New constraints on Galactic cosmic-ray propagation

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Abstract
An extensive program for the calculation of galactic cosmic-ray propagation has been developed. Primary and secondary nucleons, primary and secondary electrons, secondary positrons and antiprotons are included. Fragmentation and energy losses are computed using realistic distributions for the interstellar gas and radiation fields. Models with diffusion and convection only do not account naturally for the observed energy dependence of $B/C$, while models with reacceleration reproduce this easily. The height of the halo propagation region is determined, using recent $^{10}\text{Be}/^{9}\text{Be}$ measurements, as greater than 4 kpc. The radial distribution of cosmic-ray sources required is broader than current estimates of the SNR distribution for all halo sizes. Our results include an estimate of cosmic-ray antiproton and positron spectra, and the Galactic diffuse $\gamma$-ray emission (see accompanying paper: Moskalenko 1998b).

Introduction.
We are constructing a model which aims to reproduce self-consistently observational data of many kinds related to cosmic-ray (CR) origin and propagation: direct measurements of nuclei, electrons, positrons, antiprotons, gamma rays, and synchrotron radiation. These data provide many independent constraints on any model and our approach is able to take advantage of this since it must be consistent with all types of observation.

Here we present our results on the evaluation of diffusion/convection and reacceleration models based on the $B/C$ and $^{10}\text{Be}/^{9}\text{Be}$ ratios, and set limits on the halo size. A re-evaluation of the halo size is desirable since new $^{10}\text{Be}/^{9}\text{Be}$ data are now available from Ulysses (Connell 1998) with better statistics than previously. Our preliminary results were presented in Strong (1997a,b) and full results for protons, Helium, positrons, and electrons in Moskalenko (1998a). Some illustrative results for gamma-rays and synchrotron radiation are given in Strong (1997a) and Moskalenko (1998b) and all details are given in Strong (1998\textsuperscript{1}).

The model description.
The models are three dimensional with cylindrical symmetry in the Galaxy, and the basic coordinates are $(R, z, p)$, where $R$ is Galactocentric radius, $z$ is the distance from the Galactic plane, and $p$ is the particle momentum. The propagation equations are solved numerically on a grid by the method described in Strong (1998). $R_\odot$ is taken as 8.5 kpc. The propagation region is bounded by $R = R_h$, $z = z_h$ beyond which free escape is assumed. We take $R_h = 30$ kpc. The range $z_h = 1−20$ kpc is considered. For a given $z_h$ the diffusion coefficient as a function of momentum is determined by $B/C$ for the case of no reacceleration; if reacceleration is assumed then the reacceleration strength (re-
Fig. 1. Left panel: $B/C$ ratio for diffusion/convection models without break in diffusion coefficient (Strong 1998 and references therein), for $z_h = 3$ kpc, $dV/dz = 0$ (solid line), 5 (dotted line), and 10 km s$^{-1}$ kpc$^{-1}$ (dashed line); solid line: interstellar ratio, shaded area: modulated to 300 – 500 MV; data: HEAO-3, Voyager, Ulysses. Right panel: $B/C$ ratio for diffusive reacceleration models (Strong 1998) with $z_h = 5$ kpc, $v_A = 0$ (dotted), 15 (dashed), 20 (thin solid), 30 km s$^{-1}$ (thick solid). In each case the interstellar ratio and the ratio modulated to 500 MV is shown.

Illustrative results.

We consider the cases of diffusion+convection and diffusion+reacceleration, since these are the minimum combinations which can reproduce the key observations. Our basic conclusion is that the reacceleration models are more satisfactory in meeting the constraints provided by the data, reproducing the $B/C$ energy dependence without ad hoc variations in the diffusion coefficient; further it is not possible to find any simple version of the diffusion/convection model which reproduces $B/C$ satisfactorily.

Figure 1a shows the diffusion+convection model without break, $\delta_1 = \delta_2$; for each $dV/dz$, the remaining parameters $D_0$, $\delta_1$ and $\rho_0$ are adjusted to fit the data as well as
possible. It is clear that a good fit is not possible; the basic effect of convection is to reduce the variation of $B/C$ with energy, and although this improves the fit at low energies the characteristic peaked shape of the measured $B/C$ cannot be reproduced. If we allow $\delta_1 \neq \delta_2$ it can clearly be fitted, but the break has to be large and the procedure is ad hoc.

Figure 1b illustrates a diffusive reacceleration model and shows the effect on $B/C$ of varying $v_A$ ($= 0 \div 30$ km s$^{-1}$) for $z_h = 5$ kpc. This shows how the initial form becomes modified to produce the characteristic peaked shape. Reacceleration models thus lead naturally to the observed peaked form of $B/C$, as pointed out by previous authors (e.g., Letaw 1993, Seo 1994, Heinbach 1995); a value $v_A \sim 20$ km s$^{-1}$ seems satisfactory.

Figure 2a summarizes the limits on $z_h$ and $dV/dz$ for diffusion/convection, using the $^{10}\text{Be}/^{9}\text{Be}$ ratio at the interstellar energy of 525 MeV/nucleon appropriate to the Ulysses data (Connell 1998). We conclude that in the absence of convection $4 \text{ kpc} < z_h < 12 \text{ kpc}$, and if convection is allowed the lower limit remains but no upper limit can be set. In the case $dV/dz < 7$ km s$^{-1}$ kpc$^{-1}$, this figure places upper limits on the convection parameter for each halo size. These limits are rather strict, and a finite wind velocity is only allowed in any case for $z_h > 4$ kpc. Figure 2b shows $^{10}\text{Be}/^{9}\text{Be}$ for the reacceleration models as a function of $z_h$ at 525 MeV/nucleon corresponding to the Ulysses measurement and we again find that $4 \text{ kpc} < z_h < 12 \text{ kpc}$.

Figure 3 (left panel) shows the effect of halo size on the radial distribution of 3 GeV CR protons, for the reacceleration model. For comparison we show the CR distribution deduced by model-fitting to EGRET gamma-ray data ($> 100$ MeV) from Strong (1996b), which is dominated by the $\pi^0$-decay component; the analysis by Hunter (1997), based on a different approach, gives a similar result. The predicted CR distribution using the SNR source function is too steep even for large halo sizes; in fact the halo size has a relatively small effect on the distribution. Other related distributions such as pulsars have an even steeper falloff. Based on these results we have to conclude, in the context of the present models, that the distribution of sources is not that expected from the (highly uncertain) distribution of SNR. In view of the difficulty of deriving the SNR distribution...
Fig. 3. Left panel: radial distribution of 3 GeV protons at $z = 0$, for diffusive reacceleration model with halo sizes $z_h = 1, 3, 5, 10, 15, \text{and } 20 \text{kpc} \text{(solid curves)}$. Dashed line: the source distribution is that for SNR given by Case (1996), histogram: the CR distribution deduced from EGRET $>100 \text{MeV}$ gamma rays (Strong 1996b). Right panel: radial distribution of 3 GeV protons at $z = 0$ for the source distribution actually adopted (dashed line), for diffusive reacceleration model with various halo sizes $z_h = 1, 3, 5, 10, 15, \text{and } 20 \text{kpc} \text{(solid curves)}$.

this is perhaps not a serious shortcoming; if SNR are indeed CR sources then it is possible that the gamma-ray analysis gives the best estimate of their Galactic distribution. Therefore, we have chosen a CR source distribution to fit the $\gamma$-ray data after propagation (Figure 3, right panel). The possibility of anisotropic diffusion (preferentially in the radial direction) has not yet been addressed in our models.

The positron fraction computed is in good agreement with the measured one between 1 and 10 GeV, where the data are rather precise. Our positron predictions from Moskalenko (1998a) have been compared with more recent absolute measurements in Barwick (1998) and the agreement is good; for the positrons this new comparison has the advantage of being independent of the electron spectrum (see also Moskalenko 1998b).

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