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A Study of the Propagation of Cosmic Rays in the Galaxy Using a Monte Carlo Diffusion Model – Calculation of the $^3He/^4He$, B/C and Sub Fe/Fe Ratios and a Comparison with Measurements

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Abstract

We have used a Monte Carlo diffusion model to calculate the $^3He/^4He$, B/C and sub Fe/Fe ratios after propagation in the Galaxy. The latest cross sections for the production of the secondary nuclei are used. The source spectra are taken to be $\sim P^{-2.25}/\beta$. The above 3 ratios are required to be fit simultaneously at 1, 10 and 100 GeV/nuc. This fixes the energy dependence of the diffusion coefficient (escape length)$^{-1}$ to be $\sim P^{0.50}$. The matter density as well as the boundary of the propagating region (size of halo) are variables along with the diffusion coefficient. A fit to the measurements of these ratios at all energies can be achieved to a precision of a few percent for several combinations of the above parameters but in each case a very narrow range of parameter space is required. The choice of which combination of parameters is appropriate can be made using the surviving fractions of the radioactive decay isotopes. The implications of this "parameter balance" are discussed.

1. Introduction

The traditional Leaky Box Model (LBM) used to describe cosmic ray propagation in the Galaxy provides very precise answers to a wide variety of observations. As such it is useful for an initial comparison with measurements. However, it provides very little insight into the features of this propagation and the parameters used to describe it. All of these details are basically contained in two parameters, the path length in g/cm^2 and its energy dependence and an average matter density, n, for the entire propagating region. Diffusion models can be made physically more realistic but analytical diffusion models are also limited in the description of the many parameters and their spatial and energy dependence needed to fully describe this propagation in the Galaxy.

We have recently presented a Monte Carlo diffusion model (Webber, 1993 and Webber and Rockstroh, 1997), and here we describe its precise application to the propagation of cosmic ray nuclei including radioactive ones. The three important ratios that provide limits on the details of this propagation are the $^3He/^4He$, B/C and sub Fe/Fe ratios which describe the build up of secondary nuclei during this propagation. Because these ratios involve primaries with greatly different nuclear interaction probabilities they sample different spatial scale features of this propagation and must be examined simultaneously to fully explore this propagation. The interstellar matter density and its distribution is a most important parameter of this propagation as are the nuclear cross sections, particularly those for the production of secondary nuclei. Space does not prevent us to describe how these details are handled here. The general details of this Monte Carlo program are described in Webber and Rockstroh, 1997. Here we note the following: The source spectra of all components are taken to be $\sim P^{-2.25}/\beta$. The above three ratios are required to be fit simultaneously at 1-10 and 100 GeV. This fixes the energy dependence of the diffusion coefficient (escape length)$^{-1}$ to be $\sim P^{0.50}$ above 1 GV rigidity. We find no need for a break in this rigidity dependence above 1 GV as in the case of the LBM. The IS values of the B/C and sub Fe/Fe ratios are very insensitive to the dependence of K on P below ~3 GV in this model. We believe that this is due to the effects of ionization energy loss which controls the shape of the IS spectrum below ~1 GeV/nuc (3 GV) in the Monte Carlo diffusion model because of the much higher matter densities near the plane in this model than in the LBM where a global average density is used.

The IS matter density as well as the boundary of the propagating region (size of halo) are variables along with the value of the diffusion coefficient. A fit to the measurements of these 3 ratios can be achieved to a precision of a few percent for several combinations of the above parameters, but in each case only a narrow range of parameter space is required. In Figure 1 we show a fit to the data for all three secondary/primary ratios for K_0 (1)=2 x 10^{28} cm^2 sec^{-1}, n_0= 1.2 exp $^{-Z}/z_m$ cm^{-3} where z_m=0.2 kpc, and for a boundary at z_b=3 kpc. As noted in the abstract, there are various other combinations of these parameters that will fit the three ratios simultaneously almost equally well. Several of these combinations are listed in Table 1. A common feature of each of these 4 combinations is that they result in approximately the same amount of matter traversed (similar to the path length in the LBM).

Table 1
Parameters used to fit $^3H/^4He$, B/C and sub Fe/Fe Ratios

Density (n_0 –cm^{-3})	Halo Size (z_b=L-kpc)	Line Integral (I_m-10^{20} cm^{-2})
3.0	1.33	8.4
2.0	2.00	8.4
1.3	3.00	8.4
0.9	4.50	8.4

These different combinations may be distinguished, first if the line integral, n·dz, of the matter density is comparable to that actually measured near the sun (e.g. 0.6-1.2 x 10^{21} cm^{-2}) and second from the cosmic ray data itself using the radioactive isotopes. In Figure 2 we show calculations for the surviving fraction of ^{10}Be for the 4 different examples given in Table 1, along with the latest Voyager and Ulysses low energy measurements of this surviving fraction. These measurements give a best fit for n_0=1.2±0.2 cm^{-3} , z_b=3.0±0.3 kpc, e.g., close to example 3 used to construct Figure 1. The other radioactive isotopes ^{26}Al, ^{36}Cl and ^{54}Mn give the same values of n_0 and z_b within the experimental errors of the data. The two parameters n_0 and z_b are together in a sense similar to the average density values obtained in the LBM.

Finally we note the very important fact that the cosmic ray data on these decay isotopes can be used as a probe of the local matter density. The value of the line integral, $I_m=\int n \cdot dz$, obtained in this way is (8.4±1.7)x10^{20} cm^{-2}, about the same as the sum of the directly measured H1, H2 and H_{II} components currently given in the literature.

3. Summary and Conclusions

We use a Monte Carlo diffusion model to fit simultaneously the measured cosmic ray $^3He/^4He$, B/C and sub Fe/Fe ratios from ~1 GeV/nuc to high energies. From this fit the diffusion coefficient is found to be ~$P^{0.50}$. Various sets of propagation parameters are found to fit the data on the charge ratios equally well, roughly equivalent to using the same path length in the LBM, however, when the measurements of the surviving fraction of the radioactive decay isotopes are used, this parameter space is restricted to the combination K_0=2.0 x 10^{28} cm^2 sec^{-1}, n_0=1.2 cm^{-3}, z_b=3 kpc and I_m, the matter line integral = (8.4±1.7) x 10^{20} cm^{-2}.

References

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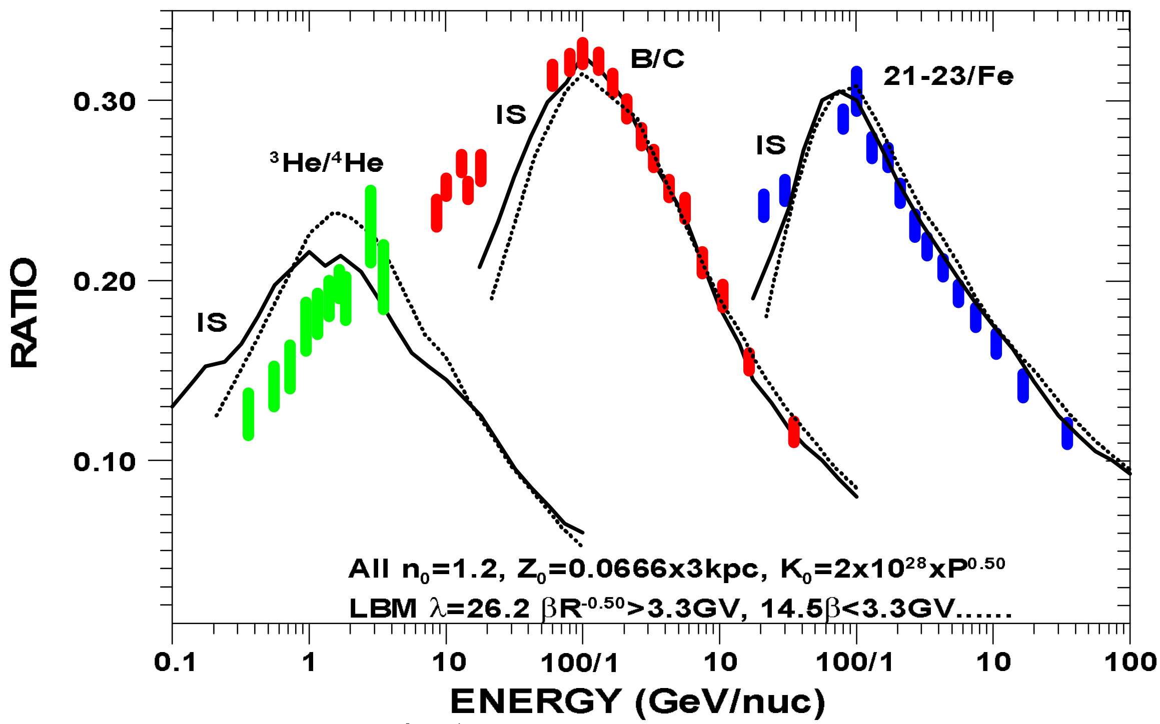

Figure 1: Calculated and measured $^3He/^4He$, B/C and (21-23)/Fe IS ratios as a function of energy. Solid curve, Monte Carlo calculation with n_0=1.2 cm^{-3}, z_m=0.067 x z_b and K_0=2 x 10^{28} x $P^{0.50}$ $cm^2 \cdot sec^{-1}$. Dotted curve ≡ LBM with $\lambda=26.2\beta R^{-0.50}$>3.3GV, 14.5β<3.3 GV. Measurements are from Engelmann, et al., 1990, for B/C and (21-23)/Fe ratios above 0.6 GeV/nuc and various spacecraft measurements at lower energies; and from Reimer, et al., 1998, for the $^3He/^4He$ ratio.

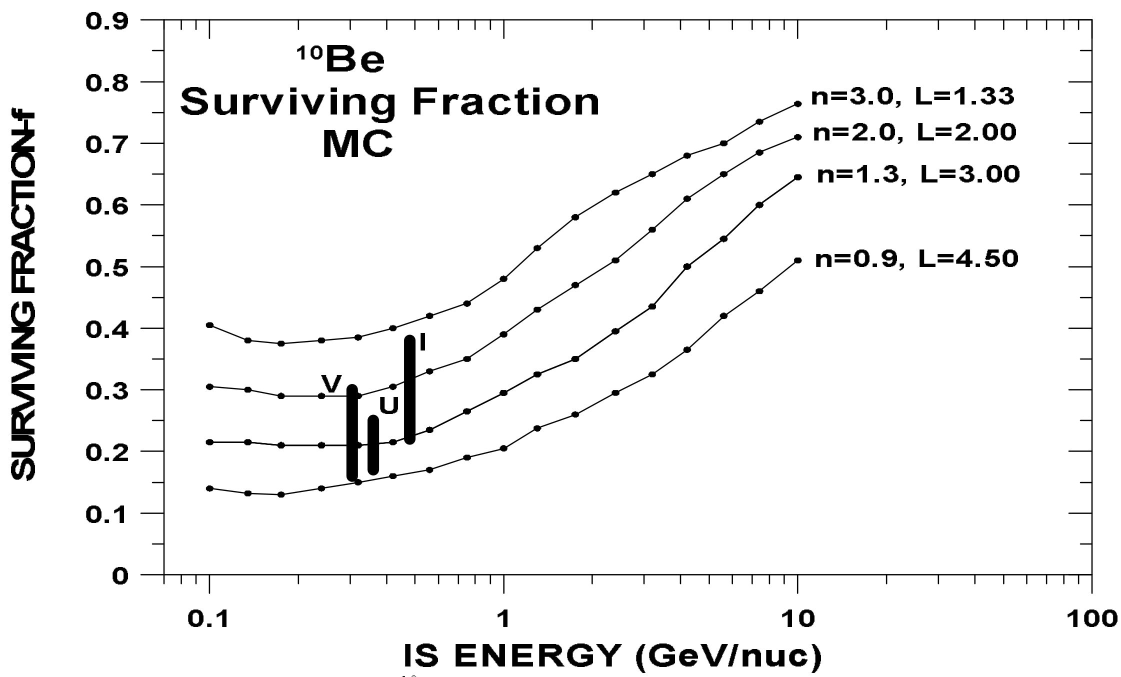

Figure 2: Surviving fraction, f, for ^{10}Be calculated using a Monte Carlo propagation model for the various parameters as indicated. ISSE, Ulysses and Voyager measurements of f are shown-see summary of Webber, 1999.