Test of the Diffusion Halo and the Leaky Box Model by means of secondary radioactive Cosmic Ray Nuclei with different lifetimes

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Abstract

At this time there are no measurements available on the energy dependence of the surviving fraction of secondary radioactive cosmic ray nuclei. Such a measurement can be used to distinguish between the Leaky Box and the Diffusion Halo Model. Available data gather around 200 MeV/nucleon. We show that these data at a fixed energy can also be used for a model distinction if one makes use of the different lifetimes of the various radioactive nuclei such as ^{10}Be, ^{26}Al and ^{36}Cl.

1 Introduction

It has been pointed out many years ago (Ginzburg, Khazan & Ptuskin, 1980) that the sources of CR should be distributed within the thin galactic disk and that the escape from the disk into the halo and finally into the intergalactic space is determined by diffusion. In the literature this Diffusion Halo Model (DHM) competes with the very popular Leaky Box Model (LBM). The LBM describes an equilibrium model, in which the cosmic ray sources, and the primary and secondary cosmic ray particles are homogeneously distributed in a confinement volume (box, galaxy) and constant in time with no gradient of CR density into any direction. Thus in the LBM the transport of CR is not controlled by diffusion but by a hypothetic leakage process at the imaginary boundaries. After traversing a mean interstellar gas density of $\lambda_{esc}(E)\,[g/cm^2]$ the particles escape from the confinement volume but the mechanism of their escape is not addressed as well as the physical size of the volume. These two, the DHM and the LBM, are currently the basic competing models in CR propagation calculation. It is true that the precision and details of the data have not provided yet a tool to favour one model over the other. But as pointed out by Ginzburg, Khazan & Ptuskin (1980), the energy dependence of the surviving fraction of secondary radioactive nuclei such as ^{10}Be $(\tau_d = 2.3\cdot 10^6\ years)$, ^{26}Al $(\tau_d = 1.0\cdot 10^6\ years)$ and ^{36}Cl $(\tau_d = 4.5\cdot 10^5\ years)$ are model dependent and can be used to check on the physical reality of these two models. We here show that one can also check on these models by comparing the surviving fraction of different radioactive isotopes with different decay times at a fixed energy.

2 The transport equations for the Leaky Box Model and the Diffusion Halo Model

In order to calculate the surviving fraction of secondary radioactive cosmic ray isotopes within these two models one has to solve the appropriate equilibrium equations for the LBM:

$$N_i(E)\left\{\frac{1}{\tau_{esc}(E)}+\frac{1}{{}_i\tau_{\text{int}}(E)}+\frac{1}{\gamma(E)\cdot{}_i\tau_{dec}}\right\}=\sum_{k>i}\frac{N_k(E)}{\tau_{\text{int}}^{k\to i}(E)}-\frac{\partial}{\partial E}\left\{\left(\frac{\partial E}{\partial t}\right)\cdot N_i(E)\right\} \qquad (1)$$

and for the one dimensional DHM:

$$0=\frac{\partial}{\partial z}\left\{D(E,z)\cdot\frac{\partial}{\partial z}N_i(E,z)\right\}-N_i(E,z)\left\{\frac{1}{{}_i\tau_{\text{int}}(E,z)}+\frac{1}{\gamma(E)\cdot{}_i\tau_{dec}}\right\}$$
$$+\sum_{k>i}\frac{N_k(E,z)}{\tau_{\text{int}}^{k\to i}(E,z)}-\frac{\partial}{\partial E}\left\{\left(\frac{\partial E}{\partial t}\right)\cdot N_i(E,z)\right\} \qquad (2)$$

These two Equations contain similar and different terms. In the LBM the quantities $N_i(E)\,[cm^{-3}\,GeV^{-1}]$ and $N_k(E)\,[cm^{-3}\,GeV^{-1}]$ stand for the number densities of different types of nuclei of kinetic energy E and in Equation 2 $N_i(E,z)$ and $N_k(E,z)$ describe the number density of particles at a given position z. The first term of the right side in Equation 2 describes the diffusion and D(E,z) means the diffusion coefficient at position z. For simplicity we allow D(E) to be independent of position. The second bracket on the right side of Equation 2 accounts for the losses of *i*-type particles similar to those in Equation 1, where ${}_i\tau_{\text{int}}(E)$ stands for the mean lifetime of the *i*-type particles against interaction in the interstellar gas and $\gamma(E)\cdot{}_i\tau_{dec}$ accounts for the loss due to radioactive decay (γ is the Lorentz-factor). The quantity $\tau_{\text{int}}^{k\to i}(E)$ means the mean time which a *k*-type nuclei needs to produce an *i*-type secondary in the interstellar gas. This quantity depends on the production cross section and the interstellar gas in terms of density and composition. $\frac{\partial}{\partial E}\left\{\left(\frac{\partial E}{\partial t}\right)\cdot N_i(E)\right\}$ accounts in both equations for the energy loss process. The above equations can be solved by different mathematical techniques and we refer to the literature. We like to note that care has to be taken when energy changing processes are involved (Heinbach & Simon 1995, Stephens & Streitmatter 1998, Garcia-Munoz et al 1987, Gaisser & Schaefer 1995).

3 Results of the Surviving Fraction

Both models, the LBM and DHM, deal with free parameters. As can be seen in Equation 1 the LBM has only one free parameter which is the mean escape time $\tau_{esc}(E)$. This $\tau_{esc}(E)$ translates into an escape length $\lambda_{esc}(E)=\langle m\rangle\cdot n\cdot c\cdot\beta\cdot\tau_{esc}(E)$, where <*m*> means the mean mass of the interstellar gas, *n* [cm^{-3}] the mean density and $c\cdot\beta$ the velocity of the particle. This free parameter $\lambda_{esc}(E)$ can be obtained by fitting a measured secondary-primary-ratio of stable nuclei such as B/C. In our calculation here we adopted such a fit and used the $\lambda_{esc}(E)$-dependence as recently published by Webber et al. 1996. The mean interstellar gas density *n* [cm^{-3}] can then be derived in the framework of the LBM by matching the calculated surviving fraction of secondary radioactive isotopes, or some appropriate ratios such as ^{10}Be/^{9}Be, with existing data. Such a fit is shown by the upper curve labeled LBM in Figure 1. This fit was obtained by using a mean gas density of *n*=0.3 H-*Atoms/cm*^{3}. The increase of the curve with energy is due to the relativistic time dilatation.

The DHM deals with more parameters. There is the disk size h_d, the halo size *H*, the mean gas density in the galactic disk *n* [cm^{-3}] and the diffusion coefficient *D*(*E*). All these parameters have in principle an impact on the solution of Equation 2 but they are of different importance. Is the halo size H and the diffusion coefficient D(E) which count most, hence it is legitimate to make reasonable assumptions for the disk size and disk gas density. We took $h_d=100\ pc$ and $n_d=1$ H-*Atom/cm*^{3}. Under these assumptions the adopted $\lambda_{esc}(E)$-dependence fixes a ratio between *D*(*E*) and *H* according to the following relation:

$$\lambda_{esc}(E) = \frac{n_d \cdot \langle m \rangle \cdot \beta \cdot c \cdot h_d \cdot H}{D(E)} \tag{3}$$

In order to fix $D(E)$ and H separately one can use secondary radioactive nuclei. This works in the following way. They are produced in the thin galactic disk via interactions between cosmic ray particles and the interstellar gas and then diffuse out into the halo. The more they diffuse out, the larger is the volume they pervade and thus the surviving fraction becomes smaller. Thus a fit to the measured $^{10}Be/^{9}Be$-ratio allows to determine $D(E)$ and H. Such a fit to the existing low energy data is shown in Figure 1

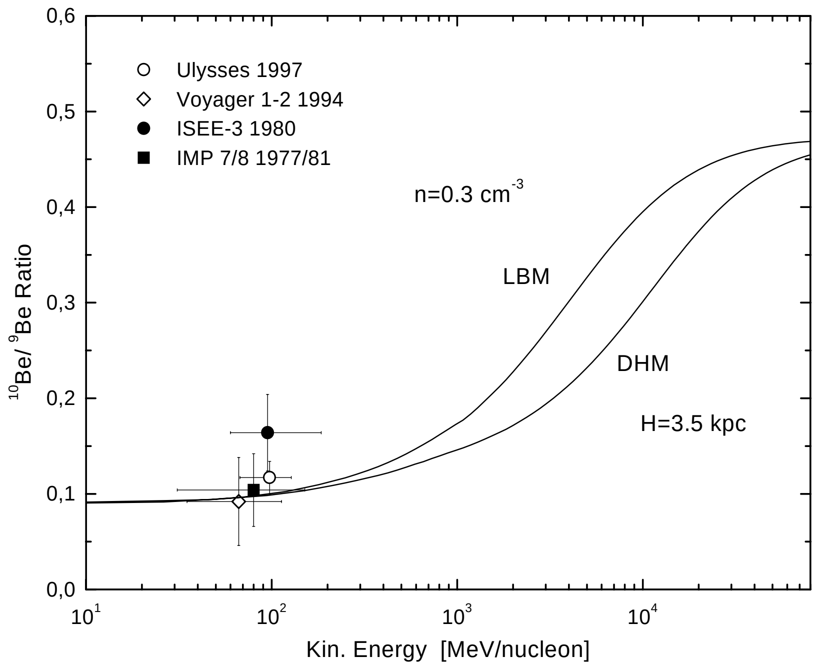

Figure 1 - The two curves show the calculated $^{10}Be/^{9}Be$-ratio in the framework of the LBM and the DHM. The free parameters in the two models were adjusted so that the low energy data could be fitted. As can be seen measurements on the energy dependence of this ratio will allow to favour one model over the other.

labeled DHM. We note that the fit to the currently existing data on the $^{10}Be/^{9}Be$-ratio which gather around 100 MeV/nucleon cannot be used to favour one model over the other. Only measurements of the energy dependence of this ratio into the GeV regime could tell, as Figure 1 depicts. The ISOMAX experiment is currently aiming for such a measurement (de Nolfo et al. 1999, Hams et al. 1999, Mitchell et al. 1999, Geier et al. 1999) . But in Figure 2 we illustrate that simultaneous measurements of radioactive isotopes with different decay times at low energies have also the potential to separate between the LBM and the DHM. In Figure 2 we show the surviving fraction of ^{26}Al and ^{36}Cl calculated in the framework of the LBM and the DHM respectively using those parameters which were determined by the fit to the existing $^{10}Be/^{9}Be$ data as illustrated in Figure 1. As can be seen in Figure 2, according to their different decay times the surviving fractions of ^{10}Be, ^{26}Al and ^{36}Cl respond differently in the two models.

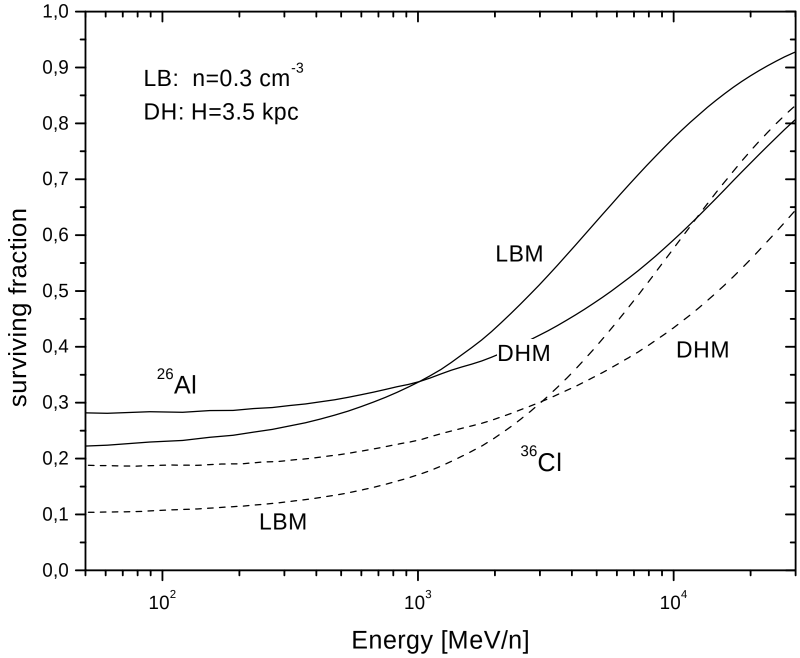

Figure 2 Surviving fractions for the two radioactive isotopes ^{26}Al and ^{36}Cl, calculated in the framework of the LBM and DHM. This calculation was performed with those parameters which allowed to fit the ^{10}Be/^{9}Be-ratio at low energies, see Figure 1. As can be seen simultaneous measurements of the radioactive isotopes of different decay times at the same energy can be used to favour one model over the other.

4 Discussion

These results show that a check on the reality of the LBM or the DHM can be reached by a measurement of the surviving fraction of an individual secondary radioactive isotope such as ^{10}Be as a function of energy. But Figure 1 clearly illustrates that such a measurement should at least extend into the GeV regime where the distinction between the two models becomes more pronounced. As Figure 2 however illustrates, such a distinction can also be reached at low energies by taking radioactive isotopes with different decay times into consideration. The precision of these measurements however should be within the percent range, so that they allow a reliable distinction between the different curves shown in Figure 2. Good data on ^{10}Be, ^{26}Al , ^{36}Cl and ^{54}Mn are expected to come soon from the ACE experiment.

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