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THE VARIATION OF THE HIGH ENERGY PRIMARY NUCLEI COMPOSITION AND THE CONFINEMENT REGION OF COSMIC RAYS.

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Using the recent measurements of cosmic ray chemical composition between 10 and 100 GeV/nucleon, it is shown that if the very high energy (10^{12} to 10^{15} eV) spectral index of 2.7 is believed to be the source spectral index, the observed variation of the primary nuclei abundances with energy is difficult to reconcile with a galactic origin and confinement with a mean escape length from the Galaxy of $\simeq 7$ g/cm^2.

The observations can be explained if the mean path length of Cosmic Rays ($\simeq 7$ g/cm^2) represents the escape length from galactic sources, or if Cosmic Rays are of extragalactic origin.

1. The first measurements of cosmic ray chemical composition at a few tens of GeV/Nucleon (Smith et al. 1973, Juliusson et al. 1973, Webber et al. 1973, Ormes et al. 1973) have shown that above several GeV/N this composition is energy dependent and can therefore provide some information about cosmic ray propagation. The main result is that secondary to parent ratios $\frac{LiBeB}{CO}$ and $\frac{Cl \text{ to } Mn}{FeNi}$ are decreasing functions of the energy and therefore that the mean amount of matter traversed by cosmic rays is itself a decreasing function of the energy.

Assuming that the cosmic ray path length distribution keeps the form $\exp(-X/\Lambda)$ derived at GeV energies, with $\Lambda(E)$, one can reproduce the observed ratios by taking $\Lambda(E) \sim E^{-\alpha}$, with $\alpha \simeq 1$, above a few GeV/N (Audouze and Cesarsky 1973, Webber 1973).

The variation with energy of the abundance ratios between primary nuclei seems to be consistent with such a behaviour of Λ (Webber et al. 1973, Meneguzzi 1973).

More information can be obtained by considering the shapes of the individual fluxes of primary nuclei. The measured spectral index is $\gamma = 2.75 \pm 0.03$ for H, $2.77 \pm .05$ for He, $2.62 \pm .05$ for C, $2.64 \pm .05$ for O and $2.14 \pm .13$ for Fe (Balasubrahmanyan et al. 1973, Ryan et al. 1972). These results are in agreement with the spectra obtained by Smith et al.

As noted by several authors, (Audouze and Cesarsky 1973, Cartwright 1973), the usual assumption that, if cosmic rays are of galactic origin, their mean path length is mainly their escape length from the Galaxy is in conflict with the absence of a break in the p and α spectra (Ryan et al. 1972) at energies where Λ becomes strongly energy dependent.

Assuming the usual leakage lifetime approximation, with a uniform source distribution, and the transfer equation

$$\frac{\partial N}{\partial t} = 0 = -\frac{N}{Te} - \frac{N}{T_N} + Q \qquad (1)$$

(N = density of a given nuclear specie in the galaxy, T_e = mean escape time, T_N = nuclear destruction lifetime, Q = source function), the density is given by $N = \dfrac{Q}{\dfrac{1}{T_e} + \dfrac{1}{T_N}}$ which for protons and He ($T_e \ll T_N$) reduces to $N = QT_e$. Therefore, the p and He spectra should reflect the T_e variation with energy.

A possible explanation is that (De Freitas Pacheco 1973) this break is not a sharp one and occurs around one GeV/N, solar modulation and energy losses preventing us from seing the source spectral index in the energy range where Λ is constant. According to this author, the observed spectra can be reproduced by taking a source spectrum $\sim E^{-\gamma}$ and an escape length of the form $\Lambda = \dfrac{\Lambda_0}{1 + E}$

($\gamma \simeq 2$, $\alpha \lesssim 1$) where E is in GeV/N. At high energies, one has $N \sim E^{-(\alpha+\gamma)}$ for the observed spectrum.

However, since the total cosmic ray spectrum is known to keep the same spectral index from 10 to 10^6 GeV, one has to assume that $\Lambda \sim E^{-\alpha}$ with the same value of α, i.e. the same energy dependence of the escape length from the Galaxy in this whole energy range, and this appears difficult to explain.

We consider here another possible explanation, i.e. that low and medium energy cosmic rays are largely confined in their source regions. This can be qualitatively envisaged as follows. Let us suppose that at energies between 10^3 and 10^6 GeV, the measured spectral index of the total radiation is the source spectral index, (= 2.7), cosmic rays of such high energies escaping freely from the source regions, while all nuclear species cosmic rays of energies below a few GeV/N have traversed 7 g/cm^2 (after acceleration) in a confinement region around their sources.

If one assumes that equation (1) can be applied to the confinement region (with N_s, T_s, and Q_s for density, lifetime and source function), then $N_s = \frac{Q_s}{\frac{1}{T_s} + \frac{1}{T_N}}$, and the injected flux in the Galaxy is proportional to

$$\frac{N_s}{T_s} = \frac{Q_s}{1 + \frac{T_s}{T_N}} = \frac{Q_s}{1 + \frac{\Lambda_s}{\Lambda_N}} \quad (\Lambda_s = \rho_s c T_s \text{ in g/cm}^2).$$

Then, if the spectral index is not further affected by energy dependent propagation conditions in the Galaxy (at least in the energy range considered) the fluxes of nuclei of primary origin in the galaxy would also be proportionnal to

$$\frac{Q_s}{1 + \frac{\Lambda_s}{\Lambda_N}}$$

. Now, Λ_N is $\simeq 2$ g/cm^2 for Fe, $\simeq 17$g/cm^2 for He and several tens of g/cm^2 for protons. Therefore in the energy range where Λ_S decreases from 7 g/cm^2 to a fraction of a g/cm^2, one expects an increase of the spectral indices, with the strongest effect on Fe, a much smaller effect on He, and practically none on H. In other words, at GeV energies, Fe is highly destroyed before being injected in the galactic medium, while protons are not, and this effect disappears at higher energies.

Results of this calculation for He, C+O , and Fe spectra are shown in figure 1 for source spectra $Q_s \sim W^{-2.7}$ (W = total energy per nucleon) and

$$\begin{aligned} \Lambda_s(E) &= 7\text{g/cm}^2 && \text{for } E < 3 \text{ GeV/N} \\ &= \frac{21}{E} \text{ g/cm}^2 && \text{for } E \geq 3 \text{ GeV/N} \end{aligned}$$

which reproduces the observed secondary to parent ratios (Audouze and Cesarsky 1973).

Note that the observed abundance ratios would be the same as in the usual galactic confinement model with $\Lambda_G(E)$ representing the escape length from the Galaxy. Differences appear only in the shapes of the spectra. At high energies, where $\Lambda_s \ll \Lambda_N$, one expects $N \sim Q \sim Q_s$ for the source confinement model, which therefore predicts that all spectra should become parallel at E $\gtrsim 10^3$GeV/N, and proportionnal to $E^{-2.7}$. This is also predicted by the above mentioned galactic confinement model (De Freitas Pacheco 1973), with the hypothesis $\alpha+\gamma = 2.7$ between 10 and 10^6GeV/N.

Of course, the transfer equation used here is an oversimplified one, but the qualitative result should be correct. Note that for protons, in the range where $T_s \sim E^{-\alpha}$, one has $N_s \sim E^{-(\alpha+\gamma)}$ and $N_G \sim E^{-\gamma}$ in the Galaxy, as soon as $L_s \ll L_N$. The spectrum in the source region is steeper than the galactic spectrum. If the same thing holds for electrons, and supposing that supernova remnants are the invoked confinement regions, one could hope to see the effect on the corresponding synchrotron spectra. However, one cannot use such a simple calculation to predict observable effects on the electron spectrum, because of the various energy losses which become important, but rather a diffusion equation with proper boundary conditions.

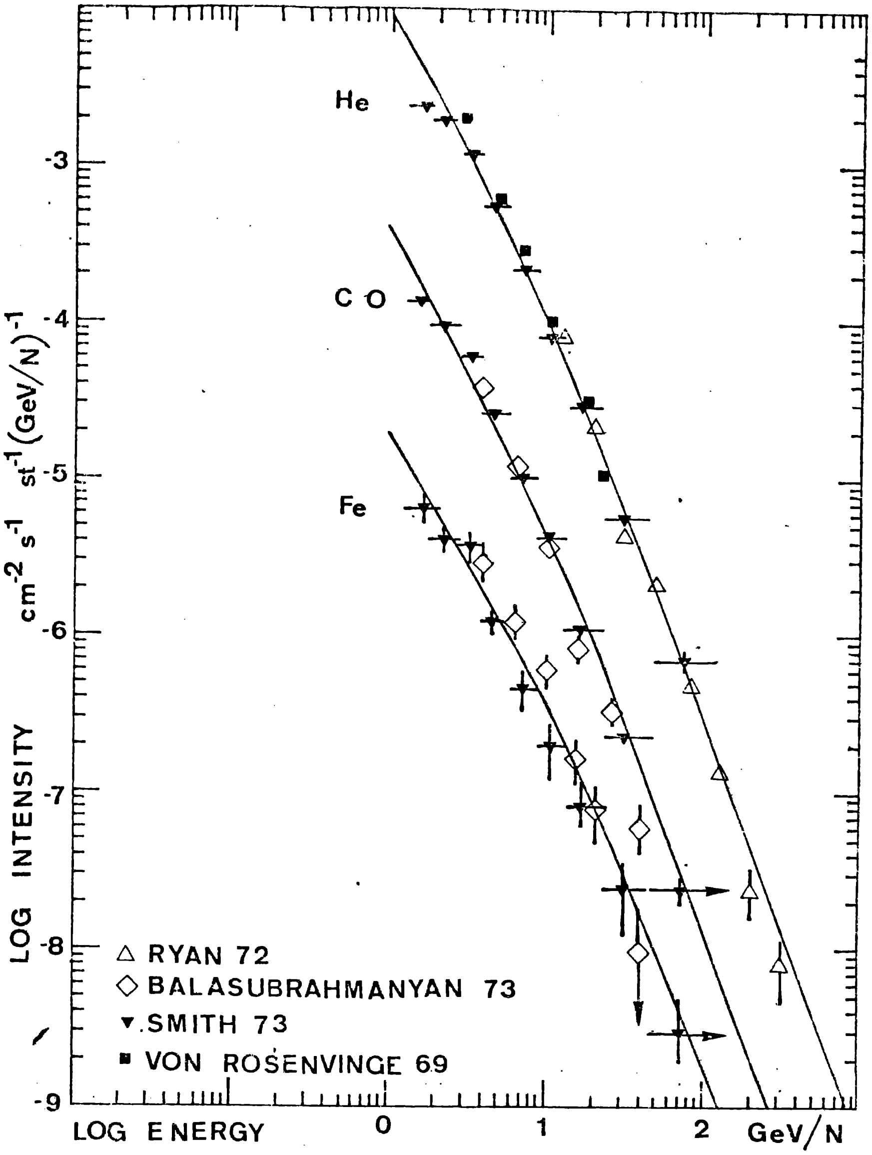

Figure 1. Energy spectra of He, C+0 and Fe calculated with a source spectrum proportional to $W^{-2.7}$ (W=total energy per nucleon), a mean path length in the sources $\Lambda_s(E)$ as given in the text and an energy independent small escape length from the Galaxy, compared with the available data.

Discussion. This model could be criticized on the basis of the observed cosmic ray low anisotropy. However, at energies below 100 GeV/N, cosmic rays can be isotropized by the interplanetary magnetic field (Lingenfelter 1971), and no observation is available in this energy range. In any case, if the present results are confirmed by future measurements, a short cosmic ray storage time in the galaxy is inferred from the secondary to parent ratios at $E \gtrsim 100$ GeV/N. For L (100 GeV/N) $\lesssim 0.5$ g/cm^2 and $n_H \simeq 0.5$ cm^{-3} in the Galaxy, one finds $T \lesssim 6\text{x}10^5$ years, while for the escape lifetime from the source region, assuming n_H (source) $\gtrsim 10$ cm^{-3}, $T_s \lesssim 3\text{x}10^5$ years. If this is the case, the observed ^{10}Be flux should be compatible with no decay of this isotope ($\tau_{^{10}Be} = 1.5 \times 10^6$ years, Yiou 1972). The measurements of the Be/B ratio give conflicting results (Shapiro 1971), but recent preliminary data on ^{10}Be / Be (Webber 1973) give a value of 7 % (7 ^{10} Be nuclei out of a total of 100 Be nuclei) , not contradictory with ^{10}Be survival. For such a short cosmic ray age, a measurement of the ^{26}Al abundance ($\tau_{^{26}Al} = 7.4 \times 10^5$ years) would be of even greater interest (Schramm 1971).

The total number of particles emitted per second by galactic sources is $\frac{N_G V_G}{T_G}$, where V_G is the volume of the Galaxy. It can also be written

$$\frac{N_G V_G}{T_G} = \frac{\Phi_G M_G}{\Lambda_G} = \frac{\Phi_G M_g}{\Lambda_S + \Lambda_G} \left(1 + \frac{\Lambda_S}{\Lambda_G}\right)$$

(M_g is the mass of the galactic gas, $\Phi_G = N_G c$ is the cosmic ray omnidirectional flux in the Galaxy, and $\Lambda_S + \Lambda_G = 7$ g/cm^2). Therefore, the total power emitted by the sources which is currently estimated to be, in the galactic confinement model, of the order of 10^{40} erg s^{-1} (Ginzburg 1964), would be multiplied by a factor $1 + \frac{\Lambda_S}{\Lambda_G}$. Consequently, since the above estimate is of the same order than the total cosmic ray power one can expect from supernovae, the factor $\frac{\Lambda_S}{\Lambda_G}$ cannot be larger than 10.

On the other hand, if Λ_S is several g cm^{-2}, the confinement regions are expected to be strong sources of $\pi°$ decay gamma rays. The total gamma ray luminosity of the Galaxy around 100 MeV would also be multiplied by a factor $1 + \frac{\Lambda_S}{\Lambda_G}$. According to Stecker (1973), the present upper limit of the galactic flux (Clark 1968) is consistent with the flux expected from the interaction of cosmic rays with the galactic gas (except for the excess from the direction of the galactic center). If this result is confirmed, a still smaller upper limit would result for $\frac{\Lambda_S}{\Lambda_G}$. But, at present, a value of several g cm^{-2} for Λ_S cannot be excluded.

An other way of explaining the shapes of the observed nuclei spectra is to assume an extragalactic origin of cosmic rays, no matter if their path length has been traversed in extragalactic sources or in our own Galaxy (Audouze and Cesarsky 1973, Cartwright 1973). In the first case, the present calculation can be applied, but the ^{10}Be content of the cosmic radiation, as well as the upper limit of the extragalactic gamma ray flux, seem to favor the second case.

Let us finally mention that a behaviour of the nuclei spectra similar to what is observed would also arise in a more complex situation If cosmic ray diffusion perpendicularly to magnetic field lines of force is severly limited and cosmic ray diffuse one dimensionally along a single tube of force, it could be that we are not sampling a mean cosmic ray composition in the Galaxy, but that we are detecting nuclei from a particular region, which have had little chance to escape from the Galaxy. The observed spectral shapes would then be explained by an increase of the one dimensional diffusion coefficient with energy.

In conclusion the possibility that low and medium energy cosmic rays ($E \lesssim 50$ GeV/N) have traversed most of their path length in confinement regions close to their sources cannot presently be excluded, and would explain the observed energy spectra of the individual elements between 1 and 100 GeV/N.

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