quantifies the effect of propagation on cosmic-ray spectra and composition is the grammage traversed by cosmic-ray particles as they diffuse from their sources to the Earth. The simplest way to infer the grammage is to compare the flux of secondary particles with that of the primary particles responsible for their production [1,5]. From the comparison of B/C and Sub-Fe/Fe ratios, the best fit parameters for several proposed models have already been established [8]. In a previous work [16] we have shown that

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analysis of other secondary spectra, such as antiprotons, may enable us to distinguish among the different models. Another important secondary element whose spectra has been measured with improved accuracy in recent years and which may be crucial in the identification of the correct propagation model is the deuteron. It is the aim of this paper to compare the calculations of deuteron spectra with recent observations [3,10,18,19].

## 2. Production of Deuterons in Interstellar Medium

Secondary cosmic-ray deuterons are produced in two different interactions of primary cosmic-ray particles with the interstellar protons. The first is the fusion of two protons to produce a deuteron, $P + P \rightarrow D + \pi^+$, which has a threshold of approximately 290 MeV. The second interaction, $He + P \rightarrow D + X$, is a spallation process and the main source of deuterons in GeV range. The P-P cross section has a sharp maximum around 600 MeV and falls off rapidly at energies above that [12]. The cross section at the maximum is $\sigma_{\rm max} \approx 3\,{\rm mb}$. As a result the P-P interaction is only important for production of deuterons of energies below one GeV. The cross sections for these interactions, as well as for destruction of deuterons, are well tabulated and can be found online at HEPDATA webpage [6].

## 3. Propagation Models

### *3.1. Standard Leaky Box Model*

The most elementary model for cosmic-ray propagation is the Standard Leaky Box (SLB) model [1]. The basic physical ingredients of this model are 1) rapid diffusion of cosmic-ray particles leading to a homogeneous and isotropic distribution; 2) balance of production rate with destruction and escape from the Galaxy, leading to a stationary state, and 3) ionization losses. For non-decaying particles such as deuterons, the Leaky Box model is equivalent to the plain diffusion model with an extended cosmic ray halo (see e.g. [8]).

### *3.2. Galactic Wind Model*

In the Galactic Wind model we investigated, a simplified convection of constant velocity perpendicular to the Galactic disk has been added to the description of cosmic-ray transport [7,8]. In this model cosmic-ray particles lose energy by adiabatic expansion in addition to ionization losses.

### *3.3. Stochastic Reacceleration Model*

In the Stochastic Reacceleration model [15,8], ionization energy losses during propagation may be augmented or countered by energy exchange with random hydrodynamic waves. The resulting diffusion in energy is dominated by energy gains, although particles may also lose energy to the hydrodynamic turbulence.

## 4. Discussions and Results

One main ingredient in our calculation is the interstellar primary flux, which is inherently uncertain at low energies due to solar modulation. In this calculation we have used the best fit to the latest and most accurate combined measurements [2,11,14]. Nevertheless, appreciable uncertainties remain. Accurate cross sections are also pivotal in pinning down the best propagation model. Large uncertainties persist in laboratory measurements of the cross sections and are reflected in any spectral calculation or model determination. Moreover, the energy per nucleon of secondary cosmic-rays produced in spallation are thought to be conserved. This approximation has been validated for Boron and heavier nuclei [9,13,17], but its applicability to lighter elements has not yet been fully investigated. Furthermore, a sufficient understanding of the solar modulation process is required to return any meaningful comparison between calculations and observations. While the modulation model we have employed [4] is well established, its main parameter $\phi$ at any given epoch is only approximately known. The calculated spectrum of the cosmic-ray deuterons for the above three models for a solar modulation value of $\phi = 500$ is shown in Fig. 1. No attempt has been made to fit the data. The calculations serve to illustrate the distinction among the three propagation models. It is shown that the deuteron flux in the reacceleration model is larger than the flux in the SLB or the Wind model. A kink below $\sim$ GeV in the SLB calculation, due to PP interaction cross section, is washed out by the effects of reacceleration and wind. The three scenarios differ in their predictions, both in a qualitative and a quantitative way. Flux calculations for deuterons may be contrasted with calculations for antiprotons [16] for which the same models were investigated. For the latter, the reacceleration model yelids a smaller flux than the other two. Since deuteron abundance is more sensitive to primary helium flux than $\bar{p}$ abundance, however, this contrast may not be as severe.

## 5. Acknowledgment

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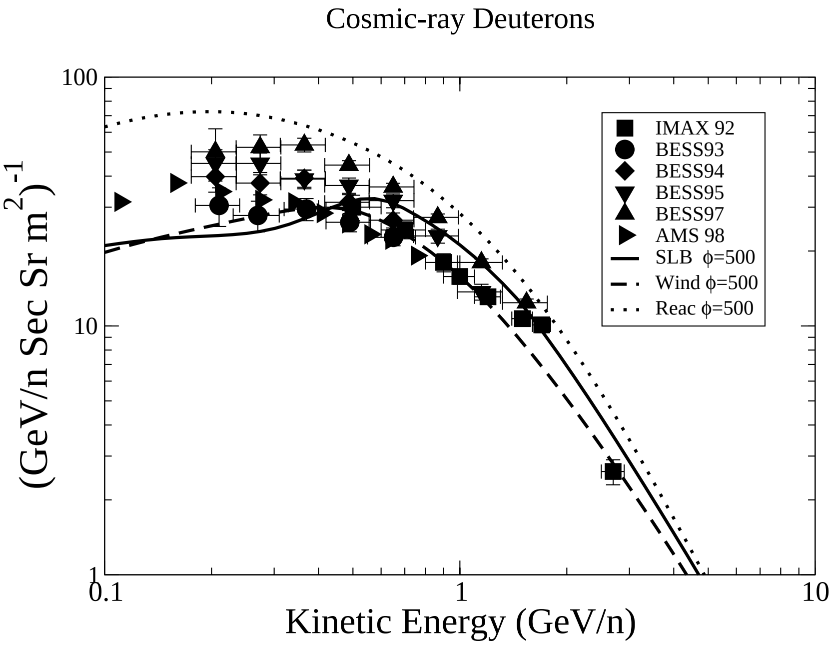


**Fig. 1.** Comparison of observed (IMAX [3], BESS [18,19], AMS [10]) and calculated deuteron spectrum.


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