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Decaying cosmic ray nuclei in the local interstellar medium

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Abstract. Secondary radioactive isotopes that are used for the determination of cosmic ray age, have relatively short decay lifetimes. The measured abundance of these isotopes at low energies is representative of the cosmic ray diffusion and the gas distribution in a region of a few hundred parsecs around the Sun. We show how to determine the local cosmic ray diffusion coefficient in the Galaxy using the data on decaying cosmic ray nuclei.

Key words: cosmic rays – ISM: general

1. Introduction

The presence of considerable amount of secondary nuclei in cosmic rays produced almost purely in the course of propagation and nuclear fragmentation of primary cosmic ray nuclei in the interstellar gas provides an important information on the nature of cosmic ray transport in the Galaxy. The content of stable secondary nuclei (B, Sc+Ti+V,^{2}H, ^{3}He, etc.) makes it possible to determine the characteristic escape length X=$<$n$>$vT, where $<$n$>$ is the averaged gas number density, v is the particle velocity, and T is the characteristic escape time of cosmic rays from the Galaxy. Radioactive secondaries allow to find the value of $<$n$>$ and T separately, see e.g. Simpson & Garcia-Munoz (1988) for review. The radioactive isotopes that are used or may be used for this procedure are: ^{10}Be (2.3 10^6 yr),^{26}Al (1.3 10^6 yr),^{36}Cl (4.3 10^6 yr),^{54}Mn ($\sim 10^6$ yr),^{14}C (8.2 10^3 yr), etc. Here the decay life times at rest are indicated in brackets. The decay life time of completely ionized ^{54}Mn is not yet well determined.

The interpretation of observations of radioactive nuclei is rather sensitive to the model of cosmic ray propagation in the Galaxy. In particular, the diffusion model and the so called leaky box model turn out to be not equivalent (Prishchep & Ptuskin 1975; Ginzburg & Ptuskin 1976). The difference is mainly due to the inhomogeneous interstellar gas distribution where the secondary nuclei are produced. Slow diffusion and relatively fast decay of radioactive secondaries may make their spatial distribution strongly inhomogeneous whereas the leaky box model assumes a uniform distribution for all cosmic ray species. The well studied effect of this kind is caused by the most prominent feature in the large scale gas distribution in the Galaxy: the concentration of a large fraction of the mass of the interstellar gas in a relatively thin gas disk (Prishchep & Ptuskin 1975, Ginzburg & Ptuskin 1976, Prishchep & Ptuskin 1979, Freedman et al. 1980, Ptuskin & Soutoul 1991, Webber et al. 1992, Bloemen et al. 1993). The spatial scale which is important here is of order d=$(D\tau)^{1/2}$, where D is the cosmic ray diffusion coefficient and τ is the lifetime for decay (including relativistic factor). The typical value of D at energies less than 2 GeV/n is about 10^{28}cm^2/s and the value of d may range from 30 to 300 for the isotopes listed above (the relativistic factor must be also taken into account for rapidly moving nuclei). The variations of the gas density are essential on these scales and must be incorporated in the calculations of the surviving fraction in the diffusion model. An appropriate procedure is suggested in the present work.

A strong motivation for this work comes from the good agreement between satellite measurements of the ^{10}Be abundance in low energy cosmic rays (Simpson & Garcia-Munoz 1977, 1988, Wiedenbeck & Greiner, 1980; Lukasiak et al. 1994), the availability of satellite data on ^{26}Al(Wiedenbeck 1983, Lukasiak et al. 1994),^{36}Cl (Leske & Weidenbeck 1993), and ^{54}Mn (Leske 1994, Lukasiak et al. 1995), expected results on radioactive isotopes from the Ulysses experiment, and from the prospect from planed experiments on cosmic ray isotopes; in particular the Advanced Composition Explorer (ACE) which will provide a collective power about 100 times greater than existing instruments (Stone et al. 1990). This stimulates the development of improved models of cosmic ray propagation in the Galaxy.

2. Diffusion model for radioactive nuclei

The steady state transport equation for secondary radioactive nuclei that describes their diffusion, nuclear fragmentation and decay has the form:

$$-\nabla D\nabla N_2 + nv\sigma_2 N_2 + \frac{N_2}{\tau} = nv\sigma_{12}N_1 \quad (1)$$

Here N_2 and N_1 are the number densities of primary and secondary nuclei; D is the cosmic ray diffusion coefficient, n is the interstellar gas density, v is the cosmic-ray particle velocity,

σ_2 and σ_{12} are the total and production cross sections for secondaries. The effect of ionization energy losses is not explicitly included in Eq. (1) but is taken into account in our actual calculations as will be described below. In the left hand side of Eq. (1) for the radioactive isotopes listed above, the term for decay is larger than the term for fragmentation, so that the interstellar medium is only weakly non transparent against fragmentation during the typical time interval spent by these isotopes in the Galaxy. In these circumstances we suggest the following procedure for obtaining an approximate solution of Eq. (1).

First we set σ_2 = 0 and write the solution of Eq. (1) in the following form

$$N_2(\mathbf{r}, \sigma_2 = 0) =$$

$$v\sigma_{12} \int\int\int d^3r_0 n(\mathbf{r_0}) N_1(\mathbf{r_0}) G(\mathbf{r}, \mathbf{r_0}, \tau) \quad (2)$$

where the Green function G obeys the equation:

$$-\nabla D \nabla G + \frac{G}{\tau} = \delta(\mathbf{r} - \mathbf{r_0}) \quad (3)$$

We shall consider the solutions of Eq. (3) in an unbounded medium assuming that the size of galactic cosmic ray halo is relatively large compared to d. The distances of the order of, and smaller than d are essential in the integral in Eq. (2). The density of primary nuclei N_1(r) will be considered constant on this scale, i.e. $N_1(r) \approx N_1(r_0)$ This assumption is based on the radio and gamma ray observations (see e.g. Berezinskii et al. 1990). The diffusion coefficient is also supposed to be constant. Then Eq. (2) leads to the following approximate equation:

$$N_2(\mathbf{r}, \sigma_2 = 0) = n_{ef}(\mathbf{r}, \tau) v\sigma_{12}\tau N_1 \quad (4)$$

where we introduce the effective gas density

$$n_{ef}(\mathbf{r}, \tau) = \tau^{-1} \int\int\int d^3r_0 n(\mathbf{r_0}) G(\mathbf{r}, \mathbf{r_0}, \tau) \quad (5)$$

The integration of Eq. (5) performs (with the corresponding weight) the averaging of the gas density over the volume where nuclei can diffuse to reach the observer at $\mathbf{r}$. Now one can construct the following final approximate solution for N_2 at $\sigma_2 \neq 0$:

$$N_2(\mathbf{r}) = v\sigma_{12} N_1 \int\int\int d^3r_0 n(\mathbf{r_0}) G(\mathbf{r}, \mathbf{r_0}, \tau_m) \quad (6)$$

with

$$\tau_m^{-1} = \tau^{-1} + v\sigma_2 n_{ef}(\mathbf{r}, \tau) \quad (7)$$

Eqs. (3), (5)-(7) determine the density of secondary radioactive isotopes.

The most simple and useful for applications are the following solutions of Eq. (3) in an unbounded medium, with constant diffusion coefficient, when Eq. (3) transforms into the Helmholtz equation:

$$G(z, Z_0, \tau) = \sqrt{\tau/4D} exp(- \mid z - z_0 \mid) \quad (8)$$

in one dimension along the z axis and

$$G(\mathbf{r}, \mathbf{r_0}, \tau) = \frac{exp(- \mid \mathbf{r} - \mathbf{r_0} \mid / \sqrt{D\tau})}{4\pi D \mid \mathbf{r} - \mathbf{r_0} \mid} \quad (9)$$

in three dimensions.

The assumption of isotropic diffusion used in Eq. (9) may not be correct because of the interstellar magnetic field which makes diffusion anisotropic, see Berezinskii et al. (1990), for discussion. The assumption of isotropic diffusion used in the present consideration is justified by the lack of detailed knowledge about the structure of the Galactic magnetic field. The same may be said for the assumed independence of the diffusion coefficient on position.

The measured abundance of radioactive isotopes in cosmic rays may be conveniently expressed through the surviving fraction s defined as follows:

$$s = N_2(\tau)/N_2(\tau = \infty) \quad (10)$$

Here $N_2(\tau = \infty)$ is the density for the isotope considered stable. It is clear that the value of the surviving fraction is limited by the inequality s <1. It is well known that the empirical leaky box model successfully reproduces the abundance of stable secondary isotopes. One has the following equation for cosmic ray number density in the framework of this model:

$$\left(\frac{1}{T} + n_{lb} v\sigma_2\right) N_2 + \frac{\partial}{\partial E}\left(\left(\frac{dE}{dt}\right) N_2\right) = n_{lb} v\sigma_{12} N_1 \quad (11)$$

Here n_{lb} represents the (constant) gas density, and the term with $(dE/dt)_{ion} < 0$ describes the ionization energy losses. The leaky box escape length X = n_{lb}vT is determined from the observed abundance of stable secondary nuclei, e.g. from the B/C ratio in cosmic rays. The value of X found in this way and defined through the mean gas mass density ρ_{lb} as $X_{lb} = \rho_{lb}$vT is approximately equal to 15β g/cm^2 at energies less than 2 Gev/nucleon, here β =v/c (Engelmann et al. 1990). It may be shown that for an observer located in the galactic disk, the solution of diffusion equation for the flat halo diffusion model coincides with the leaky box formula (11) in the limit of large cosmic ray halo H >> h and when the condition σX<< H/h is fulfilled for all stable nuclei under consideration (Ginzburg & Ptuskin,1976, Ptuskin & Soutoul 1990). So, under these conditions the diffusion and leaky box models are equivalent for the description of abundance of stable nuclei and the leaky box equation may be used for the calculations of the denominator $N_2(\tau = \infty)$ in Eq. (10) for both models.

Finally, we have the following equation for the surviving fraction of secondary radioactive isotope:

$$s = \frac{v\sigma_{12} N_1}{N_2(\tau = \infty)} \int\int\int d^3r_0 n(\mathbf{r_0}) G(\mathbf{r}, \mathbf{r_0}, \tau_m) \quad (12)$$

where

$$\tau_m = \frac{\tau}{1 + v\sigma_2 \int\int\int d^3r_0 n(\mathbf{r_0}) G(\mathbf{r}, \mathbf{r_0}, \tau_m)} \quad (13)$$

with the Green function G given by Eq. (8) and Eq. (9) for the one dimensional and three dimensional cases respectively. Combination of Eqs. (8), (9) allows to construct the Green functions for complicated distributions of the interstellar gas.

The choice of the spatial gas distribution for the propagation of cosmic rays within a few hundred parsecs from the Sun is not an easy one. Observations show complicated gas structures with possible traces of supernova explosions during the last 10^6 years (Paresce 1984, Bochkharev 1987, Cox & Reynolds 1987, Dickey & Lockman 1990, Frisch 1995). In particular, the Sun is located in a cloud (the Local Fluff) with diameter a few parsecs. The local fluff is inside a low density cavity (the Local Bubble) which is separated from another hot bubble circumcised by Loop I, by the wall of hydrogen. The size of all this system is about 300 pc.

For the purpose of illustration of the approach suggested in the present work we choose a simplified model of gas distribution. It includes three gas layers with exponential profiles: n(z) $=\Sigma n_a$ exp(- $|z|/h_a$), a = 1, 2, 3, where the component with parameters n_1=0.45 cm^{-3},h_1= 130 pc represents the smeared out contribution of small numerous neutral clouds, the component n_2=0.21cm^{-3}, h_2=200 pc, represents the more extended warm medium, and the component n_3= 0.025cm^{-3},h_3=1kpc represents the ionized hot gas. In addition we take into account the individual molecular clouds inside a circle of 1 kpc around the Sun as described by Dames et al. (1987). Beyond 1 kpc we take a uniform molecular gas distribution with a surface density 1.3 $M_\odot$ pc^2. Here $M_\odot$ is the solar mass.

The outlined gas distribution was corrected for the above mentioned HI Hole in the vicinity of the Sun. We withdraw all atomic hydrogen described as the components 1 and 2 from a cylindrical cavity with diameter 400 pc and full height 260 pc and replaced it with a radial dependent gas distribution built from the absorption map presented by Paresce (1984). The integral for calculating $N_2(\mathbf{r})$ can be evaluated with the help of Eqs. (8)-(9) and it reads as follows:

$$\int\int\int d^3r_0 n(\mathbf{r_0})G(\mathbf{r},\mathbf{r_0},t) =$$

$$\sum_{a=1,2,3} \frac{n_a t}{\sqrt{1+\sqrt{Dt}/h_a}} + \sum_i \frac{M_i}{4\pi m D R_i} exp(-R_i/\sqrt{Dt})$$

$$+\frac{\eta}{2}\sqrt{t/D} exp(-R_e/\sqrt{Dt}) -$$

$$\sum_{a=1,2,3} n_a h \sqrt{t/D} \left\{ \frac{1-exp(-h/h_a - h/\sqrt{Dt})}{h/h_a + h/\sqrt{Dt}} \right.$$

$$\left. -\int_0^1 dy exp(-\frac{yh}{h_a} - \sqrt{\frac{R^2+y^2h^2}{Dt}}) \right\}$$

$$+\int\int\int d^3r_0 \frac{n(\mathbf{r_0})}{4\pi D r_0} exp(-\frac{r_0}{\sqrt{Dt}}) \quad (14)$$

The successive terms on the right hand side of Eq. (14) describe the effects of the three exponential gas layers, the individual molecular clouds (M_i and R_i are the cloud masses and distances; m is the averaged atomic mass), the external δ(z) disk of molecular hydrogen with gas number surface density η, the negative "yield" from the gas withdrawn from the HI hole (R = 200 pc is the hole radius) and the integral over the HI Hole with the actual gas distribution from Paresce (1984).

The ionization energy losses were incorporated in the calculations of the diffusive propagation of radioactive nuclei through the modification of total crossections. These modified crossections were adopted in Eq. (13). At the energy 0.4 GeV/nucleon the nuclear cross sections were increased by a factor 1.00, 1.03, 1.06, 1.03 respectively for ^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl. The presence of 10% of He in the interstellar gas was taken into account in the calculations of nuclear fragmentation and ionization energy losses. Also, the yield of the fraction of ionized gas was taken into account in the consideration of the ionization energy losses (Soutoul et al. 1990).

3. Results and discussion

The calculations of the survivving fractions for ^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl as functions of the diffusion coefficient are presented in Fig. 1. Together with the basic model with the HI Hole described above (labeled "WH" in Fig. 1) we show the results of the calculation (labeled "NH" in Fig. 1) with uniform gas surface density without the HI Hole but with the three HI layers and the molecular clouds as was described above. Also, the results of the calculations for two simplified models, one with a single exponential gas layer (labeled "SL" in Fig. 1) with the height h = 100 pc, and another with an infinitely thin gas layer (labeled "δ" in Fig. 1) are presented. In the last two cases the total gas surface density is taken the same as in the model "NH". Shaded areas in Fig. 1 show the present range of cosmic ray observations when expressed in terms of surviving fractions. The calculations are performed at the particle energy 0.4 Gev/nucleon in the interstellar medium.

The combined measurements from IMP 7-8 (Simpson & Garcia-Munoz 1977, 1988), ISEE-3 (Wiedenbeck & Greiner 1980), and Voyager 1-2 (Lukasiak et al. 1994) experiments give for the surviving fraction of ^{10}Be the value of s(^{10}Be) = 0.21 $\pm$ 0.04. Fig. 1 shows that the corresponding diffusion coefficient derived from the WH and NH curves is equal to D = (3.4 (+2.8,-1.4)) 10^{28} cm^2/s. The use of the models with very simple interstellar gas distribution such as the one-layer and δ-layer approximation may be too crude. Ignoring the local HI Hole does not affect this relatively large value of D. Taking the HI Hole into account is important for rapidly decaying ^{14}C as is seen from Fig. 1. The ^{10}Be data imply the value n_{lb} = (0.29 ($\pm$ 0.07)) nucleon/cm^3 when the interpretation is made in the framework of the leaky box model.

The above value of the diffusion coefficient is in agreement with that accepted in the flat halo diffusion model with relatively large halo (Ginzburg et al. 1980, Berezinskii et al. 1990 Ptuskin & Soutoul 1990, Ptuskin 1997). It is also in conformity with the results of investigation on the diffusion of electrons with very high energies about 10^3 GeV, see Dorman et al. (1983) and Nishimura et al. (1995). These electrons, observed at the

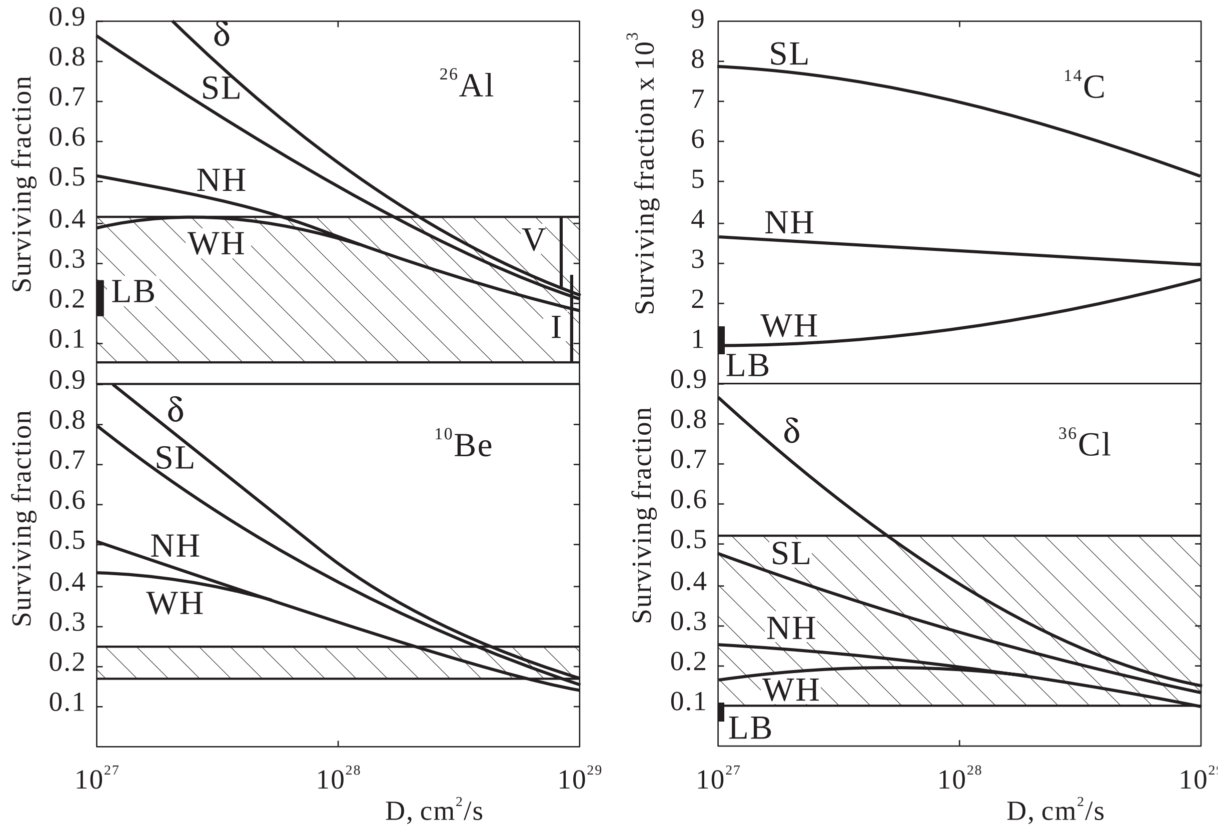

Fig. 1. The surviving fractions of ^{10}Be,^{26}Al,^{36}Cl, ^{14}C, in the bottom left panel, the top left panel, the bottom right panel,and the top right panel respectively as functions of the diffusion coefficient for cosmic rays. Symbols of the curves: δ: delta disk gas layer,**SL**: single gas layer,**WH**: layers with HI Hole,**NH**: layers without HI Hole (see text for details).

Earth, may come only from local sources (presumably, from the local supernovae remnants) since their life time relative to the synchrotron and inverse Compton energy losses is of the order 3 10^5yr.

Under the assumption that the diffusion coefficient is constant in the entire Galaxy and that there is an absorbing boundary of galactic cosmic ray halo at some distance H, one can find this distance, the size of the halo, from the relation between the escape length and the parameters of the flat halo model (Ginzburg & Ptuskin 1976):

$$X = \frac{vH\eta_{tot}}{2D} \quad (15)$$

Here η_{tot} is the total surface density of the gas and it is assumed that all interstellar gas is concentrated in a region with scale height much smaller than the halo size H. Using the above value of the diffusion coefficient and Eq. (15), one can determine the value of H = (4.9 (+4,-2)) kpc. This value is not in disagreement with the radioastronomical observations (Beuermann et al. 1985) which indicate the presence of thick nonthermal galactic radio disk with the full equivalent width (3.6 ($\pm$ .4)) kpc. Our simple model implies that the density of relativistic stable nuclei is halved at 2.4 kpc. The characteristic time of cosmic rays diffusion from the Galaxy is estimated in the one-dimensional approximation as $H^2/2D$ = (1.1 (+1.2, -0.5)) 10^8 yr while it is only T = X/(vn_{lb}) = (3.3 (+1.1, -0.6)) 10^7 in the leaky box model.

The available data on ^{26}Al and ^{36}Cl shown in Fig. 1 are still not sufficiently accurate, and they are not in disagreement with the ^{10}Be data. The Voyager data on ^{26}Al, which has the highest statistics, agrees better with the diffusion model than with the leaky box model, although with still marginal statistical significance (Lukasiak et al. 1994). Similar tendency is present in the ISSE-3 data on ^{36}Cl (Leske & Weidenbeck 1993, Ferrando 1994).

There is a one to one correspondance between the values of the surviving fractions of the isotopes at each value of the diffusion coefficient. In Fig. 2 the surviving fraction of ^{36}Cl is shown as a function of the surviving fraction of ^{10}Be. The full curves are for values of the diffusion coefficient between 10^{27} and 10^{29} cm^2/s. The dashed part of the curve labeled ”WH” is for values of the diffusion coefficient between 10^{26} and 10^{27} cm^2/s.

There is as yet no data on ^{14}C isotope in cosmic rays. The short decay time of this isotope and correspondingly very small expected surviving fraction (see Fig. 1) demands a new generation of instruments with large collecting power (Stone et al. 1990). Fig. 1 shows that because of this short lifetime ^{14}C is rather sensitive to the local interstellar gas distribution. The splitting between the “NH” and “WH” models is quite marked especially at small diffusion coefficients. So the measurements of ^{14}C abundance are needed to clearly demonstrate the effect

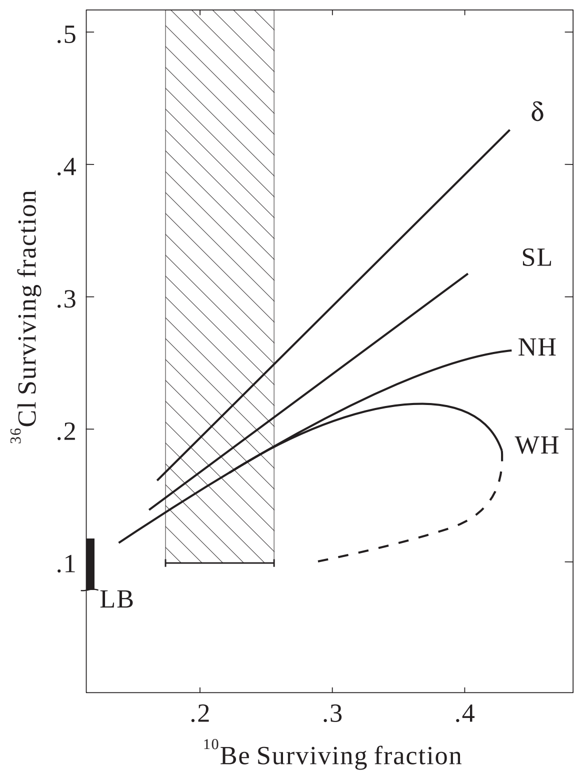

Fig. 2. The surviving fraction of ^{36}Cl as a function of the surviving fraction of ^{10}Be. Symbols as in Fig. 1. Full curves values of the diffusion coefficient between 10^{27} and 10^{29} cm^2/s;dashed curve:values of the diffusion coefficient between 10^{26} and 10^{27} cm^2/s

of the HI Hole. Such a demonstration would not be just one more sophisticated confirmation of this well established feature of the local gas distribution around the Sun. The point is that the radioactive isotopes carry information about the galactic gas distribution i.e. on a time scale of a few thousand years for ^{14}C and of 5.10^5-5.10^6 for the other ones. One can expect considerable changes of the structure of the local gas over these periods mainly because of star evolution and supernovae activity, see e.g. Gehrels and Chen (1993). Note that the value of density of the very local interstellar medium is affected with some uncertainty.

Convective transport of cosmic rays may exist in the Galaxy along with diffusion. Both the real motion of the interstellar medium and the flux of the hydromagnetic waves in a medium at rest can result in the convective transport for energetic particles scattered by magnetic field homogeneities. Convection is less important than diffusion for rapidly decaying isotopes, provided that the convection velocity u is sufficiently small, i.e. $u << (D/\tau)^{1/2} \approx 100(D/10^{28})$ km/s, where the last estimate is done for the ^{10}Be at 0.4 GeV/nucleon. Whereas a probable convective velocity and Alfven velocity are most probably limited by the value of about 30 km/s at the distances less than 1 kpc from the galactic midplane. Thus, for the found value of D = 3.4 10^{28} cm^2/s, it is valid to say that convective transport is not important and we were consistent in our consideration of pure diffusion propagation. However, for small diffusion coefficient of the order 10^{27} cm^2/s convection may be important and relatively small surviving fraction of ^{10}Be might be accomplished through the prevalence of convection over diffusion. This situation is realized in some models where the existence of wind flow in our Galaxy is postulated, see e.g. Berezinskii et al. (1990), Webber et al. (1992), Bloemen et al. (1993). Such models are not considered in the present work mainly because the spatial profile of wind velocity is not yet well determined in the vicinity of the galactic plane.

Nevertheless, we emphasize that the value of the diffusion coefficient found in the present consideration may be not unique and much smaller values may also fit the observed abundance of ^{10}Be in the model where the prevalence of convection over diffusion is assumed.

In connection with this discussion, it is interesting to note that the predictions of the most recently suggested selfconsistent model where cosmic rays itself drive the galactic wind (Zirakashvili et al. 1996, Ptuskin et al. 1997) diverge from the predictions of semiempirical wind models cited above. In the selfconsistent model the pressure of cosmic rays generated in the galactic disk determines the structure of galactic wind flow. Cosmic ray stream instability balanced by the nonlinear Landau damping on thermal ions determines the level of MHD turbulence. So, the transport coefficients for cosmic rays (the convection velocity and the diffusion coefficient) are not prescribed but are calculated under this approach. The model is in a good agreement with the cosmic ray data. The cosmic ray stream instability is not effective in the region close to the galactic plane $z < 0.5$ - 1.0 kpc because frequent ion-neutral collisions results in heavy wave damping. It is why the cosmic rays with energies below 2 GeV/nucleon move almost freely there (formally, with very large diffusion coefficient, and it makes a difference with earlier models where diffusion was usually assumed to be independent of position). But particles are effectively scattered by the wave barrier at the boundary of this region and thus behave much like particles in a leaky box. This may represent a physical realization of the widely accepted leaky box model. Energetic particle has small probability of the order u/v not to be reflected by the wave barrier and to be carried out of the Galaxy by a wind flow. The wave barrier is not effective for particles with energies higher than 2 GeV/nucleon and their propagation may be described as some combination of diffusion and advection.

The anisotropic diffusion of strongly magnetized cosmic ray particles probably makes the interpretation of cosmic ray data more complicated than discussed so far. Particles diffuse mainly along the magnetic field lines and depending on unknown field geometry may spend more time in dense or on the contrary in rarefied regions than calculated with the isotropic diffusion model.

Another critical point is our assumption of constant distribution of primaries. Local supernovae remnants like Geminga and Loop I could have produced variation of cosmic rays in the past correlated with considerable distortions of the galactic gas distribution and the magnetic field structure. The supernovae outburst which 3.10^4-3.10^5 years ago gave rise to the gamma and X-ray pulsar Geminga was probably responsible for the variation of cosmic ray intensity by a factor of ~ 2 (Raisbeck & Yiou 1987, Konstantinov et al. 1991; Dorman et al. 1983, Sonnet et al. 1987, Ramadurai 1995), for the formation of the local gas bubble with extremely low density (Gerhels & Chen 1993), the orientation of the local magnetic field along the bubble shell (Frisch 1995). This local source could also explain the observed cosmic ray anisotropy at 10^{12}-10^{14} eV and the observed intensity of very high energy electrons at about 10^{12} eV (Dorman et al. 1983, Nishimura et al. 1995). The elaboration of appropriate non linear models may become desirable as new data on decaying isotopes are available.

At present we even cannot unambiguously distinguish between the diffusion models described in this work and the leaky box model. These models when normalized to the same abundance of stable secondaries and to the same surviving fraction of ^{10}Be give different surviving fractions for other isotopes. In Fig. 1 the predicted values of the surviving fractions $s_{lb}(^{10}\mathrm{Be})$, $s_{lb}(^{26}\mathrm{Al})$, $s_{lb}(^{36}\mathrm{Cl})$, $s_{lb}(^{14}\mathrm{C})$ are indicated under the assumptions that the diffusion and the leaky box models are fitted to the observed $s_{lb}(^{10}\mathrm{Be})$ and the B/C ratio. The differences between models are rather small since the ratios of respective decay times to destruction times are not very different. The case of ^{36}Cl looks promising in connection with the Ulysses and ACE missions. Also, the measurements of even a single radioactive isotope, for example ^{10}Be, in an extended energy range is very useful because the Lorenz factor changes the decay time of relativistically moving isotope. For the proposed ISOMAX experiment at about 4 GeV/nucleon (Streitmatter et al. 1993) the diffusion model (resp. the leaky box model) predicts $s(^{10}\mathrm{Be}) = 0.45$ (resp. 0.58) assuming that $s(^{10}\mathrm{Be}) = 0.21$ at 0.4 Gev/nucleon.

4. Conclusion

It is clear from Eqs. (12)-(13) that the surviving fraction of rapidly decaying radioactive secondary isotopes in cosmic rays is determined by the value of the density of the interstellar gas in the sphere with radius of the order of $(Dt)^{1/2}$ where from the isotope can reach us without significant decay. This result generalizes the conclusion made in the frameworks of the homogeneous leaky box model that the measurement of the content of radioactive secondary nuclei is actually the experiment on the determination of the gas density in the system once the abundance of stable secondaries is known. This is also in agreement with the previous studies of the diffusion models with simplified gas distribution when different constant gas densities in the disk and in the halo were assumed. Our present investigation takes into account an actual complicated distribution of the local interstellar gas.

At given gas distribution, the abundance of radioactive secondaries at low energies ^{10}Be, ^{26}Al, ^{36}Cl,^{14}C, offers information on cosmic ray diffusion coefficient in the vicinity of a few hundred parsecs around the solar system. The surviving fraction of ^{10}Be $s=0.21\pm 0.04$ allows to find the value of the cosmic rays diffusion coefficient D = (3.4 (+2.8, -1.4)) 10^{28} cm^2/s at energy 0.4 Gev/nucleon in the interstellar medium. Under the additional assumption that the diffusion coefficient is constant over the entire Galaxy and that cosmic rays escape freely at some distance H above the galactic plane one can determine the value of H = (4.9(+4, -2)) kpc which is the size of the cosmic ray halo in this model and the time of cosmic ray diffusion from the Galaxy is $H^2/2D$ = (1.1 (+1.2, -0.5)) 10^8 yr. The leaky-box gas density which corresponds to the ^{10}Be abundance indicated above is equal to n_{lb} = (0.29 ($\pm$0.07)) nucleon/cm and the leaky-box leakage time is equal to $X/(vn_{lb})$ = (3.3 (+1.1, -0.6))10^7 yr which is small compared with the prediction of the diffusion model.

Some essential simplifying assumptions were made in the present work: isotropic cosmic ray diffusion and a constant primary cosmic ray density within a few hundred parsecs around the Sun, together with a steady state conditions in the local interstellar medium on a time scale of 10^7 years. The validity of some of these assumptions may be clarified in future studies of radioactive isotopes in cosmic rays.

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