path length is correct, a variation in the Li+Be+B/C+O ratio should also be observed, for Li, Be, and B are also secondary nuclei and are produced mainly by C+O nuclei. The data on this ratio and the predictions are shown in Fig. 3. There is some evidence for a decreasing ratio with increasing energy above a few GeV nucleon^{-1} although this conclusion is much less convincing than for the other ratios presented and is dependent on the rather inconsistent high energy data of Smith *et al.*[6]. In any case the variation in Li+Be+B/C+O ratio does not seem to be as drastic as predicted by an escape matter length $\sim E^{-1}$ which will explain the variations of the C+O/Fe+Ni and $Z=17$–25/Fe+Ni ratios.

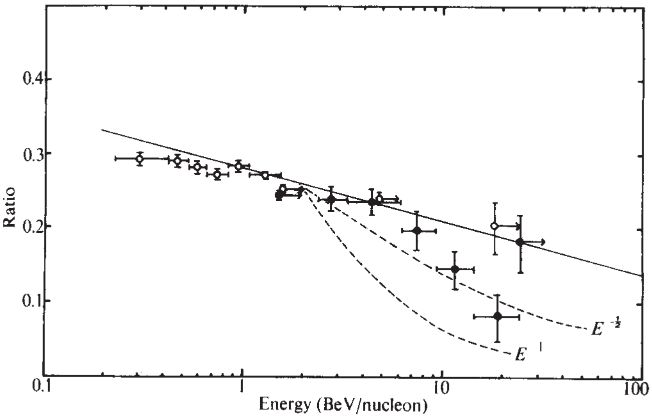

Fig. 3 Ratio of Li+Be+B to C+O nuclei as a function of energy. Symbols are as in Fig. 2. Solid line has same arbitrary slope as in Fig. 2.

It may be that this picture is too simple. We recognize that the concept of a leakage length is only a crude approximation to the actual diffusion of cosmic rays in the Galaxy[9], and one should more correctly be dealing with the energy dependence of the related diffusion coefficients to describe the data. It is also possible that the charge ratios could be highly dependent on the cosmic ray source distribution, which is assumed to be uniform in the model we have chosen.

An energy dependent leakage length will predict changing C/O and B+N/C+O ratios, however, and these may have already been observed[2,5]. It will also predict variations of the proton and helium nuclei spectra and the P/He ratio which could be observed. And finally, it will predict important changes in the charge ratios at energies $\lesssim 1$ GeV nucleon^{-1}, if the energy dependence extends to lower energies.

We are investigating some of these possibilities at present. We thank Dr Catherine Cesarsky and Dr J. A. de Freitas Pacheco for discussions. This work was supported by NASA.

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Mean Path Length of High Energy Galactic Cosmic Rays in the Galactic Disk

An important measurement of the composition of cosmic ray nuclei at high energy ($20<E<100$ GeV nucleon^{-1}) has been reported by Juliusson, Meyer and Müller[1]. They show that the ratio of galactic secondary nuclei to primary nuclei decreases very steeply when the energy of the observed nuclei is above 30 GeV nucleon^{-1}. The ratio of predominantly secondary nuclei to predominantly primary nuclei

$$\frac{\mathrm{B+N+F+Na+Al}+(14<Z<26)}{\mathrm{C+O+Ne+Mg+Si+Fe}}$$

which is ~ 0.31 at energies of 1.5 GeV/N is found to be 0.23 ± 0.03 at 25 and 30 GeV/N and $0.12^{+0.05}_{-0.07}$ at 90 GeV/N. Juliusson *et al.*[1] conclude that this effect may be explained in terms of particle propagation in the Galaxy: the leakage term which describes the probability that galactic cosmic rays leave the Galaxy must be energy dependent. Here we present a quantitative estimation of this dependence and discuss the implications of such a dependence.

Because this effect has been observed at high energy where the energy losses of the cosmic ray nuclei to ionization are negligible, a simple relation derived from the general transport equation[2] used by Meneguzzi, Audouze and Reeves[3] relates the leakage path λ_e with the primary and secondary component of the galactic cosmic rays

$$\varphi_j = \frac{\dfrac{Q_j}{n_H} + \sum\limits_i \varphi_i \left(\sigma_{pij} + \dfrac{n_{He}}{n_H}\,\sigma_{\alpha ij} \right)}{\sigma_{pj} + \dfrac{n_{He}}{n_H}\,\sigma_{\alpha j} + \left(M_H + \dfrac{n_{He}}{n_H}\, M_{He} \right) / \lambda_e} \qquad (1)$$

where λ_e is the escape path expressed in g cm^{-2}; φ_j is the flux of an element j; φ_i represent the fluxes of all the nuclei which contribute to the secondary production of the element j; where Q_j is the source term of the element j; n_H and n_{He} are the mean number densities of the hydrogen and helium atoms in the interstellar gas (here n_{He}/n_H has been taken equal to 0.1); M_H and M_{He} are respectively the masses of the H and He atoms; σ_{pij} and $\sigma_{\alpha ij}$ are the cross sections of the spallation reactions i(p,) j and i(α,) j induced respectively by the elements i on the hydrogen and helium atoms of the interstellar gas, and σ_{pj} and $\sigma_{\alpha j}$ are the total destruction cross sections of j by the hydrogen and the helium atoms respectively.

At energies of a few GeV nucleon^{-1} and below, the fluxes of the different chemical species have been measured[4–9]. For elements which are purely secondary, like lithium, beryllium, boron and fluorine, the source term $Q_j=0$ and the knowledge of the relative fluxes φ_i (refs 10, 11) and of the cross sections[3,10] involved are sufficient to determine the leakage path λ_e for energies of a few GeV nucleon^{-1}.

The calculation of λ_e at such energies is mainly based on the B/parents ratio because (i) B is an abundant secondary element in the cosmic rays ($B/C=0.27\pm0.03$) for which the composition is known with a better accuracy than the other secondary products observed in ref. 1; and (ii) the important spallation cross sections producing B from CNO nuclei have been experimentally determined. At a few GeV nucleon^{-1} with this choice of parameters the leakage path has been found to be 6.8 g cm^{-2} close to the value of 7 g cm^{-2} obtained by Meneguzzi and Reeves[11]. This value of λ_e has then been used in equation (1) to evaluate Q_i/n_H for the elements N, Na, Al, $14<Z<26$, C, O, Ne, Mg, Si, Fe appearing in the ratio measured by Juliusson *et al.*[1]. The results obtained here are comparable to those of Meneguzzi *et al.*[3] and of Shapiro *et al.*[10,11].

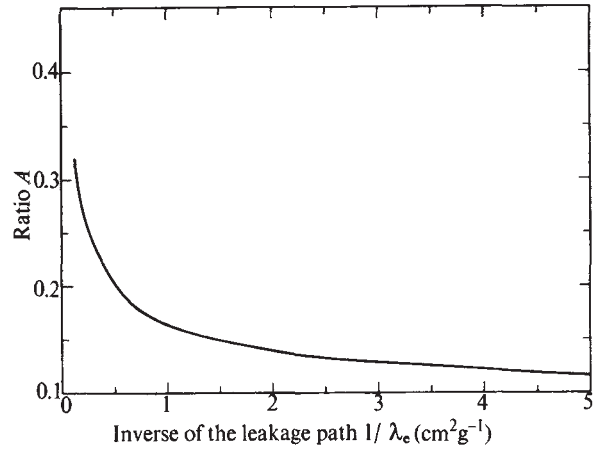

Fig. 1 Ratio of predominantly galactic secondary nuclei to predominantly primary nuclei

$$A=\frac{B+N+Na+Al+(14<Z<26)}{C+O+Ne+Mg+Si+Fe}$$

as a function of the leakage path λ_e (expressed in this figure by its inverse).

Then it has been assumed that the cosmic ray composition at the sources is independent of the energy. The fluxes of the different elements quoted above have been estimated for different values of the path length λ_e by starting with iron which can be considered as an entirely primary nucleus and calculating successively the fluxes of lower atomic mass species. In Fig. 1 the ratio

$$A=\frac{\varphi(B+N+F+Na+Al)+\varphi(14<Z<26)}{\varphi(C+O+Ne+Mg+Si+Fe)}$$

is presented as a function of $1/\lambda_e$. The dependence of A versus $1/\lambda_e$ is used together with the measured values of $A(E)$ where E is the energy in GeV nucleon^{-1} taken from Juliusson *et al.*[1]: in Fig. 2 the relation between log λ_e and log E is shown. The lower curve (*a*) is obtained by taking the mean values of A reported by Juliusson *et al.*[1]. The upper curve (*b*) is obtained from their upper limits for A. The intermediate curve (*c*) is obtained from the mean values for their first three points and the upper limits for the remainder. We consider the slope of the curve thus determined to be the smallest value consistent with their measurements. The results for $20<E<100$ GeV nucleon^{-1} approach a power law for the dependence of λ_e versus A

$$\lambda_e(20<E<100\ \mathrm{GeV/N})=\lambda_e(20)\times(E/20)^{-\alpha} \qquad (2)$$

with α ranging from 0.55 ± 0.05 (curve 3) through 1.2 ± 2 (curve 2) to 2 ± 0.2 (curve 1). In particular at energies of 90 GeV/N the path length λ_e is short ($0.3\leq\lambda_e\leq1.5$ g cm^{-2}).

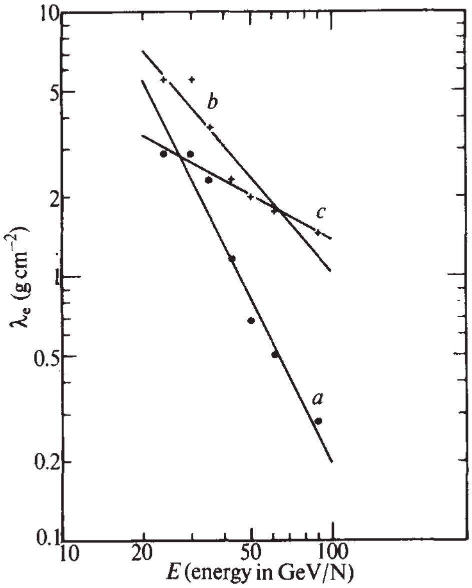

Fig. 2 Dependence of the leakage path λ_e with the energy of cosmic rays between 20 to 100 GeV/N using the measurements of Juliusson *et al.*[1] (dots) and the upper limits of A (crosses). The three lines, *a*, *b* and *c* are obtained by a least squares fit and relate respectively (*a*), the mean values of A ($\alpha=2$); (*b*), the upper limit of A ($\alpha=1.2$); *c*, the less sloped line compatible with the data of Juliusson *et al.*[1] ($\alpha=0.55$).

This result, if confirmed, would be a serious blow to the theories of disk confinement of cosmic rays: the spectrum of cosmic rays is a power law in energy without breaks up to 10^6 GeV/N and the cosmic rays are isotropic at energies of 2×10^4 GeV/N and higher[12]. If cosmic rays are confined only inside the disk of the galaxy, their age τ (expressed in millions of years) would be of the order of λ_e. Thus equation (2) for cosmic rays of energy $20<E<100$ GeV/N leads to

$$\tau(E\ \text{in GeV/N})\simeq4\times(E/20)^{-\alpha}\,10^6\ (\text{yr}) \qquad (3)$$

Two cases can be distinguished: (*a*) The $\lambda(E)$ dependence of equation (2) cannot be extrapolated to energies higher than $E_1\gtrsim100$ GeV/N. In this case if the cosmic ray spectrum at the sources is a power law of the energy, the observed spectrum should show a break at $E=E_1$ which is not present in the observations. (*b*) The $\lambda(E)$ dependence of equation (2) can be extrapolated to energies as high as 2×10^6 GeV/N. According to Jokipii and Parker[13] and Jones[14], the lines of force of the galactic magnetic field reach the border of the disk after a path of a few hundred parsecs. As a consequence, the time for cosmic ray nuclei to leave the Galaxy along a magnetic field line at 1/3 of the speed of light is $\sim5\times10^3$ yr. Thus cosmic rays for which equation (3) predicts a lifetime $\tau<5\times10^3$ yr would not be trapped at all in the galactic disk, but would cross it at the speed of light. Then the lifetime τ of the cosmic rays is given by equation (3) if $E<E_2$ and is equal to 5×10^3 yr, if $E\gtrsim E_2$, where E_2 is given in GeV/N by

$$\log\left(\frac{E_2}{20}\right)\simeq\frac{3}{\alpha} \qquad (4)$$

If the energy spectrum at the sources is a straight power law, a break in the observed cosmic ray spectrum should occur at $E=E_2$. If $\alpha\lesssim0.6$, the extrapolation of the $\lambda(E)$ dependence derived from the Juliusson *et al.*[1] measurements is consistent with the break observed at 2×10^6 GeV/N. If $\alpha>0.6$, the break would occur at lower energies $E_2\simeq2\times10^4$ GeV/N for

$\alpha = 1$ and 630 GeV/N for $\alpha = 2$. Furthermore it would become difficult to account for the isotropy of the high energy cosmic ray flux[2].

Thus the fluxes of secondary elements determined at such high energies are of great aid in distinguishing between models of disk confinement and halo confinement. This is particularly important now that the half life of ^{10}Be has been shown to be too short to be of real relevance to this problem[15].

In conclusion a reasonable extrapolation of the observations of Juliusson *et al.*[1] implies that, if the high energy ($E \gtrsim 2 \times 10^4$ GeV/N) cosmic rays are galactic, they are trapped in regions much larger than the galactic disk. Otherwise, it is possible that these high energy cosmic rays are of extra-galactic origin.

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Energy Dependence of Primary Cosmic Ray Nuclei Abundance Ratios

RECENT measurements of cosmic ray chemical composition between 1 and 100 GeV nucleon^{-1} (refs 1–3) show a decrease of the abundance ratios of secondary to parent nuclei above $\simeq 10$ GeV/N. This suggests that above this energy the mean path length of cosmic rays decreases with increasing energy[3,4]. Indeed, the variations of the abundance ratios $\frac{17 \leq Z \leq 25}{\text{Fe Ni}}$ and $\frac{\text{Li Be B}}{\text{C O}}$ imply a decrease of the mean path length from several g cm^{-2} at $E \simeq 2$ GeV/N to a fraction of a gram at $E \simeq 100$ GeV/N.

The same observations also show an energy dependence of the primary nuclei abundance ratios. The presently observed variations of these ratios seem to be consistent with (and give more support to) the conclusion drawn from secondary to parent nuclei ratios, without any need for additional hypothesis, such as charge dependence of the mean path length or charge dependence of the source spectral index.

I take as an example two nuclear species i and j emitted by cosmic ray sources, with the same spectral index, and assume an exponential path length distribution (justified by studies at GeV energies[5]); their abundance ratio at a few GeV/N is given by

$$\frac{N_i}{N_j} = \left(\frac{N_i}{N_j}\right)_{\text{source}} \frac{\dfrac{1}{\lambda_j} + \dfrac{1}{\lambda}}{\dfrac{1}{\lambda_i} + \dfrac{1}{\lambda}} \qquad (1)$$

where λ is the cosmic ray escape length (or mean path length) at this energy, and λ_i and λ_j are the nuclear destruction path lengths. If λ decreases with increasing energy, the second factor on the right hand of equation (1) approaches one when escape dominates nuclear destruction, that is, when λ reaches a fraction of a g cm^{-2}. Therefore, if the conclusion of the first paragraph is correct, I expect $\frac{N_i}{N_j}$ to decrease by a factor

$$\frac{\dfrac{1}{\lambda_j} + \dfrac{1}{\lambda(2\ \text{GeV/N})}}{\dfrac{1}{\lambda_i} + \dfrac{1}{\lambda(2\ \text{GeV/N})}}$$

between $E \simeq 2$ GeV/N and $E \simeq 100$ GeV/N, and to become nearly equal to the source value at $E \simeq 100$ GeV/N.

Table 1 Expected and Measured Abundance Ratios

Abundance ratios	$E \simeq 2$ GeV/N	$E \gtrsim 50$ GeV/N	Reduction factor	Expected reduction factor	Calculated source ratio[7]
$\frac{\text{C O}}{\text{Fe Ni}}$	20±3 (refs. 1–3)	8±5 (ref. 1)	2.5±1.4	1.8	8.2
		7±2 (ref. 2)	2.9±0.8		
$\frac{\text{He}}{\text{Fe Ni}}$	330±60 (ref. 1)	160±100 (ref. 1)	2 ±1.4	2.5	110
$\frac{\text{He}}{\text{C O}}$	20±2 (ref. 1)	20±9 (ref. 1)	0.7±0.3	1.3	13.5

Applying this calculation to the ratios $\frac{\text{C O}}{\text{Fe Ni}}$, $\frac{\text{He}}{\text{Fe Ni}}$ and $\frac{\text{He}}{\text{C O}}$ with $\lambda \simeq 7$ g cm^{-2} of interstellar matter (using the technique of ref. 5) and with nuclear destruction path lengths of respectively 16.2, 7.2 and 2.8 g cm^{-2} for He, CO and Fe (with 90% H and 10% He in interstellar matter), I find that these ratios must decrease by factors 1.8, 2.5 and 1.3 respectively. Table 1 shows a comparison between the expected and measured variations of these ratios with energy. The agreement is good