# Propagation of galactic cosmic rays and the AMS-02 experiment

Miguel Pato*

*Institut d'Astrophysique de Paris,*
*98bis bd Arago, 75014, Paris, France*
**E-mail: pato@iap.fr*

*Dipartimento di Fisica, Università degli Studi di Padova,*
*via Marzolo 8, I-35131, Padova, Italy*

Dan Hooper

*Center for Particle Astrophysics,*
*Fermi National Accelerator Laboratory, Batavia, IL 60510*

*Department of Astronomy and Astrophysics,*
*University of Chicago, Chicago, IL 60637*

Melanie Simet

*Department of Astronomy and Astrophysics,*
*University of Chicago, Chicago, IL 60637*

A precise determination of cosmic ray spectra up to TeV energies and light isotope separation are crucial steps in understanding the origin and propagation of galactic cosmic rays. Using the expected capabilities of the upcoming Alpha Magnetic Spectrometer (AMS-02), we anticipate the measurements of B/C, $^{10}$Be/$^{9}$Be and the proton flux. This projected data set, which represents a great improvement upon the current status of GeV-TeV cosmic ray data, is then used to constrain models of injection and propagation of cosmic rays in the Milky Way. Minimal or next-to-minimal setups turn out to be tightly constrained. Nevertheless, the precise AMS-02 anticipated measurements will not be sufficient to distinguish between models with different assumptions regarding the rigidity dependence of the diffusion coefficient, source distribution and abundances or stochasticity.

*Keywords*: galactic cosmic rays, cosmic ray propagation

## 1. Introduction

The origin and propagation of cosmic rays are puzzling issues of major importance for astrophysics. Over the years many composition studies and the complementarity between different measurements have taught us a lot about the environment where cosmic rays are accelerated as well as how they travel through the interstellar medium until the Earth. Nevertheless, a fully-consistent picture has not yet been assembled. At low energies − meaning energies below the knee at $\sim 10^{15}$ eV − the bulk of the cosmic ray flux is believed to be of galactic origin. Once injected in the galactic medium, charged cosmic rays − unlike photons or neutrinos − undergo several processes capable of steering, degrading energy or determining their extinction along the path towards us. Besides diffusion through magnetic irregularities and spallation on the interstellar medium, cosmic rays may also be affected by energy losses, radioactive decays, reacceleration and convection winds. All these processes and their relative importance may be studied using the measured local spectra of individual cosmic ray species. In particular, stable secondary-to-primary ratios (e.g. B/C) and unstable ratios (e.g. $^{10}$Be/$^{9}$Be) are useful tools in constraining injection and propagation parameters. While stable secondary-to-primary ratios provide information about the effective column density cosmic rays pass through before reaching the Solar System, unstable ratios roughly fix the time interval since spallation. These two observables have been used before to constrain the properties of different propagation setups. There are some degeneracies between the parameters so that the present data do not point to a single propagation scheme. But the situation is expected to improve greatly with data from the Alpha Magnetic Spectrometer AMS-02. Besides largely improved statistics, AMS-02 will also provide cosmic ray flux measurements up to $\sim$ TeV/n and hopefully separate Be isotopes up to $\sim$ 10 GeV/n.

In the present work we focus on the expected performances of AMS-02, mainly regarding B/C, $^{10}$Be/$^{9}$Be and the proton flux, and investigate the impact that its data may have on our knowledge about cosmic ray physics. Using GALPROP numerical code[1,2] to model injection and propagation of galactic cosmic rays, we address the question of whether AMS-02 will give us enough information to single out an unique propagation scheme and whether we will be able to distinguish between setups with different assumptions.

## 2. Prospects For AMS-02

The second and final version of the Alpha Magnetic Spectrometer (AMS-02)[3,4] is a large acceptance cosmic ray detector scheduled to be placed on-board the International Space Station soon. Over its mission duration, it will measure with unprecedented statistics and precision the spectrum of cosmic rays over an energy range of approximately 100 MeV to 1 TeV. The AMS-02 instrument will be able to detect and identify nuclei as heavy as iron ($Z \lesssim 26$) with rigidity up to a few TV, and separate isotopes of light elements (namely, H, He and Be) over a kinetic energy range of 0.5−10 GeV/n. High precision measurements of the ratios B/C and sub-Fe/Fe (D/p, $^3$He/$^4$He and $^{10}$Be/$^9$Be) up to energies of ∼1 TeV/n (∼10 GeV/n) are anticipated. We try to estimate in a reasonable manner the capabilities of the AMS-02 instrument to measure B/C, $^{10}$Be/$^9$Be and the proton flux − details of the adopted procedure may be found in Ref. 5. To reduce the dependence on solar modulation, we apply an energy cut $T > 5$ GeV/n throughout our analysis.

## 3. Results

We start by fixing the Alfvén speed to $v_A = 36$ km/s, and neglecting the effects of convection ($V_{c,0} = dV_c/dz = 0$). Proceeding in a fashion similar to Ref. 6, we run GALPROP 245 times, in a 7x7x5 grid of the parameters $(D_{0xx}, L, \alpha)$ [a] over the following ranges: $D_{0xx} = 4.54 - 8.03 \cdot 10^{28}$ cm$^2$/s, $L = 3.5 - 6.5$ kpc and $\alpha = 0.39 - 0.43$. Figure 1 shows the 1, 2 and $3\sigma$ contours from the combination of B/C and $^{10}$Be/$^9$Be projected AMS-02 data. As this figure demonstrates, the upcoming measurements on B/C and $^{10}$Be/$^9$Be are sufficient (within the context of the simple models presently being considered) to determine the underlying propagation parameters with an accuracy of $\Delta D_{0xx} \sim 1.4 \cdot 10^{28}$ cm$^2$/s, $\Delta L \sim 1.0$ kpc, and $\Delta\alpha \sim 0.02$ (at $1\sigma$). This precision is much greater than that obtained with present (pre-AMS-02) data; see Refs. 6 and 7. In particular the degeneracy between $D_{0xx}$ and $L$ is broken as can be seen in the upper left frame of Figure 1 where we have overplotted in dashed the $3\sigma$ contour from Ref. 6.

Thus far, we have not considered any effects of convection and/or variations in the Alfvén velocity from our default value of $v_A = 36$ km/s. As the quantity and quality of cosmic ray data improves, however, it will become increasingly possible to test these assumptions, and determine the related

[a] $D_0xx$ is the normalisation of the diffusion coefficient at a rigidity of 4 GV, $\alpha$ is its slope, and $L$ is the half-height of the cylindrical diffusive region.

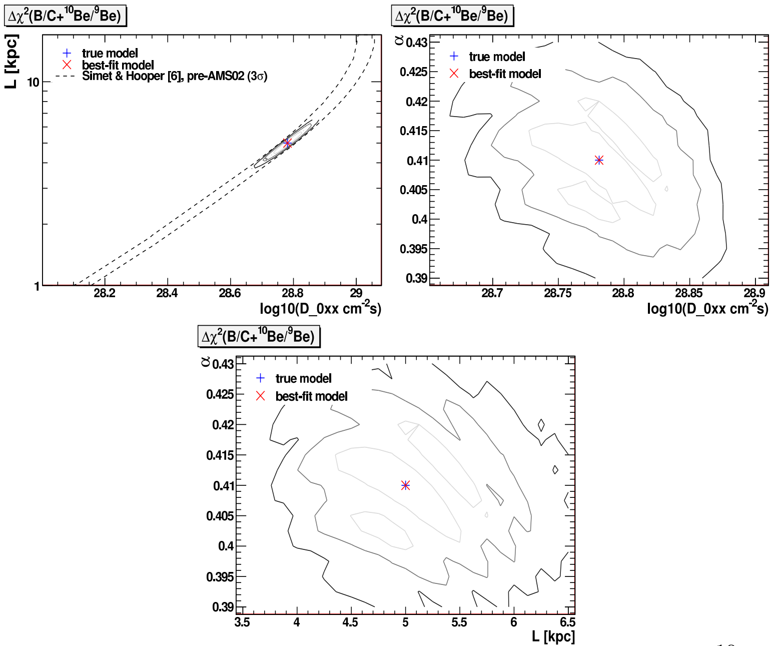


Fig. 1. Regions consistent (within 1, 2 and $3\sigma$) with projected B/C and $^{10}$Be/$^{9}$Be AMS-02 data in the $L$ vs. $D_{0xx}$, $\alpha$ vs. $D_{0xx}$, and $\alpha$ vs. $L$ planes. We have assumed $v_A = 36$ km/s, $V_{c,0} = dV_c/dz = 0$. In the top left frame we show in dashed the $3\sigma$ contour from Ref. 6.

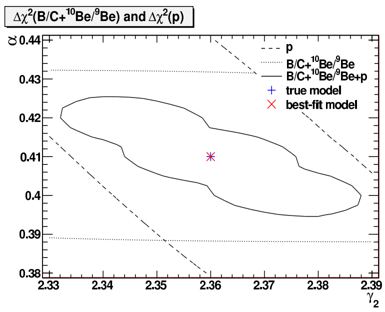


Fig. 2. Inferred parameter regions (within $3\sigma$) in the plane $\alpha$ vs. $\gamma_2$. The dashed (dotted) [solid] lines refer to the case where the AMS-02 projected data set consisted of the proton flux (B/C and $^{10}$Be/$^{9}$Be) [proton flux, B/C and $^{10}$Be/$^{9}$Be]. We have assumed $v_A = 36$ km/s, $V_{c,0} = dV_c/dz = 0$.

parameters. In order to study such possibility, we have repeated the procedure using the following values for the Alfvén velocity and the convection velocity: $(v_A[\text{km/s}], dV_c/dz[\text{km/s/kpc}]) = \{(36, 0), (15, 0), (0, 0), (0, 10)\}$, while leaving $V_{c,0} = 0$. As greater departures from our default assumptions are considered, the fits to the projected data become considerably worse. In particular, even modest (∼10 km/s/kpc) amounts of convection lead to very poor fits to the projected data. Large variations in $v_A$ also lead to observable effects, thus enabling AMS-02 to be sensitive to the details of diffusive reacceleration.

In order to make the questions addressed in this study tractable, we have relied on a number of simplifying assumptions. In particular, we have assumed homogeneity of the diffusion coefficient $D_{xx}$ over the volume of the diffusion zone, considered cylindrical symmetry for the system, and adopted a smooth distribution of cosmic ray sources with universal injected chemical composition and spectra. While such assumptions are reasonable and have been useful up to this point in time, they will eventually have to be discarded or revised as they break down under the increasing precision of future cosmic ray data. We have loosen a few of the usual assumptions and found that AMS-02 precise data will not be sensitive to probe stochasticity, source abundances and distribution, and the detailed energy-dependence of the diffusion coefficient (unless an abrupt break is present well inside AMS-02 energy range).

Finally, we turn our attention to the source spectral index. Up to now the injection spectrum at the sources was assumed to be a double power law in rigidity with indices $\gamma_1 = 1.82$ and $\gamma_2 = 2.36$ respectively below and above $\tilde{R}_0 = 9$ GV. We now release this assumption by taking several values for $\gamma_2$ − the low energy rigidity index $\gamma_1$ and the break $\tilde{R}_0$ are kept fixed since we are focussing on high energy data only. To proceed further and quantify how sensitive AMS-02 will be to the cosmic ray injection spectrum, we scan the parameter space $(D_{0xx}, \gamma_2, \alpha)$ and fix $v_A = 36$ km/s, $V_{c,0} = dV_c/dz = 0$, and $L = 5$ kpc (notice that $D_{0xx}$ and $L$ are approximately degenerate). Figure 2 shows the $3\sigma$ regions in the $\alpha$ vs. $\gamma_2$ plane from the projected AMS-02 measurements of the *(i)* proton flux (dashed lines), *(ii)* B/C and $^{10}$Be/$^{9}$Be (dotted lines), and *(iii)* B/C, $^{10}$Be/$^{9}$Be and proton flux (solid lines). The ratios B/C and $^{10}$Be/$^{9}$Be are efficient probes of the diffusion index but insensitive to $\gamma_2$, while the proton flux constrains essentially the quantity $\alpha+\gamma_2$. Hence, within minimal propagation models, AMS-02 has the potential to pinpoint both the diffusion index $\alpha$ and the high energy source spectral index $\gamma_2$ with good accuracy. Note that this result stems exactly from the combination of the B/C and $^{10}$Be/$^{9}$Be ratios and the proton flux. While a reasonably precise high energy proton flux has been measured by past and present instruments (e.g. PAMELA) − allowing correspondingly precise estimates of $\alpha+\gamma_2$ −, only AMS-02 (or future detectors) will be able to break down the degeneracy between $\alpha$ and $\gamma_2$ with high energy quality cosmic ray ratios.

## 4. Conclusions

In this work, we have considered the ability of the upcoming AMS-02 experiment to measure stable secondary-to-primary and unstable ratios (such as boron-to-carbon and beryllium-10-to-beryllium-9), and studied to what extent this information could be used to constrain the model describing cosmic ray propagation in the Milky Way. We find that in propagation models with 3 free parameters − namely, the normalisation and slope of the diffusion coefficient and the half-thickness of the cylindrical diffusive region − AMS-02 data will effectively break existing degeneracies and provide measurements of the parameters with much better accuracy than currently possible. The same holds for models where the normalisation and slope of the diffusion coefficient and the source spectral index are varied freely. Furthermore, a significant degree of sensitivity to convection (and, to a lesser extent, reacceleration) is also predicted. However, when certain assumptions are loosen − including the rigidity dependence of the diffusion coefficient, source distribution and abundances and stochasticity −, AMS-02 upcoming measurements will likely be insufficient to pinpoint propagation parameters correctly. Inaccurate assumptions may, in particular, lead to a very well-fit, but incorrect, cosmic ray propagation model from AMS-02 data.

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