COSMIC-RAY LIFETIME IN THE GALAXY: EXPERIMENTAL RESULTS AND MODELS

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Abstract. The containment lifetime of the cosmic radiation is a crucial parameter in the investigation of the cosmic-ray origin and plays an important role in the dynamics of the Galaxy. The separation of the cosmic-ray Be isotopes achieved by two satellite experiments is considered in this paper, and from the measured isotopic ratio between the radioactive ^{10}Be (half-life = 1.5×10^6 yr) and the stable ^{9}Be, it is deduced that the cosmic rays propagate through matter with an average density of 0.24 ± 0.07 atoms cm^{-3}, lower than the traditionally quoted average density in the galactic disk of 1 atom cm^{-3}.

This paper reviews the implications of this result for the cosmic-ray age mainly in the context of two models of confinement and propagation: the homogeneous model, normally identified with confinement to the galactic gaseous disk, and a diffusion model in which the cosmic rays extend into a galactic halo. The propagation calculations use:

(1) a newly deduced cosmic-ray pathlength distribution,

(2) a self-consistent model of solar modulation,

(3) an up-to-date set of fragmentation cross sections.

The satellite results and their implications are compared with the information on the cosmic-ray age derived from other cosmic-ray radioactive nuclei and the measured differential energy spectrum of high-energy electrons.

It is a major conclusion of this paper that in a homogeneous model the cosmic-ray age is 15(+ 7, − 4) million years, i.e., about a factor 4 longer than early estimates based on the abundances of the light nuclei Li, Be, and B and a nominal interstellar density of 1 atom cm^{-3}. The lifetime is even longer when the satellite results are applied to a diffusion halo model.

The deduced traversed matter density, together with other astrophysical considerations, suggest the population of a galactic halo by the cosmic rays.

1. Introduction

The residence time of the cosmic radiation, propagating through the confining galactic magnetic fields, is a crucial parameter for understanding not only its origin but also the dynamics of the Galaxy. The determination of the cosmic-ray age gives information on the cosmic-ray production rate. It also gives information on how the cosmic rays are distributed in the Galaxy, e.g., whether they are confined to the gaseous galactic disk or are extending throughout a galactic halo.

This paper is a summary review of the efforts, to date, to determine this age and its implications for models of cosmic-ray confinement and propagation.

Following the discovery of heavy nuclei in the cosmic rays, Bradt and Peters (1948) and others pointed out that the cosmic rays Li, Be, and B were absent at the cosmic-ray source and were secondary elements totally produced by spallation of primary cosmic rays interacting during propagation with interstellar matter. They estimated that this

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production required approximately 5 g cm^{-2} of interstellar matter. Under the assumption of an interstellar density of 1 atom cm^{-3} this thickness of interstellar matter means that the cosmic-ray age is about 3 million years.

As early as 1958 Hayakawa *et al.* (1958), realized that the abundance of a radioactive secondary isotope could be used as a 'clock' to determine independently the cosmic-ray age. Three constraints are required for a suitable clock: (1) the lifetime of the radioactive isotope should be comparable to the estimated cosmic-ray age, (2) the isotope must be a pure secondary, i.e., must be absent in the cosmic-ray source, and (3) it should be possible to calculate accurately the rate of production during interstellar propagation.

The ^{10}Be isotope, with a half life of 1.5×10^6 yr and with production cross sections extensively studied in the laboratory, fulfills well the above conditions. Other cosmic-ray radioactive isotopes, and their half lives, less suitable to the determination of the cosmic-ray age, are: ^{26}Al(8.7×10^5 yr, excluding electron capture), ^{36}Cl(3×10^5 yr), and ^{54}Mn (about 2×10^6 yr).

High-energy cosmic-ray electrons have a 'radiative lifetime' determined by their energy losses through synchrotron radiation and inverse Compton collisions. The differential energy spectrum of high-energy electrons depends on the relative values of the radiative and escape lifetimes and, therefore, the electron spectral shape can convey information on the electron lifetime in the Galaxy. We will consider this information later in this paper.

In order to determine the cosmic-ray age from ^{10}Be measurements, the cosmic-ray experiments need good isotopic resolution, which in turn requires intrinsic mass resolution, efficient background rejection and good statistics. At present the best isotopic resolution is achieved with instruments which measure stopping cosmic-ray particles (Simpson, 1983) which implies particles with energy below 1 GeV nucl^{-1}. The best background rejection is that of the satellite measurements where there is no contamination of secondary particles produced in the Earth atmosphere like in the balloon experiments. Satellite measurements can also provide good statistics because of very long measuring times that often span several years of observation.

Two models of cosmic-ray propagation are considered in detail in this paper: (a) a model of confinement of the cosmic rays to the gaseous disk of the Galaxy, and (b) a model in which the cosmic rays leave the disk and populate a galactic halo. Section 2 reviews the measurements. Section 3 reviews the interpretation in terms of an empirically determined pathlength distribution, a formerly developed model of solar modulation and the above propagation models. Section 4 considers briefly models with a galactic wind. Section 5, other radioactive 'clocks' and Section 6, the cosmic-ray electron lifetime derived from the high-energy electron differential energy spectrum.

2. The Measurements

Measurements claiming isotopic resolution of Be cosmic rays were first reported in 1975. Table I lists the most significant measurements, to date, of the isotopic composition of cosmic-ray Be from which the relative abundance of surviving ^{10}Be can be used

TABLE I

Comparison of beryllium measurements by different experiments

Item	Hagen *et al.* (1977)	Webber *et al.* (1977)	Buffington *et al.* (1978)	Webber and Kish (1979)	Garcia-Munoz *et al.*, (1975, 1977a, 1981c)	Wiedenbeck and Greiner (1980)
Experiment	Balloon	Balloon	Balloon	Balloon	Satellites IMP 7, 8	Satellite ISEE-3
Date	15 Aug., 1973	Summer, 1974 (two flights)	28–29 May, 1977	Sept. 1979		
Exposure time	23 hours		About 7 hours	About 50 hours	Feb. 1973– May, 1980	Aug. 1978– Aug. 1979
Atmospheric Depth (g cm^{-2})	3.5–5.0	2.8	5.9	3.3		
Analysis method	Total energy and range	Partial and residual energy loss	Mag. rigidity and partial energy loss	Partial and residual energy loss	Partial and residual energy loss	Partial and residual energy loss
Energy interval (MeV $nucl^{-1}$)	161–416	145–301	175–640	200–406	31–151	60–185
Number of events	303	222	236	350	906	345
Mass resolution (σ, amu)	0.42	0.32	0.3	0.33	0.25[a]	0.15

[a] For a subset of events.

to determine the cosmic-ray age. All of them have been carried out at energies below 1 GeV $nucl^{-1}$. Four of these measurements were performed in balloon flights and two aboard Earth satellites.

Propagation calculations show that even if ^{10}Be were a stable nuclide the amount of ^{10}Be expected in these measurements would not be greather than 20% of the total element. Therefore, a good separation of the three isotopes requires not only an adequate mass resolving power of the instrument but also an efficient and accurate background rejection. A major difficulty of the balloon Be isotope measurements is the correct separation of the cosmic-ray Be signal from the secondary Be produced in the residual atmosphere overlying the balloon at measurement altitude which, as can be seen in

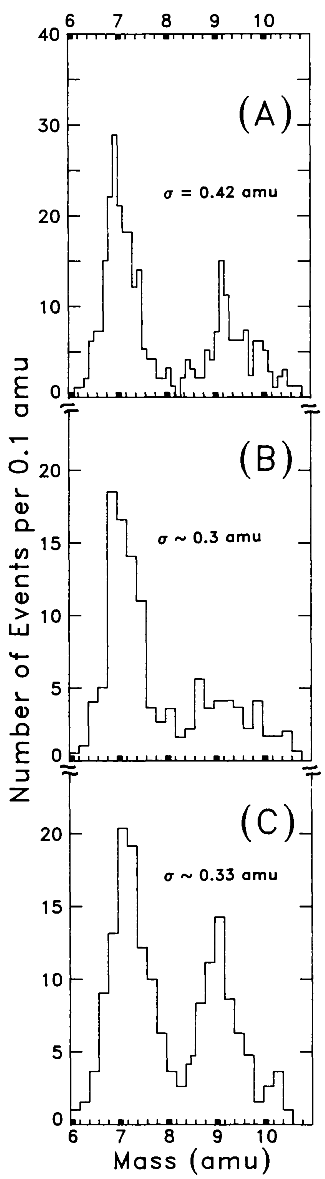

Fig. 1. Cosmic-ray Be mass histograms obtained in the balloon experiments together with the mass resolution claimed by their authors. (A) Hagen *et al.* (1977); (B) Buffington *et al.* (1978); (C) Webber and Kish (1979).

Table I, is from 3 to 6 g cm^{-2} of atmospheric depth. This ^{10}Be secondary contribution is usually a high fraction of the cosmic-ray signal itself.

Figure 1 shows the Be mass histograms resulting from the balloon measurements, together with the mass resolution claimed by their authors.

The satellite measurements are free from the perturbations of the Earth atmosphere. However, the satellite instruments have much smaller geometrical factors and, in order to obtain good statistics a very long collection time is needed, during which detectors and associated electronics may experience drifts of some of their characteristics. A correction of these drifts may be necessary in the data analysis. The University of Chicago measurements on the IMP satellites had the longest exposure time and, during the second part, 1976–1980, of the measuring period, small shifts, less than 5% in pulse

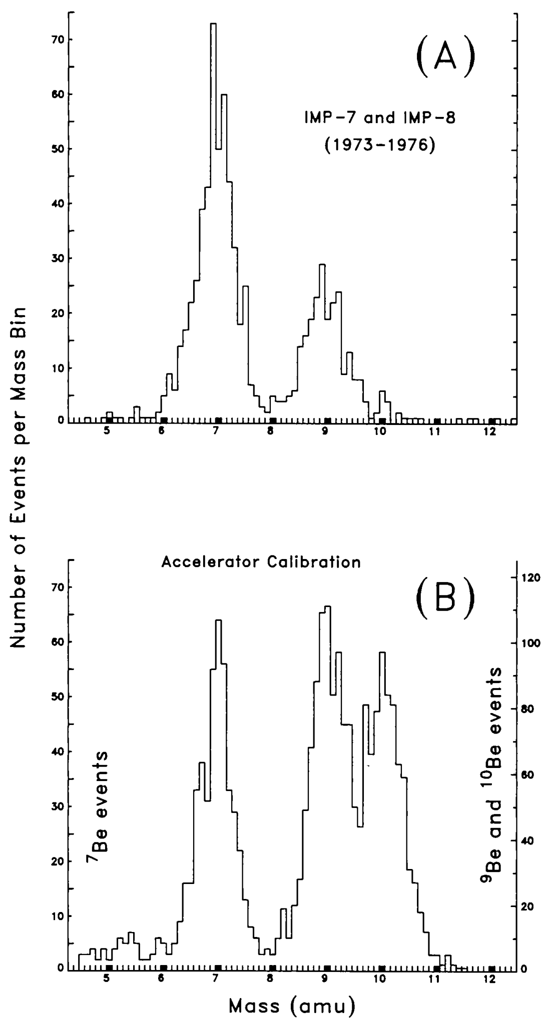

Fig. 2. Comparison of the Be mass histograms obtained: (A) with flight data from the IMP 7/8 satellite experiments, and (B) with data from the calibration of the IMP backup telescope at the Bevalac accelerator of the Lawrence Berkeley Laboratory, using individual Be isotopic beams.

height amplitude, were observed in the IMP-8 instrument response. Consequently, careful drift corrections were applied to the data (Garcia-Munoz *et al.*, 1981c).

In order to determine unambiguously the mass resolution of the University of Chicago cosmic-ray telescope an identical back-up instrument was calibrated at the Bevalac accelerator of the Lawrence Berkeley Laboratory with individual Be isotopic beams in the energy range of the measured Be cosmic rays. This calibration demonstrated clearly the instrument ability to separate the Be isotopes. Figure 2 shows a comparison of the Be mass histogram derived from the flight data (Figure 2(a)) with the Be histogram obtained in the Bevalac calibration (Figure 2(b)).

Figures 3 and 4 show the isotopic mass histograms obtained in the satellite cosmic-ray measurements. Figure 3(a) shows the histogram from the University of Chicago IMP 7/8 measurements which corresponds to a high mass resolution subset of the total data set (Garcia-Munoz *et al.*, 1981c). The curves of Figure 3(b) are a maximum likelihood fit to this histogram, giving a mass resolution $\sigma = 0.25$ amu. Figure 4 shows the mass histogram from the ISEE-3 measurement. The inset in this figure emphasizes the complete separation of the two contiguous isotopes ^{10}Be and ^{9}Be.

Because of their higher mass resolution and the much smaller difficulty in making an accurate background rejection we will consider here only the results of the two satellite measurements and will use a combination of these results in the derivation of the cosmic-ray age in models of cosmic-ray confinement and propagation. Table II gives the Be isotope fractions measured by the two satellite measurements.

Detailed reports on the measurements, both in balloons and satellites, can be found in the references given in Table I.

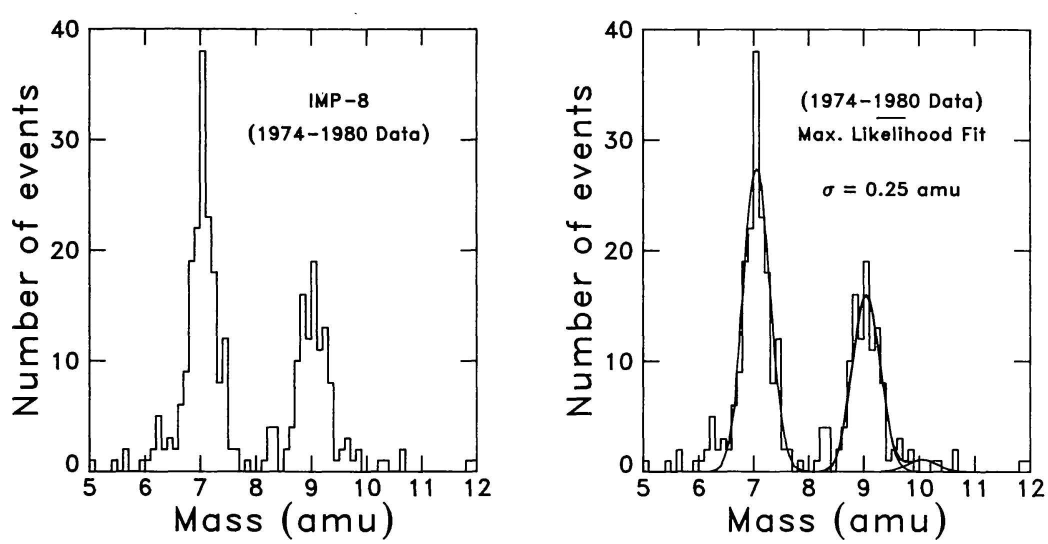

Fig. 3. Mass histogram of cosmic-ray Be obtained in the IMP 7/8 satellite experiments. This histogram is a high mass resolution subset of the total data (see Garcia-Munoz *et al.*, 1981b). The curves in the right part of the figure are maximum likelihood fits of the same data subset.

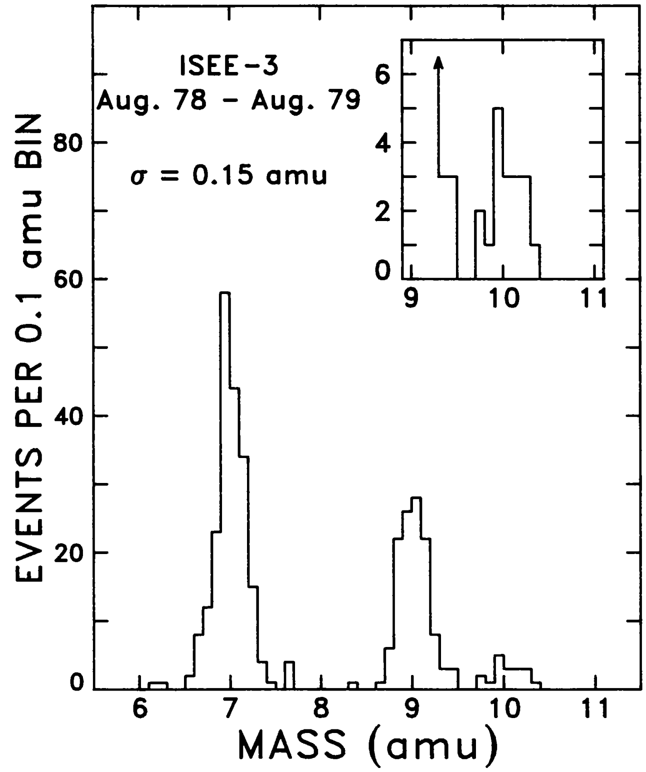

Fig. 4. Cosmic-ray Be mass histogram obtained in the ISEE-3 satellite experiment. The inset emphasizes that the instrument mass resolution can separate the ^{10}Be and ^{9}Be peaks from each other.

TABLE II

Be isotopic fractions from the satellite measurements

Isotope fraction	ISEE-3 (60–185 MeV/n)	IMP 7/8 (46–135 MeV/n)
^{7}Be/Be	0.546 ± 0.029	0.585 ± 0.026
^{9}Be/Be	0.390 ± 0.029	0.376 ± 0.025
^{10}Be/Be	0.064 ± 0.015	0.039 ± 0.014

3. Interpretation of the Results

In order to derive the cosmic-ray age from the ^{10}Be/^{9}Be ratio measured at Earth orbit, the interpretation of the results requires:

(1) A knowledge of the shape of the cosmic-ray pathlength distribution (PLD), and its energy dependence.

(2) A model of solar modulation, because the measurements have been carried out at relatively low energies and over varying levels of solar modulation.

(3) A model of the cosmic-ray confinement and propagation.

3.1. The cosmic-ray pathlength distribution

If it is assumed that all the primaries traverse the same amount of interstellar material (slab PLD) (see reviews by Simpson, 1983; and by Shapiro and Silberberg, 1970), then it is not possible to explain simultaneously the observed abundances and spectra of the secondary cosmic-rays (Li, Be, B on one hand and the sub-Fe elements Sc to Mn on the other) by spallation of the primary cosmic rays during interstellar propagation. Various alternatives to explain the early measurements were considered including that of Cowsik *et al.* (1967), who showed that, within the accuracy of the cosmic-ray abundances available at the time, this difficulty could be removed by using a simple exponential function for the pathlength distribution.

Extensive measurements of the cosmic-ray abundances as a function of the energy showed that at energies greater than a few GeV/n the secondary-to-primary ratios decrease with increasing energy. This fact has been interpeted as a consequence of the decrease of the amount of matter traversed by the cosmic radiation (Juliusson *et al.*, 1972; Smith *et al.*, 1973). Also, more accurate determinations of the relative abundances led to the conclusion that the PLD is not a pure exponential but it is actually an exponential distribution deficient in short pathlengths ('truncated' PLD), (e.g., Shapiro and Silberberg, 1970; Garcia-Munoz *et al.*, 1977b).

Garcia-Munoz *et al.* (1979a, 1981a, 1981b, 1987), considering the experimental evidence presently available and the effects of solar modulation on the cosmic-ray abundances measured at the orbit of Earth, have carried out a comprehensive study of the shape and the energy dependence of the cosmic-ray PLD. They have concluded that the PLD mean pathlength not only decreases with increasing energy above a few GeV nucl^{-1} but it also decreases with decreasing energy below about 1 GeV nucl^{-1}. Furthermore, the PLD is deficient in short pathlengths, i.e., it is truncated. This truncation is energy dependent in such a way that it is zero at about 1 GeV nucl^{-1} and increases with decreasing energy. A detailed analysis appears in Garcia-Munoz *et al.* (1987). These studies demonstrate that a propagation calculation using a PLD with the above characteristics can reproduce simultaneously the boron/carbon and the sub-iron/iron ratios over the full range of energy covered by the existing experimental data. We use this PLD and its energy-dependence in the propagation calculations of this work.

3.2. Solar modulation

Solar modulation significantly modifies the intensity and the energy spectra of the low-energy cosmic rays penetrating the heliosphere. Therefore, in order to compare the satellite measurements of Table II with the propagation calculations, it is necessary to calculate the effects of solar modulation on the elemental abundance and isotopic composition of the cosmic-ray Be arriving to the nearby interstellar space.

We have calculated the effects of solar modulation using a modulation model in which the heliosphere has spherical symmetry and the physical processes responsible for the modulation, which are assumed to be in equilibrium, are convection, diffusion, and adiabatic deceleration (Parker, 1965). Drifts due to interplanetary magnetic field gradients and curvatures are not included in the model. These processes are represented by a Fokker–Planck equation in which the parameters are the solar wind velocity (assumed to be a constant), the radius of the modulation region (taken as 50 AU) and the diffusion coefficient. The diffusion coefficient, together with the differential energy spectra in the local interstellar space as a boundary condition, determines the modulation strength or modulation depth.

The nucleonic (protons, helium, and heavier elements) differential energy spectra in the local interstellar space are determined by (1) comparing the cosmic-ray differential energy-electron spectrum measured at Earth, with the electron spectrum in the local interstellar space as determined from synchrotron radiation (Cummings *et al.*, 1973) and (2) using this modulation level to demodulate the nucleonic differential energy spectra measured at Earth orbit, to obtain the spectra in the local interstellar space.

At any other time of the solar modulation cycle the self-consistency of the model demands that, using the local interstellar spectra so determined, a single empirical diffusion coefficient (chosen so as to be consistent with other experimentally determined modulation constraints) gives a good simultaneous fit to the electron, proton, helium, and heavier nuclei spectra measured at that time.

The modulation strength or 'modulation depth', at a heliospheric radius r, is given by the modulation parameter (Gleeson and Axford, 1968),

$$\phi = \tfrac{1}{3} \int_r^R (V(r')/\kappa(r'))\, dr' ,$$

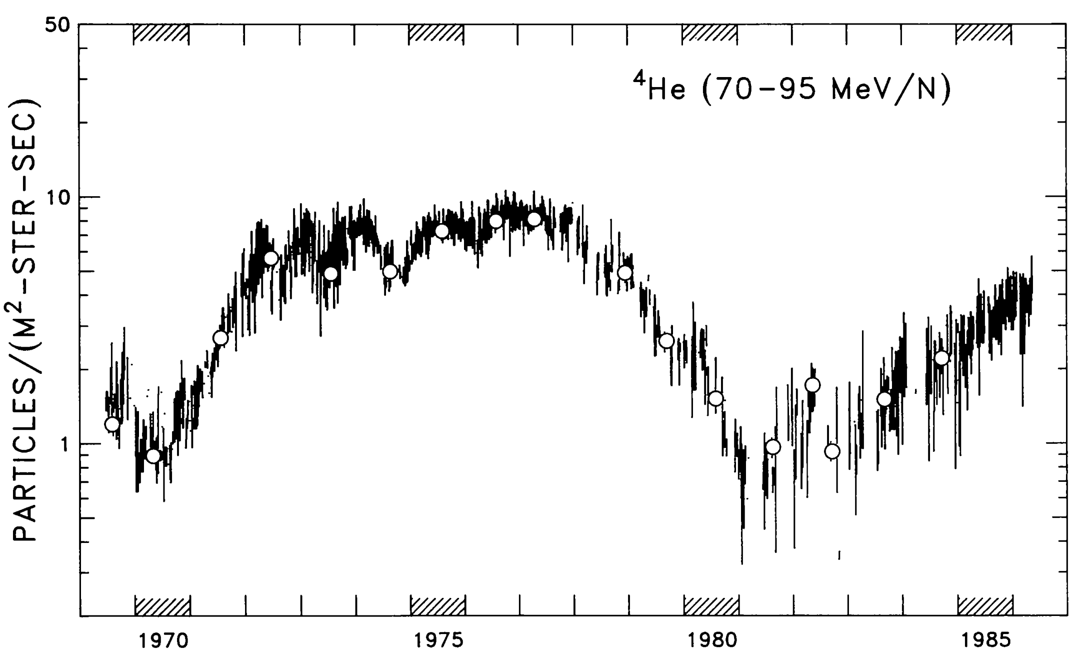

Fig. 5. Time dependence of the 70–95 MeV nucl^{-1} flux of galactic cosmic-ray ^{4}He as measured by the University of Chicago IMP 5/6/8 satellite experiments, reflecting the variation of the solar modulation level during the times of the Be cosmic-ray measurements. The curve with spikes represents 1-day averages and has been normalized to discrete measurements of differential energy spectra represented by circles.

where $V(r')$ is the solar wind velocity, $\kappa(r')$ the radial part of diffusion coefficient, and R the radius of the heliosphere. The average energy loss that particles with charge Ze experience in penetrating to radius r is given by

$$\Phi = |Ze| \, \phi(r) .$$

Figure 5 is a plot of the time variation of the 70–95 MeV nucl^{-1} ^{4}He cosmic-ray flux as measured by the University of Chicago cosmic-ray telescopes on board the satellites IMP 5, 6, and 8, from 1969 to 1986. The ^{4}He intensity variations reflect the changes in the modulation depth as the solar cycle progresses from the 1970 solar maximum, through the 1972–1977 solar minimum plateau and through the 1981 maximum.

Evenson *et al.* (1983), and Garcia-Munoz *et al.* (1985) have shown that the above modulation model yield results which are in remarkable good agreement with the cosmic-ray proton and helium spectra measured from 1970 to 1984.

3.3 Models of cosmic-ray confinement and propagation

In this section we examine the values of the cosmic-ray lifetime which are implied, in the context of some models of cosmic-ray confinement and propagation, by the measured ^{10}Be/^{9}Be ratio at 1 AU and the PLD characteristics and the modulation model described above.

3.3.1. *The 'Leaky Box' Homogeneous Model*

We will consider first the widely used homogeneous model ('leaky box' model), of cosmic-ray confinement and propagation, in which the propagation and the source volumes coincide and are homogeneous.

Physically the homogeneous model is commonly identified with the confinement of the cosmic rays and the cosmic-ray sources to the gaseous disk of the Galaxy. The empirically found exponential (or near-exponential) distribution of cosmic-ray pathlengths is often interpreted as a consequence of an assumed frequent visiting by the cosmic rays of the disk boundaries where they have at all times a small probability of leaking out of the Galaxy ('leaky box').

The University of Chicago Be measurements were carried out mostly during 1974–1978 (see Figure 5) and, in the modulation model of Evenson *et al.* (1983), the estimated average modulation depth during this period was 476 MV (cf. Garcia-Munoz *et al.*, 1981c), while during the ISEE-3 measurements, performed in 1978–1979, the average modulation depth was ϕ = 685 MV.

We have calculated the cosmic-ray propagation in the context of the homogeneous model, using the propagation code, the pathlength distribution deduced in Garcia-Munoz *et al.* (1979a, 1981a, b, 1987) and the solar modulation and modulation depths outlined above, computing the ^{10}Be/^{9}Be ratio for different values of the interstellar density as a parameter.

Complete specifications of the propagation calculations are given in Garcia-Munoz *et al.* (1987) and Guzik *et al.* (1985). Some of the most important characteristics are given in Table III.

TABLE III

The propagation calculations

Item	Comment
Method	Weighted slab technique
Propagated species	96 long lived isotopes from ^{4}He to ^{64}Ni
Radioactive isotopes	β^+, β^-, electron capture, treated explicitly
Source abundances:	
Elements	(from Dwyer *et al.*, 1981)
Isotopes	Solar system (Cameron, 1981), except Ne (see Garcia-Munoz *et al.*, 1979b)
Source spectra	$(T + 400)^{-2.6}$
Interstellar interaction:	
(1) Interstellar matter composition	Solar system (Cameron, 1981)
(2) Energy loss	Ionization energy loss included
(3) Cross sections	
(a) Partial	Semi-empirical, modified with experimental data
(b) Total	(Garcia-Munoz *et al.*, 1987)

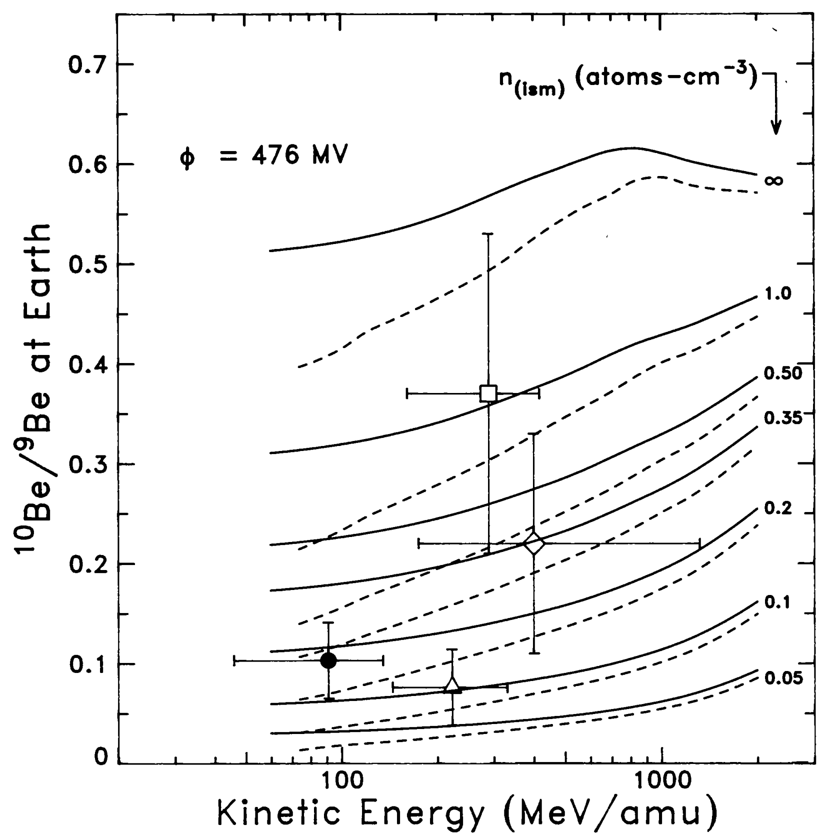

Fig. 6. Comparison of the ratios ^{10}Be/^{9}Be measured by the balloon and the IMP satellite experiments at the times of minimum or near minimum solar modulation, $\phi = 476$ MV, with the energy dependence of the ratios predicted by propagation and modulation calculation, where the interstellar matter density is a parameter. Solid curves: ratios at Earth orbit. Dashed curves: ratios at the local interstellar space. Experimental points: filled circle: Garcia-Munoz *et al.*, 1981a; triangle: Webber *et al.*, 1977; Webber and Kish, 1979; square: Hagen *et al.*, 1977; diamond: Buffington *et al.*, 1978.

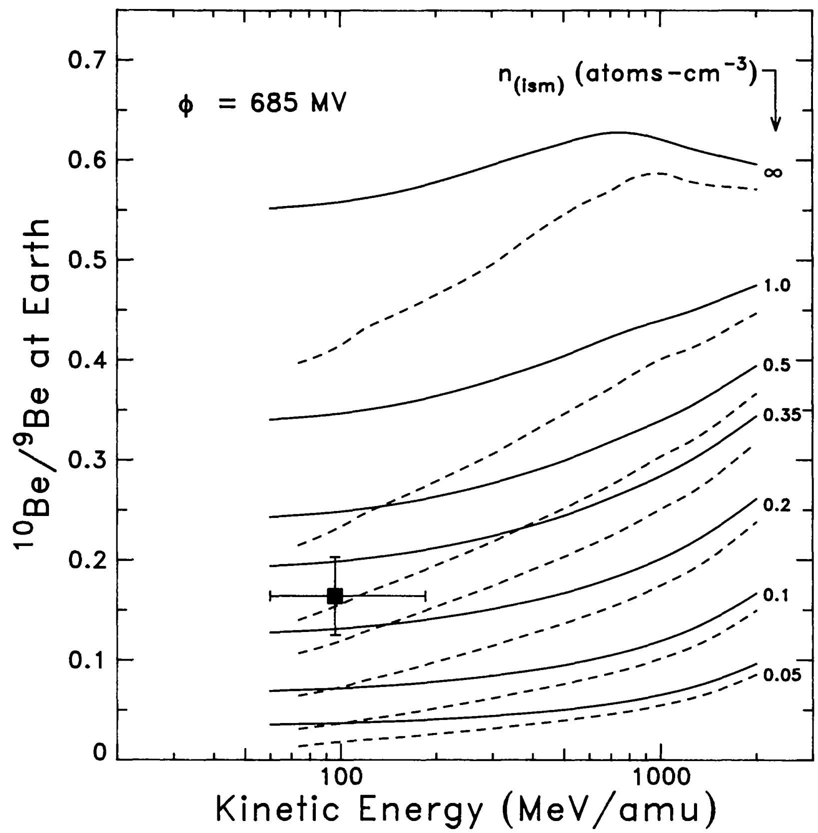

Fig. 7. Comparison of the ratio $^{10}Be/^{9}Be$ measured by the ISEE satellite experiment at an average modulation level ϕ = 685 MV, with predicted ratios at Earth orbit (solid curves) and at the local interstellar space (dashed curves).

The results of these calculations are shown in Figures 6 and 7. In Figure 6 the dashed curves are the predicted ratios in the vicinity of the solar system (modulation depth $\phi = 0$), and the solid curves the predicted ratios at Earth orbit for a modulation depth ϕ = 476 MV. These calculations are compared in the figure with the $^{10}Be/^{9}Be$ ratios measured by the University of Chicago IMP 7/8 cosmic-ray telescopes at times of this average modulation depth, and with the balloon ratios measured at very similar modulation depths.

Figure 7 shows calculations similar to those of Figure 6 but with an average modulation depth of ϕ = 685 MV corresponding to the period of the ISEE-3 satellite measurement, and compared to the ratio measured by this experiment.

Comparison of the experimental $^{10}Be/^{9}Be$ ratios with the calculations gives the average interstellar densities through which the parent nuclei of the radioactive clock ^{10}Be – mainly carbon and oxygen – have propagated. These interstellar densities for the two satellite experiments are given in Table IV. Weighting the individual satellite results by the experimental mass resolution of each experiment, the two satellite experiments together give an average interstellar density of 0.24 ± 0.07 atom cm^{-3}.

It is seen that the two satellite values of the interstellar density are only one standard deviation apart. Note that even under the extreme assumption that solar modulation was

TABLE IV

Interstellar density deduced from the satellite measurements (atoms cm^{-3})

Experiment	Modulation depth ϕ (MV)		
	476	685	0
IMP 7, 8	$0.17^{+0.09}_{-0.06}$	–	$0.31^{+0.15}_{-0.12}$
ISEE-3	–	$0.27^{+0.10}_{-0.08}$	$0.55^{+0.24}_{-0.17}$

vanishingly small during the measurement, the resulting average interstellar density would be 0.49 ± 0.13, still well below the canonical interstellar density of 1 atom cm^{-3}.

There are, however, compelling indications that, even at times of solar minimum like the 1972–1978 period (see Figure 5) solar modulation had strongly depressed the cosmic-ray intensity arriving at the orbit of Earth. Garcia-Munoz *et al.* (1977a) have detailed a list of arguments in favor of the existence of large modulation effects, even at times of minimum solar activity. Independent evidence of strong solar modulation is provided by the new measurements by the deep space probes Pioneer 10, 11, and Voyager 1, 2. For instance, it has been observed that, during the recent solar maximum, the relative decrease of the transient depressions of cosmic-ray intensity at low energy measured at 1 AU by IMP 8 and, a few months later, by Pioneer 10 beyond 30 AU, was as strong at the position of Pioneer 10 as at 1 AU. This fact indicates that the boundary of the modulation region was well beyond Pioneer 10 heliocentric radius and that the local interstellar cosmic-ray intensity is substantially higher than the intensity observed at Earth.

According to our modulation model the cosmic-ray Be measured by the satellite experiments at the orbit of Earth had an average of 380 MeV $nucl^{-1}$ at the local interstellar space, before penetrating the heliosphere. At this energy our propagation calculations give a ^{10}Be 'surviving fraction' (i.e., the ratio between the observed ^{10}Be and the ^{10}Be that would have been observed if ^{10}Be were a stable nuclide) of 27%. The study carried out by Garcia-Munoz *et al.* (1979a, 1981a, b, 1987) on the shape and energy-dependence of the pathlength distribution shows that at this energy the cosmic rays have traversed a mean pathlength of 5 g cm^{-2}. In the homogeneous model the cosmic-ray lifetime at this energy is simply the time it takes them to traverse this mean pathlength. Taking into account that these cosmic rays have gradually lost energy through ionization, the calculations give a lifetime of $15\ (+7,\ -4) \times 10^6$ yr.

It is seen that the interpretation of the satellite results in the context of the homogeneous model gives a value of the interstellar density clearly smaller than the average interstellar density of 0.8 to 1.1 hydrogen atom cm^{-3} observed in the vicinity of the solar system (Jenkins, 1976; Gordon and Burton, 1976). A possibility of reconciling these contradictory results and still keeping the cosmic rays confined to the galactic disk is to assume that the cosmic-ray propagation happens preferentially in 'tunnels' (Scott, 1975) of the coronal gaseous phase ($T \cong 5 \times 10^5$ K;

$n \cong 0.003$ atom cm^{-3}) produced by supernovae, that pervades 70 to 80% of the interstellar medium (McKee and Ostriker, 1977). Arguments against this assumption are: (1) theoretical considerations show that cosmic rays with energy greater than about 50 MeV nucl^{-1} penetrate the large, cold molecular interstellar clouds (Cesarsky and Volk, 1978), and (2) confinement of the cosmic rays to the coronal regions would result in predicted diffuse gamma-ray intensities smaller than observed and a lack of the reported correlation between diffuse gamma ray profiles and distribution of interstellar matter (Mayer-Hasselwander *et al.*, 1982).

3.3.2. *The Halo Diffusion Model*

An alternative model that would explain the small average interstellar density seen by the cosmic rays during propagation, is the diffusion halo model, in which the confinement region extends beyond the gaseous disk in a quasi-spherical volume ('halo') surrounding the disk, containing an extension of the galactic magnetic field and where the matter density is much smaller than that of the disk. The cosmic rays would diffuse in both, disk and halo, with the result that cosmic rays sampled near the Earth would have traversed a matter density that would be on average smaller than the disk density.

It was proposed in the early 1950's – see Stecker and Jones (1977), for references – that the observed high latitude nonthermal radio emission extends to a volume surrounding the galactic disk and that this radio halo is the consequence of a galactic corona containing gas, cosmic rays and magnetic field of sufficient strength to contain the cosmic rays.

The existence, characteristics, and in particular, dimensions, of the radio halo have been the subject of research and controversy since it was postulated, one of the latest investigation efforts being the search for radio halos in spiral galaxies observed edge-on. Ekers and Sancisi (1977), have reported an extensive radio halo around the galaxy NGC 4631. Although this observation seems to favour the existence of a halo in our Galaxy it should be noted that NGC 4631 differs substantially from our Galaxy.

A plausible line of argumentation in favor of the existence of a rather extensive halo of gas, magnetic field and cosmic rays, is resulting as a consequence of direct observations at high latitudes over the galactic disk, together with the emerging picture, during the last decade, of the nature of the violent interstellar medium. The early observations of high-velocity gas clouds at high galactic latitudes led to the postulation of the existence at these latitudes of hot coronal gas holding these clouds together (Spitzer, 1956). Savage and de Boer (1981), have reported observations of ultraviolet absorption lines measured with the IUE satellite, giving evidence of the existence, at several kiloparsecs from the gaseous disk, of ionized gas at moderate temperatures embedded in very high temperature coronal gas.

A coherent picture of these measurements together with the recent understanding of the nature of the interstellar medium, arises noting that, because the galactic disk is dynamically unstable due to the overwhelming pressure of the high temperature coronal gas in the disk, the coronal gas flows out of the disk forming a hot halo. Partial cooling of the outflowing gas in the halo space would produce the observed high latitude clouds that would fall back to the disk forming a 'galactic fountain' (Shapiro and Field, 1976). Because the galactic magnetic field is trapped in the coronal gas it will outflow also, dragging with it the cosmic rays.

In an alternate view, the gas is dragged out by the cosmic-ray pressure. The cosmic rays traveling through the magnetized plasma generate MHD waves which isotropize the cosmic rays and are damped by the thermal gas. As a consequence the cosmic rays are coupled to the gas and can, by themselves, drag the gas from the disk to the halo (Parker, 1968; Ipavich, 1975).

The temperature and density of the coronal gas and the cosmic-ray pressure at the edge of the disk may be high enough so that the streaming of cosmic rays out of the disk can produce a galactic wind. Depending upon the strength of this galactic wind it may result a quasi-static or a dynamical halo.

Prischep and Ptuskin (1975) and Ginzburg *et al.* (1980), have considered a quasi-static halo in a diffusion model in which the cosmic-ray sources are concentrated in the galactic disk and the cosmic rays populate both the disk and a galactic halo that extends several kiloparsecs away from the disk. They show that this halo diffusion model predicts, within the present accuracy of abundance and cross-section measurements, the same concentration of cosmic-ray stable secondary nuclei as the homogeneous model. However, its prediction of the cosmic-ray age from the measured abundance at Earth of a decaying cosmic-ray isotope may be very different from that of the homogeneous model. The simple physical reason is that in the diffusion model the cosmic-ray intensity is space coordinate dependent and the spatial distribution of a radioactive nuclide will depend on its decay lifetime. Therefore, a decaying nuclide will have its highest concentration near its sources in the galactic disk, while the homogeneous model assumes that the concentration of the nuclide over all the confinement volume is the same as measured in the disk. This fact gives for the cosmic rays a lifetime in the homogeneous model that is shorter than the lifetime in the diffusion halo model.

In the particular case of ^{10}Be, the radioactive lifetime can be considered as intermediate between the time of diffusion to the edge of the disk and the diffusion time to the halo boundary. In this case, using the halo model and averaging the disk density over the clock propagation volume gives the same average interstellar density deduced in the homogeneous model. Likewise, the mean pathlength of the homogeneous model, 5 g cm^{-2}, is obtained in the halo model from the fraction of the total lifetime that the cosmic rays spend in the disk.

Ginzburg *et al.* (1980) have analyzed a simplified, single dimensional diffusion halo model with the same diffusion coefficient for both, disk and halo propagation. Using 1 atom cm^{-3} for the average disk density, a disk semi-thickness of 100 parsec, and the above values of the average propagation density and mean pathlength deduced in the homogeneous model, this model gives the following parameters:

$$\text{diffusion coefficient} \cong 3 \times 10^{28}\ \text{cm}^2\ \text{s}^{-1}\,,$$

$$\text{halo semi-thickness} \cong 3\ \text{Kparsec}\,,$$

$$\text{cosmic-ray age} \cong 5 \times 10^{7}\ \text{yr}\,,$$

where the cosmic-ray age is simply the time it takes to the cosmic rays to diffuse out of the halo boundary.

4. Halo Models with a Galactic Wind

A model of a dynamical halo sustained by a galactic wind has been proposed by Jokipii (1976), who notes that the pressure of a cosmic-ray intensity similar to that of the galactic disk would disrupt a static halo. Jones (1979) explains the decrease of the mean pathlength with decreasing energy below about 1 GeV $nucl^{-1}$, deduced by Garcia-Munoz *et al.* (1979, 1981a, b, 1987) as a consequence of the predominance, at these energies, of convection over diffusion. Lerche and Schlickeiser (1981), have proposed to detect the existence of galactic winds in external galaxies by examining the nonthermal integral radio spectrum at relatively low frequencies. Further studies of the convective halo model have been carried out by Owens and Jokipii (1977a, b), Jones (1978), and Freedman *et al.* (1980). An overall conclusion is the wide indetermination of the model due to lack of information on the two key parameters, the convective velocity and the value and energy dependence of the diffusion coefficient.

Stecker and Jones (1977), noting that the disk longitudinal distribution of cosmic-ray intensity inferred from the observed gamma-ray galactic profiles shows considerable non-uniformity, rule-out models with a halo greater than 3 Kparsec because lateral diffusion in the halo would smooth out the observed cosmic-ray inhomogeneities in the disk. Owens and Jokipii (1977a) calculate that with isotropic diffusion in a 5 Kparsec halo, disk cosmic ray inhomogeneities of 1 Kparsec scale would be attenuated by a factor 4. However, they argue that because the dragging of the magnetic field from the disk to the halo must produce a halo magnetic field that is substantially perpendicular to the disk, lateral diffusion must be largely inhibited and this will reduce the attenuation of lateral inhomogeneities.

It is to be noted that compared with the diffusion model, a galactic wind model giving the same composition of stable and radioactive nuclides will give a larger halo (Ginzburg *et al.*, 1980).

5. Other Radioactive 'Clocks'

From the other cosmic-ray radioactive nuclides mentioned at the beginning of this paper, that can be used as clocks to determine the cosmic-ray age, ^{26}Al (half life = 8.7×10^5 yr) is, after ^{10}Be, the most experimentally accessible to isotopic separation. Wiedenbeck (1983) has reported the measurement of the isotopic composition of cosmic-ray Al in the energy range 120–300 Mev $nucl^{-1}$ with the same experiment on the ISEE-3 satellite used for the isotopic Be measurement (Wiedenbeck and Greiner, 1980). From the measured ratio ^{26}Al/^{27}Al he obtains, using the leaky box model, a cosmic-ray age consistent with the age derived from ^{10}Be.

Finally another radioactive isotope with a half life appropriate for the determination of the cosmic-ray age would be ^{54}Mn. However, the ^{54}Mn half life has not been accurately measured and the value reported is only a theoretical estimate. Furthermore, the experimental separation of the Mn isotopes is much more difficult than that of the Be or Al isotopes. Koch *et al.* (1981) have measured the energy dependence of the Mn/Fe ratio and tried tentatively to use the sensitivity of the ratio to the decay of ^{54}Mn in order to determine the cosmic-ray age. They conclude that firm results must await accurate measurements of both the ^{54}Mn radioactive half life and the Mn isotopic composition.

6. Cosmic-Ray Electron Lifetime

The differential energy spectrum of high-energy cosmic-ray electrons contains information on their acceleration and propagation. High-energy electrons lose energy mainly by synchrotron radiation and inverse Compton collisions. This energy loss, which is proportional to the square of the electron energy, determines the electron 'radiative lifetime'.

The relative values of this radiative lifetime and the time of leakage out of the Galaxy in the homogeneous model, or the time of diffusion to the halo boundary in the halo diffusion model, are the main determinant of the calculated high-energy electron spectral shape. Therefore, the electron spectrum can convey information on the age of the electron cosmic rays, and by association, of the nucleonic cosmic-ray component.

The measurement of the high-energy cosmic-ray electron spectrum is a difficult task and the results reported by different experimenters have shown in the past rather poor agreement (see Figure 1 in Tang, 1984, for a comparison of several results up to 1984). Considering the results of measurements carried out at the University of Chicago (Prince, 1979; Tang, 1984) using transition-radiation detectors capable of good background rejection, it is found that the electron spectrum shows a change of slope from -2.65 to about -3.5 in the 10–40 GeV energy interval. The earlier measurements by Meegan and Earl (1975) agree well with the Chicago results.

Interpreting this spectral shape in the context of the homogeneous model it is found that if the high-energy cosmic-ray leakage lifetime is energy-dependent (as can be inferred from experimental evidence in the case of the nucleonic component), the cosmic-ray age at 1 GeV is larger than 10^7 years, in agreement with the ^{10}Be result. It should be noted that Tang (1984) finds that propagation calculations which assume that the high-energy lifetime is energy dependent give a poor fit to his data.

Owens and Jokipii (1977b) have studied the propagation of electron cosmic rays in a convective halo diffusion model using a Monte-Carlo method. They have considered specific model parameters which are consistent with the nucleonic cosmic-ray lifetime derived from the ^{10}Be abundance. Their model gives a spectral form which is qualitatively consistent with the measurements and, in the particular case of diffusion dominated propagation, gives a cosmic-ray age of about 70 million years. The distribution of cosmic-ray electrons in the halo depends on the relative value of the radiative and escape lifetimes. If the escape lifetime is shorter than the radiative lifetime the latitudinal distribution of electrons will be similar to that of the nuclei. If the radiative lifetime is smaller than the escape time, i.e., at very high energy, the relative concentration of electrons will be higher near the disk. Because the radiative energy losses increase with energy, high-energy electrons will not propagate very far from the disk, and a radio halo will be smaller the higher the frequencies at which is observed. And because cosmic-ray nuclei do not experience strong radiative losses a large nucleonic halo can coexist with a thin high-frequency radio halo.

7. Conclusions

The cosmic-ray ^{10}Be measurements have determined reliable values for the average matter density through which low and intermediate energy nuclei propagate in the Galaxy. These measurements have been achieved mainly through the development of solid state telescopes (Simpson, 1983) with sufficient resolution to separate the isotopes of the light elements.

Measurements carried out by experiments on the IMP 7/8 and ISEE-3 satellites during the 1973–1979 time period of solar minimum and near solar minimum modulation, have yielded ^{10}Be/^{9}Be ratios that lead to consistent values of the density of the matter traversed by the low-energy cosmic rays. This density has been applied to the calculation of the cosmic-ray age in the context of two models of cosmic-ray propagation and confinement: a 'leaky box' model where the cosmic rays and their sources are homogeneously distributed and confined to the galactic disk and a diffusion halo model where the cosmic rays have their sources in the disk but populate the disk and a halo volume around the disk. The calculation utilizes the results of previous work by the authors on (1) an empirical determination of the cosmic-ray pathlength distribution and its energy dependence, and (2) a modulation model reproducing the major features of the solar modulation during the period of the Be measurements. The major conclusion of this paper is that in a homogeneous model the cosmic-ray age is longer, by about a factor 4, than the early estimates based on the light nuclei abundance and a nominal interstellar density of 1 atom cm^{-3}. As shown by Ginzburg *et al.* (1980), the lifetime is even longer when our result is applied to a diffusion halo model. The deduced traversed matter density, together with other astrophysical considerations, suggest the population of a galactic halo by the cosmic rays.

From two other radioactive isotopes, ^{26}Al gives a cosmic-ray age consistent with the value derived from ^{10}Be, while further work is needed to use ^{54}Mn as a clock.

Finally we have briefly considered the information on the age of the cosmic-ray electrons that can be inferred from the differential energy spectrum of high-energy electrons, whose shape is determined mainly by the relative values of the escape and radiative lifetimes. This spectrum is rather poorly known at energies of 100 GeV and above. Assuming that the escape lifetimes of high-energy electrons and nuclei vary similarly with energy, the electron age is in agreement with the lifetime of the nucleonic component.

It will be noted that in this work we have assumed that the cosmic-ray acceleration takes place at or near the primary nuclei and that during the propagation phase no further acceleration occurs. Considerable thought has been recently given to the possibility that there is continual acceleration, e.g., in interstellar shocks. Calculations have already appeared assuming continual acceleration, which go beyond the early work of Fermi (1949). Models including this kind of acceleration add a further degree of complexity and in particular can make predictions on the energy dependence of the radioactive clock abundances. In order to check these predictions and also to minimize the uncertainties introduced by our lack of a complete understanding of solar modulation it would be highly desirable to measure the ^{10}Be abundances at energies significantly higher than the energies of the satellite measurements. Our propagation calculations show a considerable increase in the ^{10}Be surviving fraction, measured at the orbit of Earth, for an interstellar density of 0.24 atom cm^{-3} and a solar modulation level similar to the IMP measurements: 26% at 100 MeV $nucl^{-1}$; 35% at 1 GeV $nucl^{-1}$; 53% at 2.7 GeV $nucl^{-1}$ and 83% at 10 GeV $nucl^{-1}$.

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