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Uncertainties in the production and propagation of cosmic rays in the Milky Way

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Abstract

We discuss the main sources of uncertainties in the calculation of the positron and antiproton top of the atmosphere spectra using models including diffusion and convection or reacceleration. We show that, even including uncertainties, the models that include diffusion and convection are more consistent with existing measurements. The next generation experiments like PAMELA will help to reduce the uncertainties in the values of the main free parameters of the models, thus improving our knowledge of the origin and propagation of cosmic rays.

Keywords: Cosmic rays; Propagation; Antiprotons

1. Introduction

We have chosen Galprop (Strong and Moskalenko, 1998) as a public code for the treatment of propagation of all cosmic rays (CR) together. Our scope has been to determine the total uncertainties in the calculation of e^+ and $\bar{p}$ top of the atmosphere spectra due to the uncertainties of geometrical and propagation parameters and cross sections. Here, we give very short description of processes included in propagation equation

$$\frac{\partial\psi(\mathbf{r},p,t)}{\partial t} = q(\mathbf{r},p) + \nabla\cdot(D_{xx}\nabla\psi - \mathbf{V}_c\psi) + \frac{d}{dp}p^2 D_{pp}\frac{d}{dp}\frac{1}{p^2}\,\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V}_c)\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi, \quad (1)$$

where $\psi(\mathbf{r}, p, t)$ is total phase space density. This equation is valid for all the types of particles. Isotropic diffusion is defined by the coefficient that depends from rigidity (momentum per unit of charge, $\rho = \frac{p}{Z}$) $D_{xx} = \beta D_0(\rho/\rho_0)^\delta$. In some models, we have used a break in the index δ at some rigidity ρ_0, with a value $\delta_1 = 0$ below the reference rigidity ρ_0. The convection velocity field $\mathbf{V}_c$, that corresponds to the Galactic wind, has a cylindrical symmetry and its z-component is the only one different from zero. It increases linearly with the distance z from the galactic plane , in agreement with magnetohydrodynamical models (Zirakashvili et al., 1996). Reacceleration is determined by the diffusion coefficient for the impulse space D_{pp} that is a function of the corresponding configuration space diffusion coefficient and of the Alfven velocity V_A in the framework of quasi-linear MHD theory (Berezinskii et al., 1990). Of course, Alfven velocity and convection velocity gradient in Milky Way for reacceleration and convection terms are unknown parameters of propagation (there are no other sources of information from which we could extract them, except the spectra of cosmic rays) and their

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possible range will be constrained by the analysis of fits of suitable data.

The same procedure is valid for constraining the height of the galactic halo and the other unknown parameters. This will be analyzed further in order to obtain all the possible spectra of antiprotons and positrons using the sets of the constrained parameters. Injected spectra of all primary nuclei are power law in impulse $dq(p)/dp \propto p^{-\gamma}$. This power law approximation has been shown to be allowed in the framework of diffusive shock acceleration models, as well as in model with a small break in the injection indexes γ. Source term $q(\mathbf{r},p)$ for secondaries contains cross sections for their production from progenitors on H and He targets. The last two terms in Eq. (1) are loss terms with characteristic times for fragmentation and radioactive decay. The heliospheric modulation in the vicinity of the Earth has to be taken in account. We have used a model in which transport equation (that describes diffusion processes in the heliosphere and includes effects of heliospheric magnetic field and solar wind) is solved in the force field approximation (Gleeson and Axford, 1968). In this case, solar modulation is a function of just a single parameter that describes the strength of the modulation. All the dynamical processes are simulated with relatively simple changing of the interstellar spectra during the propagation inside the heliosphere, described by the formula

$$\frac{\Phi^{\text{toa}}(E^{\text{toa}})}{\Phi^{\text{is}}(E^{\text{is}})} = \left(\frac{p^{\text{toa}}}{p^{\text{is}}}\right)^2, \quad E^{\text{is}} - E^{\text{toa}} = |Ze|\phi,$$

where E and p are energies and impulses of the interstellar and top of the atmosphere fluxes and ϕ is the unique parameter that determines the solar modulation.

2. Uncertainties of CR spectra

We have treated the two extreme cases of propagation models: the first that uses diffusion and reacceleration (DR) and the second that contains diffusion and convection (DC) (Moskalenko et al., 2002). Many parameters in the propagation equation are free and must be constrained by experimental data. Secondary to primary CR ratios are the most sensitive quantities on variation of the propagation parameters. The most accurately measured parameter is boron to carbon ratio (B/C). For DR model we have required reduced χ^2 less than 2 for the fit of the experimental data (Fig. 1). We take the data with relatively small solar modulation between 325 and 600 MV, where the force field approximation is better justified than for high modulation parameters. In Fig. 2 is shown the subFe/Fe ratio, important for testing the parameters of the propagation models.

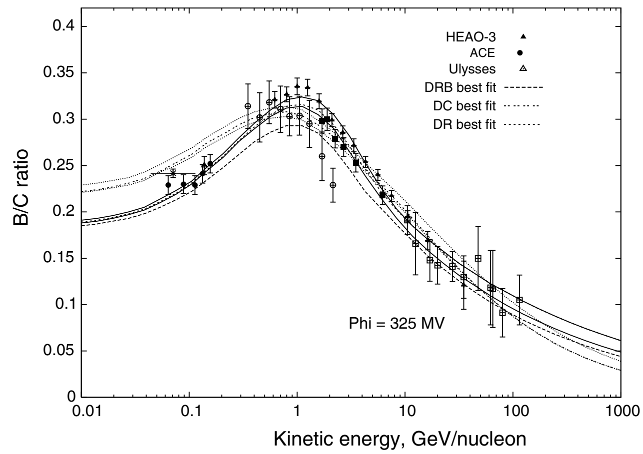

Fig. 1. Enveloping curves of all the good fits of B/C data for DR and DC model with their best fits inside and the best fit for DRB model. Experimental data are taken from Davis et al. (2000).

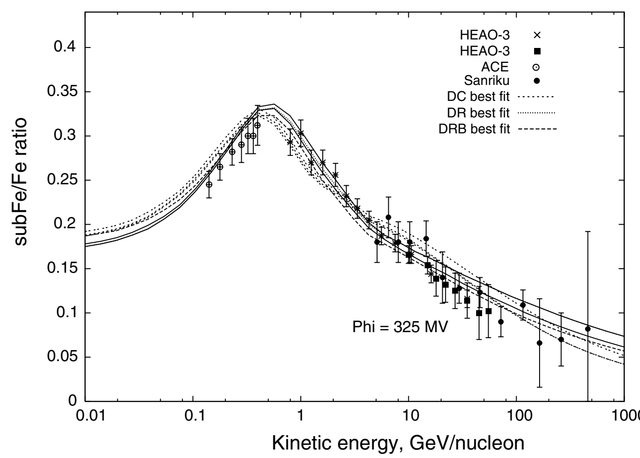

Fig. 2. Ratio (Sc + Ti + V)/Fe that corresponds to the propagation parameters that give the best fits of B/C data for the DC model is given with dashed line and it is inside the corresponding uncertainty band given with dashed lines. The ratio for the DR model is given with dotted line and it is inside the uncertainty given with solid lines, while for DRB model is given with larger-step dashed line without the uncertainty band around. Experimental data are taken from Davis et al. (2000).

For DC model (Fig. 1), we have taken all the reduced χ^2 values less than 2.8 for the variation of D_0, diffusion indexes δ_1, below, and δ_2, above the reference rigidity $\rho_0 = 4$ GV, z, $\mathbf{V}_c$ and injection index for primary nuclei γ_1 below the reference rigidity $\rho_0^{\gamma} = 20$ GV and γ_2 above it. Allowed values for the propagation parameters can be found in Table 1. We calculated the propagation uncertainty bands and PAMELA expectations for e^+ (Fig. 3), positron charge fraction (Figs. 4 and 5), antiproton proton ratio (Fig. 6) and $\bar{p}$ in the case of the best fit DC model using the PAMELA geometrical factor and detector characteristics (Picozza and Morselli, 2003) during the three years mission in which it will measure with high statistics various cosmic rays spectra.

Table 1
Allowed values for the propagation parameters for DC model

Par./val.	z (kpc)	D_0 (cm^2/s)	δ_2	$\frac{dV_c}{dz}$ (km/skpc)	γ_1	γ_2
Minimal	3.0	2.3×10^{28}	0.48	5.0	2.42	2.14
Best fit	4.0	2.5×10^{28}	0.55	6.0	2.48	2.20
Maximal	5.0	2.7×10^{28}	0.62	7.0	2.50	2.22

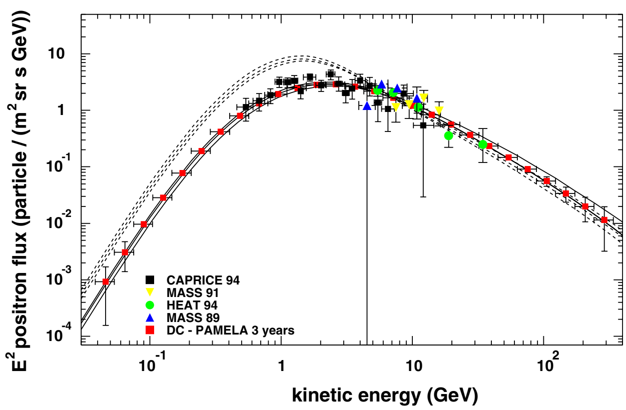

Fig. 3. Total uncertainties of e$^+$ fluxes and spectra that correspond to the parameters of the best B/C fit for DC (solid lines around the best fit) and DRB model (dashed lines around the best fit). Experimental data from Picozza and Morselli (2003) vs. PAMELA expectations for DC model.

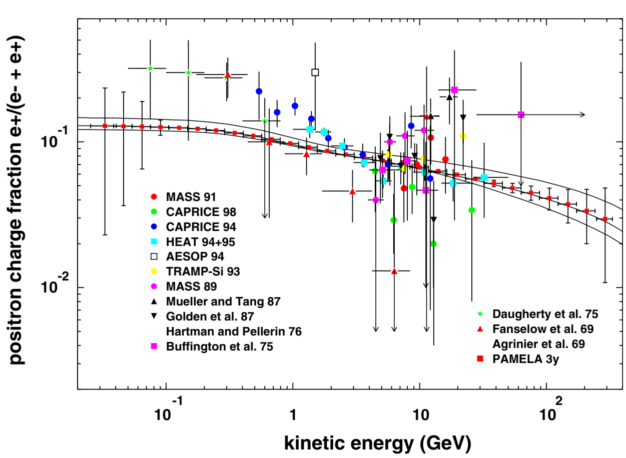

Fig. 4. Experimental data from (Picozza and Morselli, 2003) confronted with PAMELA's expectations for positron charge fraction for the DC model. The propagation uncertainty band of the positron charge fraction and the curve that corresponds to the parameters of the best B/C fit in the middle are given for better confrontation.

We have found also spectra that correspond to the parameters of the best fit of B/C data for protons, He and e$^-$ as well as corresponding uncertainties (Lionetto et al., 2004). For DC model fits are good, while DR overestimates p, He and e$^-$. To improve the DR expectations, we have considered the DR model with a break in the injection index for the primary nuclei spectra taken at rigidity of 10 GV (DRB). We determined allowed values of the propagation parameters demanding the

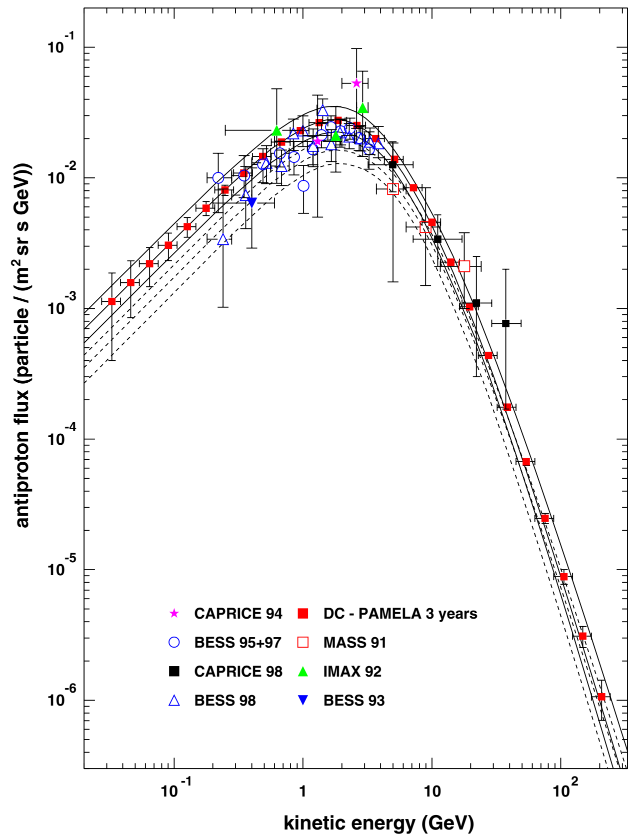

Fig. 5. Total uncertainty of $\bar{p}$ fluxes and spectra that correspond to the parameters of the best B/C fit for DC (solid lines) and DRB model (dashed lines). Experimental data from Picozza and Morselli (2003) vs. PAMELA expectations for DC and DRB model.

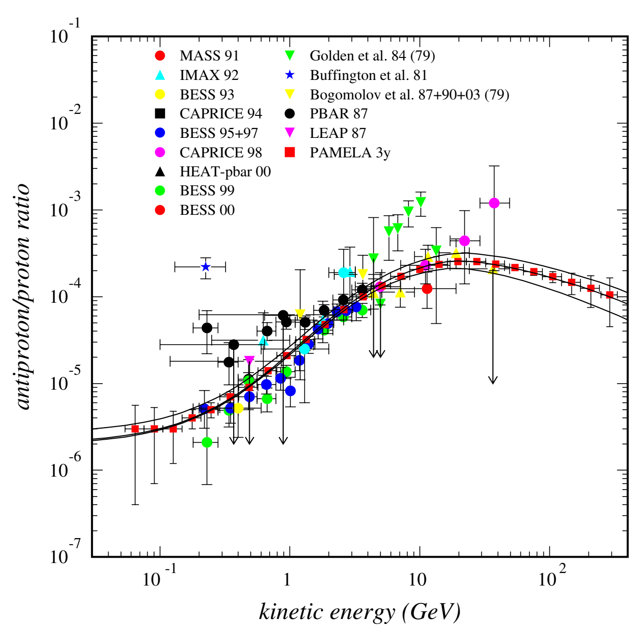

Fig. 6. Experimental data from (Picozza and Morselli, 2003) confronted with PAMELA's expectations for the antiproton proton ratio for the DC model background. The propagation uncertainty band of the antiproton proton ratio and the curve that corresponds to the parameters of the best B/C fit in the middle are given for better confrontation.

same χ^2 as for DR model (Fig. 1). Even if e^+ and primaries are fitted a little better at low energies, all of them remain overestimated while $\bar{p}$ spectra remain practically unchanged.

3. Conclusions

For positrons in the DR model, the curve of the minimal positron production still remains above the experimental results, even when the uncertainties are included. Breaking the index of the primary spectra (DRB model) does not improves the agreement with the data and slightly changes the best B/C fit (Fig. 1). Protons and helium data are still overestimated. Electrons remain largely overproduced at low energies, even more than in the case without the break. The antiprotons are underproduced. In those cases, the experimental data fits can be easily improved adding different primary components coming from neutralino annihilations or from some other exotic contributions (Lionetto et al., 2004).

For the model with diffusion and convection, all the results are in excellent agreement with the data except in the B/C case. This problem could be due to some other sources of uncertainties, like the interstellar gas distribution, solar modulation and approximations done in the cross section calculations. As a possibility for future analysis, we would like to emphasize that it is natural to take into account models that include both of the processes, convection and reacceleration. Further measurements of antiproton and positron spectra, primary to secondary CR ratios and solar modulation, as well as the precise determination and parametrization of important nuclear cross sections (Kamae et al., 2005) seem to be crucial to determine the correct propagation model. In the framework of DC model, exotic contributions remain possible at high energies ($E > 20$ GeV), and not excluded at lower energies due to the relatively large uncertainties.

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