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Theoretical uncertainties in extracting cosmic-ray diffusion parameters: the boron-to-carbon ratio

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Abstract. PAMELA and, more recently, AMS-02, are ushering us into a new era of greatly reduced statistical uncertainties in experimental measurements of cosmic ray fluxes. In particular, new determinations of traditional diagnostic tools such as the boron to carbon ratio (B/C) are expected to significantly reduce errors on cosmic-ray diffusion parameters, with important implications for astroparticle physics, ranging from inferring primary source spectra to indirect dark matter searches. It is timely to stress, however, that the conclusions inferred crucially depend on the framework in which the data are interpreted as well as on some nuclear input parameters. We aim at assessing the *theoretical* uncertainties affecting the outcome, with models as simple as possible while still retaining the key dependences. We compare different semi-analytical, two-zone model descriptions of cosmic ray transport in the Galaxy: infinite slab(1D), cylindrical symmetry(2D) with homogeneous sources, cylindrical symmetry(2D) with inhomogeneous source distribution. We tested for the effect of a primary source contamination in the boron flux by parametrically altering its flux. We also tested for nuclear cross-section uncertainties.

1. Introduction

The discussion of this Proceedings is based on our recent publication in A&A [1].

Measurements of secondary to primary ratio like the B/C have long been recognized as a tool to constraint CR propagation parameters although confidence intervals are still wide [2].
As regard to the new precise measurements released by PAMELA, and expected by AMS-02, this situation demands reassessing theoretical uncertainties to make the most in extracting (astro)physical information. We revisit this issue and found that some of them were never quantified although they can be described in a very simple 1D model. In fact, we focus on determining the diffusion coefficient, which we parameterise as conventionally in the literature: $D(\mathcal{R}) = D_0\,\beta\,(\mathcal{R}/\mathcal{R}_0)^{\delta}$. To do so we restrain the study to the high-energy regime (kinetic energy/nucleon $\geqslant 10\,\mathrm{GeV/nuc}$) which is the most constraining one for diffusion. To gauge the impact of theoretical uncertainties on a forth-coming data analysis, we compare them with statistical ones. We base our analyses on preliminary AMS-02 data of the B/C to deal with a realistic level of statistical errors ratio [3]. In the following we first recall a simple 1D diffusion model providing our benchmark for this analysis.

2. The 1D-model framework

The simplest approach to model the transport of cosmic-ray nuclei inside the Galaxy is to assume that their production is confined inside an infinite plane of thickness $2h$, that is sandwiched inside an infinite diffusion volume of thickness $2H$, symmetric above and below the plane. The former region stands for the Galactic disk, which comprises the gas and the massive stars of the Milky Way, whereas the latter domain represents its magnetic halo. These models are sketched in [1]. Our focus on energies above 10 GeV/nuc allows us to neglect safely continuous energy losses, electronic capture, and reacceleration.

The well-known propagation equation for the phase space density ψ_a of a stable nucleus a, with charge (atomic number) Z_a, expressed in units of particles cm^{-3} (GeV/nuc)$^{-1}$, takes the form

$$\frac{\partial \psi_a}{\partial t} - \frac{\partial}{\partial z}\left(D\frac{\partial \psi_a}{\partial z}\right) = 2h\delta(z)\cdot q_a + \delta(z)\sum_{Z_b \geqslant Z_a}^{Z_{max}} \sigma_{b\to a}\cdot v\frac{\mu}{m_{\rm ISM}}\psi_b - \delta(z)\cdot\sigma_a\cdot v\frac{\mu}{m_{\rm ISM}}\psi_a,$$

The cross-section for the production of the species a from the species b through its interactions with the interstellar medium (ISM) is denoted by $\sigma_{b\to a}$, whereas σ_a is the total inelastic interaction (destruction) cross-section of the species a with the ISM. The surface density of the Galactic disk is denoted by μ, while $m_{\rm ISM}$ is the average mass of the atomic gas that it contains. Solving the propagation in the steady-state regime allows expressing the flux $\mathcal{J}_a \equiv (v/4\pi)\,\psi_a$ of a nucleus a inside the Galactic disk ($z = 0$). Considering only the dominant contribution from stable nuclei, the B/C ratio writes:

$$\frac{\mathcal{J}_{\rm B}(E_k)}{\mathcal{J}_{\rm C}(E_k)} = \left\{\frac{Q_{\rm B}}{\mathcal{J}_{\rm C}} + \sigma_{\rm C\to B} + \sum_{Z_b > Z_{\rm C}}^{Z_{\rm max}} \sigma_{b\to\rm B}\cdot\frac{\mathcal{J}_b}{\mathcal{J}_{\rm C}}\right\} / \left\{\sigma^{\rm diff} + \sigma_{\rm B}\right\} \tag{1}$$

where $\sigma^{\rm diff} = (2D\, m_{\rm ISM})/\mu v H$ and $Q_B = \frac{1}{4\pi}\cdot q_B/n_{\rm ISM} \equiv N_B\,(\mathcal{R}/1\,{\rm GV})^{\alpha}$ which stands for the boron source term is expressed in units of particles (GeV/nuc)$^{-1}$s^{-1}sr^{-1}. Since no primary boron sources is commonly assumed the expression simplifies further. The impact of relaxing this hypothesis is explored in the following.

The primary purpose of our analysis is to determine the diffusion parameters D_0 and δ from the B/C flux ratio $\mathcal{F} \equiv \mathcal{J}_{\rm B}/\mathcal{J}_{\rm C}$. Basically we solve a system of triangular form(from iron to berylium), and minimize the chi-square (χ^2) of the B/C: $\chi^2_{\rm B/C} = \sum_i \left(\mathcal{F}_i^{\rm exp} - \mathcal{F}_i^{\rm th}\,(\alpha,\delta,D_0,H))/\sigma_i\right)^2$. As D_0 and H are completely degenerate when only considering stable nuclei, we therefore fix H at 4 kpc for simplicity, although it should be kept in mind that, to a large extent, variations in D_0 can be traded for variations in H. Futhermore we checked that the B/C ratio is incensitive to physical values of α i.e in the range [-2.5,-2]. Thus we decided to fix the value of $\gamma = \alpha - \delta$ of high-energy fluxes $\mathcal{J}_Z$ at Earth to the one that best fits the fluxes of the elements Z that come into play in the cascade from iron to beryllium. This choice avoid to degrade the goodness of the fits on absolute fluxes in the minimization procedure. The best-fit values defining our benchmark model as well as the best-fit plot are shown in Fig. 2. As a remark we also checked that at that stage, the statistical uncertainties are still of the same order as the systematic uncertainties generated by using different energy cuts.

3. Primary boron contamination?

Typical fits of the B/C ratio are based on the assumption that no boron is accelerated at the source. However, one can show easily that for typical astrophysical acceleration time and density, it leads to percent-level probabilities for nuclei to undergo spallation in the sources. A factor of only a few times higher than this would certainly have dramatic consequences on the information inferred from secondary-to-primary ratios. More elaborate versions of this idea and related phenomenology have also been detailed as a possible explanation of the hard spectrum of secondary positron data [4, 5], which was recently compared with the AMS-02 data [6].

Reference parameter values	
D_0 [kpc^2/Myr]	$(5.8 \pm 0.7) \cdot 10^{-2}$
δ	0.44 ± 0.03
$\chi^2_{\mathrm{B/C}}$/dof	$5.4/8 \approx 0.68$
$\gamma = \alpha - \delta$ (fixed)	-2.78

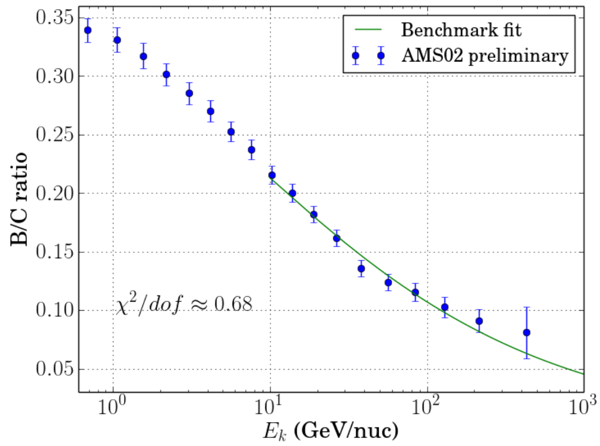

Figure 1. Benchmark best-fit parameters of the 1D/slab model, with respect to which comparisons are subsequently made. On the right panel: preliminary AMS-02 measurements of the B/C ratio [3] are plotted as a function of kinetic energy per nucleon. The theoretical prediction of the 1D/slab reference model of left-panel table is also featured for comparison.

In this study we challenge the ansatz $Q_{\mathrm{B}} = 0$ and quantify it parametrically for the first time. With the presence of a primary source Q_{B}, the B/C ratio exhibits a plateau at high energies when the cross-section ratio $\sigma_{\mathrm{C}\to\mathrm{B}}/(\sigma^{\mathrm{diff}} + \sigma_{\mathrm{B}})$ becomes negligible with respect to the primary abundances ratio $N_{\mathrm{B}}/N_{\mathrm{C}}$. When adding a primary component of boron, the spectral index δ must increase to keep fitting the B/C data at low energy, that is, here around 10 GeV/nuc. This also implies that D_0 decreases with $N_{\mathrm{B}}/N_{\mathrm{C}}$ as a result of the anti-correlation between the diffusion parameters.

We have thus scanned the boron-to-carbon ratio at the source to study the variations of the best-fit values of D_0 and δ with respect to the reference model of Table 2. Our results are illustrated in Fig. 2. The B/C fit is particularly sensitive to the last few AMS-02 points, notably the penultimate data point, around 214 GeV/nuc, for which the B/C ratio is found to be $\sim$ 9%. In the right panel, the theoretical expectation for that point is plotted (solid red curve) as a function of the primary abundances ratio, while the dashed black curve indicates how the goodness of fit varies. It is interesting to note that a minor preference is shown for a non-vanishing fraction of primary boron, around 8%, due to the marginal preference for a flattening of the ratio. The $N_{\mathrm{B}}/N_{\mathrm{C}}$ ratio is only loosely constrained to be below 13%. Such a loose constraint would nominally mean that a spectral index δ more than three times larger than its benchmark value would be allowed, with a coefficient D_0 one order of magnitude smaller than indicated in Table 2. In fact, such changes are so extreme that they should probably be considered as unphysical to be in agreement with present acceleration schemes. The message is quite remarkable however. The degeneracy of the diffusion parameters with a possible admixture of primary boron is so strong that it dramatically degrades our capability of determining the best-fit values of D_0 and δ, and beyond them the properties of turbulence, unless other priors are imposed.

4. Cross-section modeling

The outcome of cosmic-ray propagation strongly depends on the values of the nuclear production $\sigma_{b\to a}$ and destruction σ_a cross-sections with the ISM species, especially when we deal with secondary nuclei like boron. Since we consider here only the high-energy limit, we simply

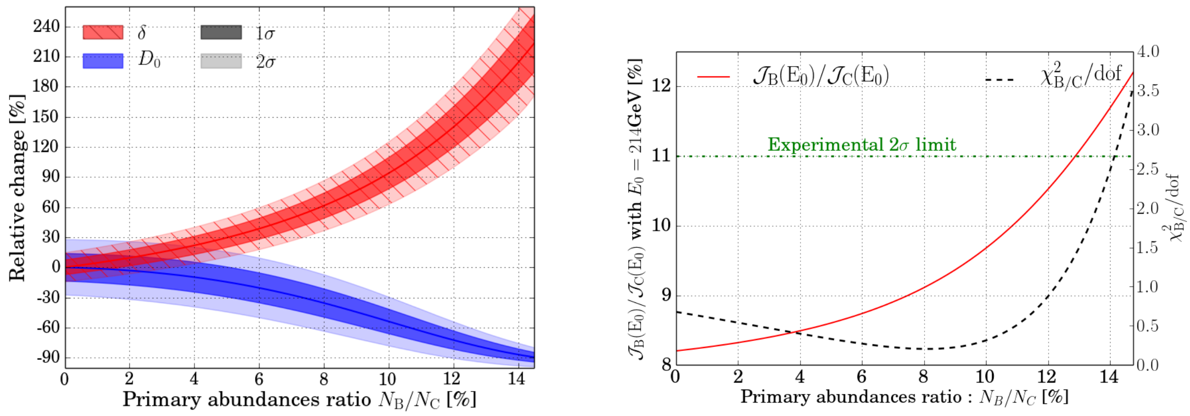

Figure 2. Left panel: variations of the best-fit propagation parameters D_0 (blue) and δ (red) relative to the benchmark values of Table 2, as a function of the primary boron-to-carbon injection ratio. The reference model corresponds to the conventional no boron hypothesis for which $N_{\rm B}/N_{\rm C}$ vanishes. Right panel: the theoretical value of the B/C ratio at 214 GeV/nuc (solid red curve) is plotted as a function of the primary boron-to-carbon injection ratio. The dashed black curve indicates the goodness of the B/C fit. As long as $N_{\rm B}/N_{\rm C}$ does not exceed 13%, the theoretical B/C ratio is within 2σ from the AMS-02 measurement (dashed-dotted green curve).

	Wind	1D/2D geometry	Cross-sections	Primary boron
$\Delta D_0/D_0$	-40%	-2 to -13%	$\pm 60\%$	0 to -90%
$\Delta\delta/\delta$	$+15\%$	0 to $+1\%$	$\pm 20\%$	0 to $+100\%$

Table 1. Summary of the main systematics found in current analyses in determining the propagation parameters by fitting the B/C ratio.

allowed for a rescaling of all the cross-sections. However, we distinguished between two cases: a correlated (↗↗) or anti-correlated (↗↘) rescaling between the production $\sigma_{b\to a}$ and the destruction σ_a cross-sections.

First, we need to assess the reasonable range over which the various cross-sections of the problem are expected to vary. For this, we compared our reference models for the destruction and production cross-sections with those used in popular numerical propagation codes such as GALPROP [7] and DRAGON [8]. And example in shown on the left panel of Fig. 3 for production cross-sections,more details are provided by [1].

On the right panel of Fig. 3 we present only the anti-correlated (↗↘) rescaling. The trend of the variations of δ and D_0 is well understood thanks to Eq. (**??**). From realistic assessments of the minimum systematic uncertainties of about 10% derived from the different cross-section models, we estimate a systematic uncertainty of 10% on δ and of 40% on D_0.

5. Conclusion

Our main results are summarised in Table 1. The table includes also geometric effect and convective wind discussed in [1], which lead to minor changes. We conclude that the Ansatz on the lack of primary injection of Boron represents the most serious bias, and requires multi-messenger studies to be addressed. If that uncertainty could be lifted, nuclear uncertainties would still represent a serious concern, which degrade the systematic error on the inferred parameters to the

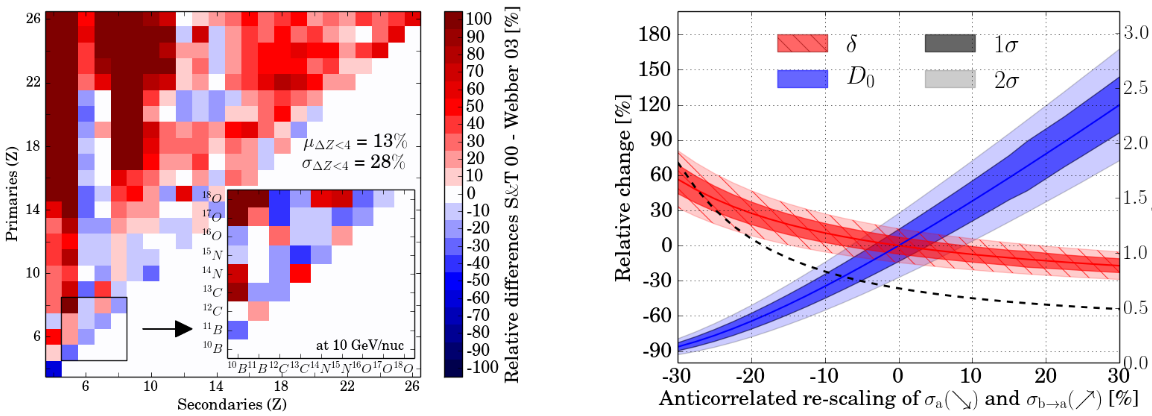

Figure 3. On the left panel: a 2D histogram feature the relative differences between two semi-empirical models currently used to calculate the production cross-sections $\sigma_{b\to a}$. Our reference model is Webber 03[9], and we compare it with S&T 00 [10]. The charges of the parent and child nuclei are given on the vertical and horizontal axes, respectively. The relative difference in each bin is given by the arithmetic mean over the various isotopes of each element. A detailed view provides the most important channels for the B/C ratio studies. For a fragmentation of $\Delta Z < 4$, we also give the first and second moments of the uncertainty distributions. On the right panel: effect of an anti-correlated rescaling of the nuclear cross-sections for boron production channels and destruction ones.

20% level, or three times the estimated experimental sensitivity. In order to reduce this, a new nuclear cross-section measurement campaign is probably required.

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