The USINE cosmic-ray propagation code and recent results from an MCMC analysis

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DOI: 10.7529/ICRC2011/V06/0876

Abstract: We implemented a Markov Chain Monte Carlo technique to estimate the probability-density functions of the cosmic-ray transport and source parameters in a diffusion model. From the measurement of the B/C ratio and radioactive cosmic-ray clocks, we calculate their probability density functions, with a special emphasis on the halo size L of the Galaxy and the local underdense bubble of size r_h. We also derive the mean, best-fit model parameters and 68% confidence level for the various parameters, and the envelopes of other quantities. Finally, we check the compatibility of the primary fluxes with the transport parameters derived from the B/C analysis and then derive the source parameters (slope, abundance, and low-energy shape). We conclude that the size of the diffusive halo depends on the presence/absence of the local underdensity damping effect on radioactive nuclei. Models based on fitting B/C are compatible with primary fluxes. The different spectral indices for the propagated primary fluxes up to a few TeV/n can be naturally ascribed to transport effects only, implying universality of elemental source spectra. The analysis relies on the USINE propagation package.

Keywords: cosmic-ray propagation and acceleration, Galactic halo size, local bubble, Markov Chain Monte Carlo

1 Introduction

The transport equation of Galactic Cosmic-Rays is described in standard textbook. It generally contains a source term (standard or exotic source/production), a diffusion term, and possibly convection, energy gain and losses, and catastrophic losses (fragmentation and decay). A full numerical treatment is generally required to solve the transport equation. However, analytical (or semi-analytical) solutions may be derived assuming a simplified description of the spatial dependence of the ingredients (e.g. the gas distribution) and some transport parameters. Such a semi-analytical solution has been implemented in the USINE propagation code[1] used below.

In the first paper [1] of a series [1, 2, 3, 4], we implemented a Markov Chain Monte Carlo (MCMC) to estimate the probability density function (PDF) of the transport and source parameters. This allowed us to constrain these parameters with a sound statistical method, to assess the goodness of fit of the models, and as a by-product, to provide 68% and 95% confidence level (CL) envelopes for any quantity we are interested in (e.g., B/C ratio, primary cosmic-ray fluxes). The analysis was initially performed for the simple Leaky Box Model (LBM) to validate the approach. We then extended the analysis for the more realistic diffusion model, by considering constraints set by radioactive (on the halo size of the Galaxy) and primary nuclei (on the CR source parameters).

We summarise below the results we obtained in the diffusion model (normalisation K_0 and slope δ of the diffusion coefficient), with a halo size L, with minimal reacceleration (Alfvénic speed V_a), a constant Galactic wind perpendicular to the disc plane V_c [5], and a possible central underdensity of gas (of a few hundreds of pc) around the solar neighbourhood r_h [6].

2 Transport parameters

The secondary-to-primary B/C ratio is a tracer of the transport in the Galaxy. For the parameter estimation of the above described transport equation (K_0, δ, V_c and V_a), the usage in the past has been based mostly on a manual or semi-automated (hence partial) coverage of the parameter space (e.g. [5]). More complete scans were performed, e.g., in [7], based on a grid analysis. The Markov Chain Monte Carlo is a step further to optimise the exploration of the parameter space.

1. http://lpsc.in2p3.fr/usine

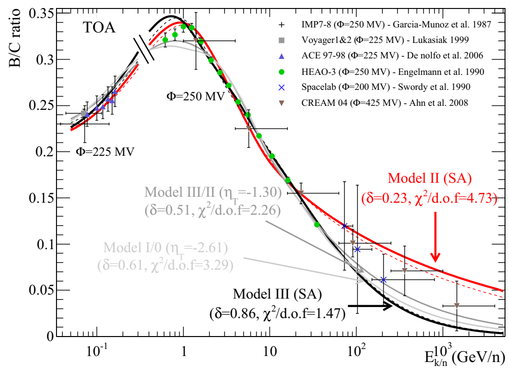

Figure 1: Best-fit of the B/C ratio for the propagation Model II (thick red) and III (thick black). Solid and thin dashed lines are for two different cross-section sets (W03 and GAL09). A more detailed description of this figure can be found in [8].

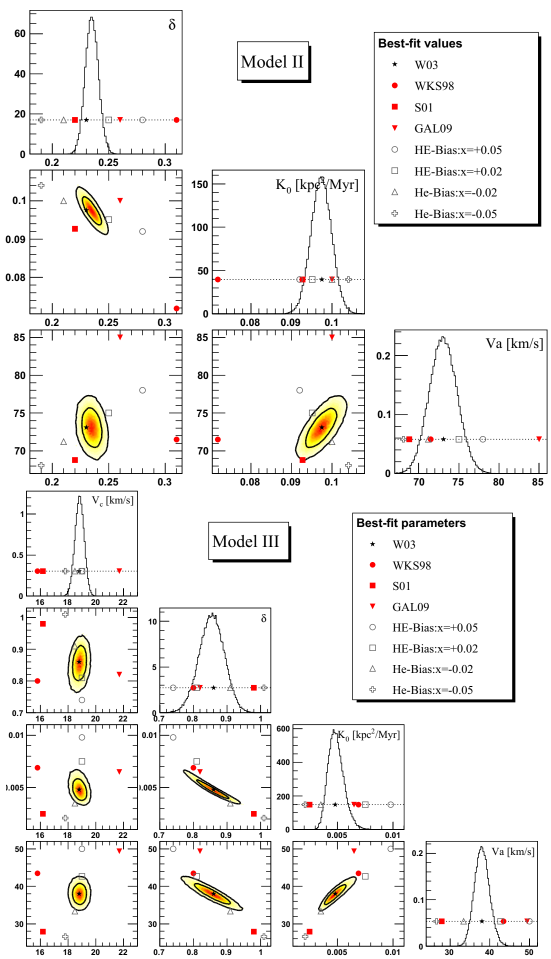

Figure 2: PDF of the transport parameters (for the reference inputs) as obtained in [2], along with the best-fit values for different production cross-section sets.

Figure 1 illustrates the best-fit B/C ratio found from a χ^2 analysis, for different propagation models and different sets of fragmentation cross-sections. Below, we will focus on the reacceleration model (Model II with $V_c = 0$) and the full convection/reacceleration configuration (Model III with $V_c \neq 0$). Figure 2 illustrates the power of the MCMC technique, which allows to retrieve the PDF of the parameters (here for the halo size fixed to $L = 4$ kpc). The symbols correspond to the best-fit values obtained from different parameterisations of the production cross-sections. Their spread illustrates the fact that systematic uncertainties in the calculation are already of the same order or larger than the statistical ones (i.e. the width of the PDFs). See [8] for more details. This will be an issue with the forthcoming high-precision measurements of AMS-02 on the ISS.

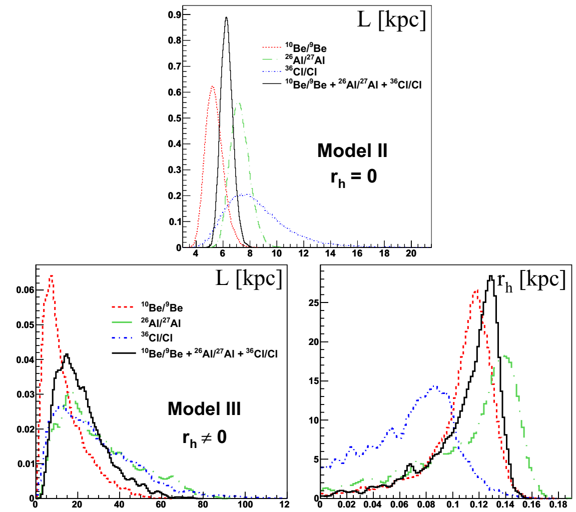

Figure 3: Marginalised posterior PDFs of L for Model II with $r_h = 0$ (top panel) and L and r_h for Model III (bottom panels). The four curves result from the combined analysis of B/C plus separate or combined isotopic ratios of radioactive species.

3 Halo size L from radioactive nuclei

The typical distance travelled in a diffusive process in a finite time is given by $l_{rad} \sim \sqrt{Dt}$. For a β-decay unstable secondary species, it means that at low energy (plugging the typical value of the diffusion coefficient), these nuclei cannot travel farther than a few hundreds of parsecs: they do not feel the halo size L and are only sensitive to the diffusion coefficient $K(E)$. In principle, this lifts the degeneracy between K_0 and L (seen from the analysis of the the stable secondary-to-primary ratio). However, things are not as simple when we have a closer look at the hundred-of-parsec scale. It happens that there is no target to produce these species in the solar neighbourhood: we live in a local bubble. This lack of targets affects their flux [6].

We find (see [2]) that II is consistent with $r_h = 0$, with $L = 5.2^{+0.7}_{-0.6}$ kpc, whereas III favours an underdense bubble of $r_h = 120^{+20}_{-20}$ pc (consistent with direct observations of the local cavity) and $L = 8^{+8}_{-7}$ kpc (see Fig. 3).

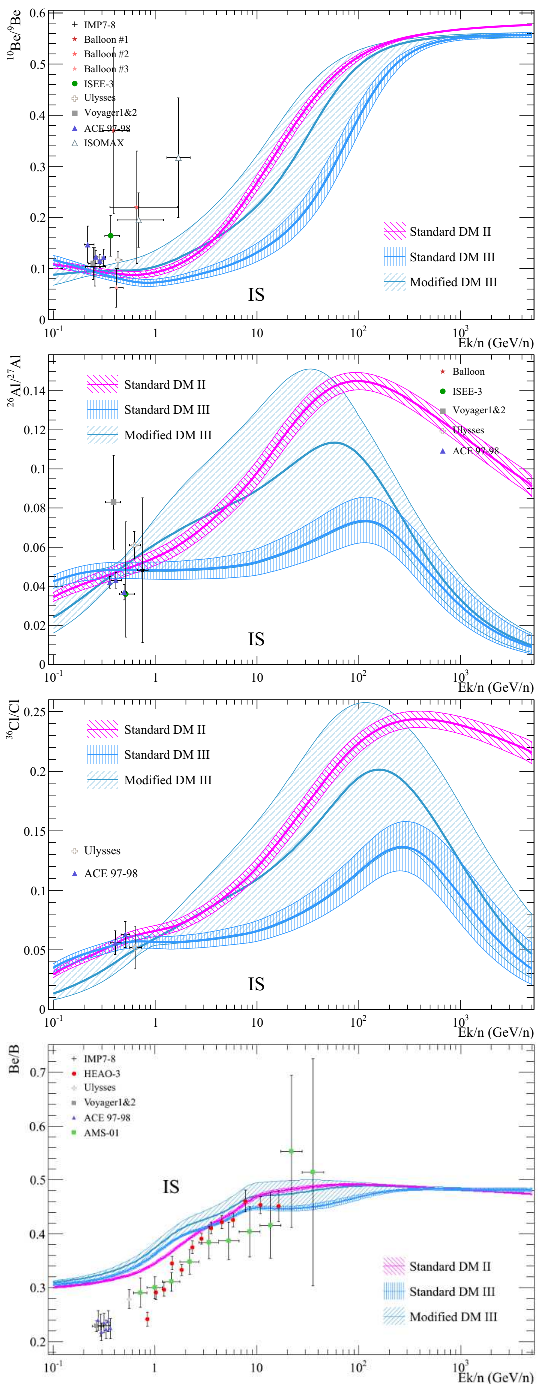

Figure 4: Envelopes of 68% CL (shaded areas) and best-fit (thick lines).

The envelopes for the isotopic ratios corresponding to the 68% CL on the parameters are shown in Fig. 4 for the standard Model II ($r_h = 0$) and the standard ($r_h = 0$) and modified ($r_h \neq 0$) Model III. As seen in the bottom panel, there is a discrepancy with the prediction from the Be/B measurement, as confirmed by the AMS-01 analysis [9]. This may be related to the production cross-section.

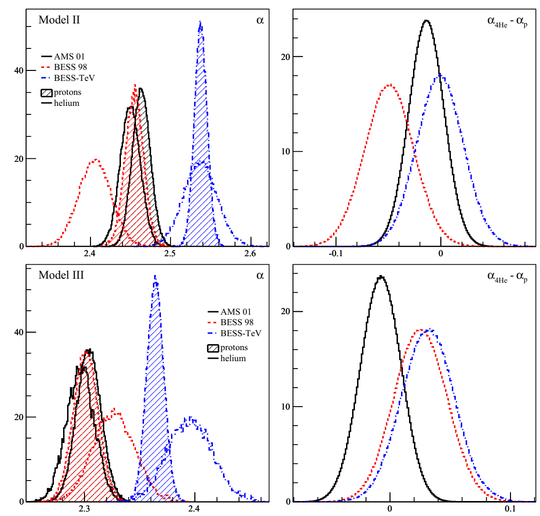

Figure 5: Left panels: PDF of the source slope α for p (unfilled histograms) and He (hatched histograms). Right panels: PDF for $\alpha_{\rm He} - \alpha_{\rm p}$. The colour code corresponds to the three experimental data used: AMS-01 (solid black line), BESS98 (dashed red lines) and BESS-TeV (dash-dotted lines).

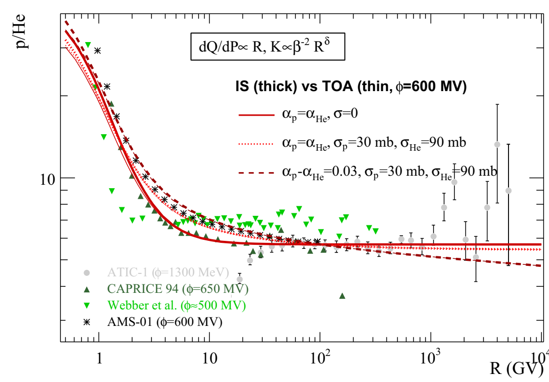

Figure 6: p/He ratio as a function of the rigidity.

4 Source parameters

The primary flux data alone are unable to select any particular propagation model, as the transport and source parameters are degenerate [3]. We thus have to fit simultaneously the primary fluxes and secondary-to-primary ratios. Below, we adopt a different approach: we select only a few propagation models (fitting well the B/C ratio and shown in Fig. 1), and restrict the parameter space to the source parameter space only.

The most important parameter is the source slope α. Figure 5 shows the PDF of this slope for the best-measured primary species, i.e. p and He, as well the difference of slope between these two species: $\alpha_{\rm p} - \alpha_{\rm He}$ is consistent with 0. Actually, the shape of the p/He ratios, when plotted as a function of the kinetic energy per nucleon, is driven by the solar modulation effect (not shown here). But the same

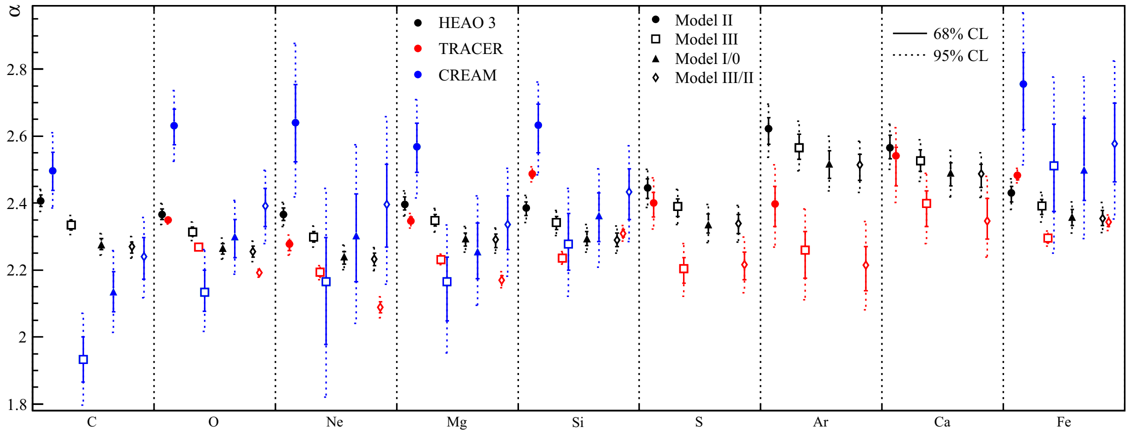

Figure 7: Best-fit value (symbols), 68% (dashed error bars) and 95% (solid error bars) CIs for C to Fe source slope parameters from CREAM-II, HEAO-3, and TRACER data (the 4 symbols correspond to the 4 models shown in Fig 1).

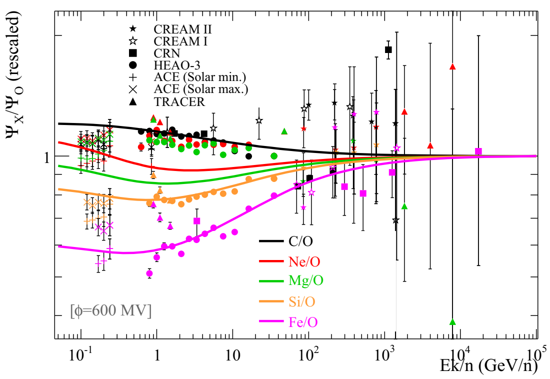

Figure 8: Ratio of various primary elements to O as a function of the kinetic energy per nucleon.

ratio plotted as a function of the rigidity minimises the effect of the solar modulation, and is well adapted to probe the values of $\alpha_{\rm p} - \alpha_{\rm He}$. This is illustrated in Fig. 6, where a simple toy model was used to reproduce the experimental data. A difference of spectral index between p and He is also not supported by the ratio, in agreement with the direct fits to p and He fluxes.

We have also studied heavier primary nuclei spectra, whose relevant destruction rate on the ISM increases roughly with atomic number. The different spectral indices for the propagated primary fluxes up to a few TeV/n can be ascribed to transport effects only, implying universality of elemental source spectra. This is illustrated on Fig. 7 that shows for a given model (symbol) similar source spectral indices for all primaries, whereas the impact of destruction on the propagated fluxes (having the same source index in a toy model) is shown in Fig. 8.

5 Conclusions and perspective

We have shown that the use of an MCMC technique is very powerful to study the source and transport parameters. The AMS-02 experiment should provide data with an unprecedented accuracy, and the MCMC technique will be a key tool to interpret them.

Acknowledgements

AP is grateful for financial support from the Swedish Research Council (VR) through the Oskar Klein Centre.

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