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COSMIC RAYS AT VERY HIGH ENERGIES: DISCUSSION OF SOME NEW RESULTS

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Recent measurements of the nuclear cosmic ray composition up to 100 GeV/n and of the spectrum of cosmic ray electrons to almost 1000 GeV have provided new evidence relevant to the origin of these particles and to their propagation in the interstellar medium. It was shown that the abundance of galactic daughter nuclei decreases with increasing energy relative to the abundance of parent nuclei. It was also found that the energy spectrum of electrons is consistent with a single power law up to 1000 GeV without much steepening.

These results are possibly related and we shall discuss them in terms of
(a) a relatively local origin of energetic cosmic rays,
(b) an extragalactic origin of the cosmic radiation, and
(c) an energy dependent confinement of galactic cosmic rays.

1. Introduction. Observations of the energy spectra and composition of cosmic rays at high energies have recently moved into the center of interest, an interest that is stimulated by the fact that unexpected changes in their composition and in their spectral form could be measured. Whatever explanation these effects will eventually have, they point toward phenomena which so far were not included into the description of the sources of cosmic rays or their propagation in the interstellar medium.

We would like in this paper to briefly and qualitatively discuss some of the possible interpretations of the changing cosmic ray composition at high energies, and to point out some consequences of these interpretations.

2. Discussion of the Experimental Situation. Recent measurements lead to the following conclusions:
A) The relative nuclear composition of cosmic rays changes with energy such that galactic secondary nuclei become progressively less abundant as energy increases. This effect may set in already at energies around 3 GeV/n (Smith et al., 1973; Webber et al., 1973; Ormes et al., 1973) and is well established in the energy range above 20 GeV/n (Juliusson et al., 1972; Juliusson and Meyer, 1973; Juliusson, 1973).
B) The differential energy spectra of individual nuclei are well represented by smooth power laws with spectral indices of order 2.5 to 3. No significant structure, break points or obvious steepening of the spectra has been observed above the energies where solar modulation affects the spectra (Ryan et al., 1972; Juliusson, 1973).
C) The spectrum of cosmic ray electrons can also be well described by a single power law of spectral index between 2.6 and 2.7 over the energy range from a few GeV to 300 GeV and even higher. Our measurements (Meyer and Müller, 1971; Müller, 1973)

do not indicate any positive evidence for a steepening of the spectrum at high energies.

Any attempts to explain these results will have to depart from prevailing ideas about the generation, propagation, and storage mechanism of cosmic rays in the galaxy.

Considering first the change in the nuclear composition we shall take as an experimental fact that high energy nuclei have traversed less matter than low energy nuclei, since both theoretical as well as experimental results indicate that the production cross-sections for the daughter nuclei do not depend strongly on energy above 1 GeV/n. The observed changes in the composition, which must be of astrophysical origin, may be due to one of the following three mechanisms:
(a) Very energetic nuclei are predominantly produced by sources which are relatively close to the solar system, (b) Parent cosmic ray particles are of extra-galactic origin, but secondary particles are mainly produced inside the galaxy and have an energy dependent confinement, (c) Cosmic radiation is of galactic origin and its confinement in the galaxy is dependent on energy.

We now discuss these possibilities in more detail:
A) The possibility of energetic particles originating from close-by sources implies a departure from the model of an equilibrium between the production and loss of the cosmic rays, which has been very successful in explaining many cosmic ray data in the past. A striking confirmation of this possibility could be the discovery of a major change in the composition of source nuclei which might be the signature of a particular source. Our measurements of the C/O ratio (Juliusson and Meyer, 1973) as well as measurements of the ratio of the iron group / (C + O) (Smith et al. 1973, Ormes and Balasubrahmanyan 1973, Juliusson 1973, Webber et al. 1973) show a change in composition which possibly cannot be fully accounted for by propagation (Fig. 1,2). However, the

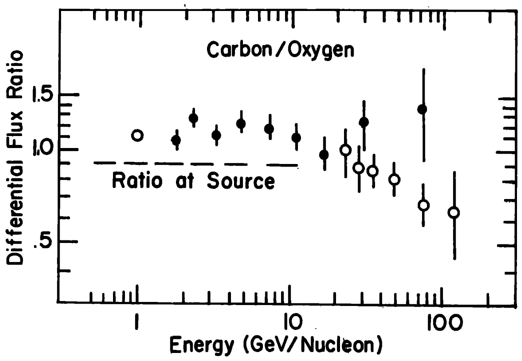

Fig. 1. Ratio of C/O as a Function of Energy

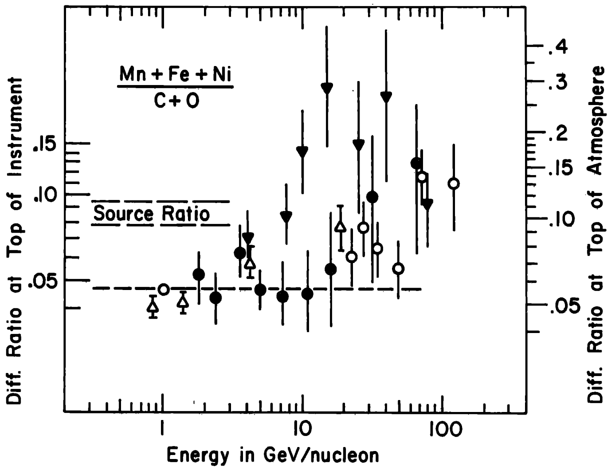

Fig. 2. Ratio of Mn+Fe+Ni/C + O as a function of energy
--- observed ratio at low energies

○ Our data, ● Smith et al. 1973, Δ Webber et al. 1973, ▼ Ormes et al. 1973.
(These symbols are used in all figures of this paper.)

uncertainties in the experimental data as well as the extrapolated source ratio prevent one at the present time to take these results as proof of the failure of the steady state model.

If it is indeed the case that high energy nuclei have their origin in a nearby source, e.g., a supernova explosion, and low energy nuclei have a different origin one might also expect more structure in the nuclear spectra than is presently observed.

A local origin of high energy electrons has been proposed (Shen and Mao 1971, Ramaty and Lingenfelter 1971) mainly to account for the absence of a steepening of the electron spectra at high energy by synchrotron and Compton processes. Unambiguous evidence for nearby sources cannot be obtained from these observations either.

B) As a second possibility one may invoke an extragalactic origin of cosmic rays. Primary cosmic rays would enter the galaxy from interstellar space and there produce secondary particles by spallation. One then assumes that the residence time of the cosmic rays in the galaxy depends on their energy, an assumption we shall discuss further under possibility C). The energy of the spectra of the parent nuclei measured inside the galaxy would be the same as the extragalactic spectra but the energy dependent lifetime of the cosmic rays inside the galaxy results in a steepening of the spectra of secondaries. The existing electron data make this explanation quite unlikely. Unless we question the existence of a universal blackbody radiation, electrons can hardly be of extragalactic origin, and the similarity between the spectral slopes of the electron and nuclear species as well as the electron-positron ratio support a common or similar origin. Therefore we do not suggest an extragalactic origin of cosmic rays as a likely interpretation of the observations (see Cartwright 1973).

C) A third alternative to explain the data can be found within the framework of a continuous galactic equilibrium distribution of cosmic rays, if the amount of matter traversed by a cosmic ray particle decreases with increasing energy. This situation could occur (1) if all cosmic ray particles are characterized by the same galactic confinement time, but if the more energetic particles preferentially traverse galactic regions of lower interstellar matter density than low energy particles during this time, or (2) if the confinement time τ (E) is dependent on the energy E of the particle and decreases with increasing energy, while all particles move in an interstellar medium of the same average density.

We do not propose to discuss here how either of these two situations may actually come about. We wish to point out, however, that some interesting observable peculiarities arise in case (2). It is well established that the nuclear composition of cosmic rays around 1 GeV/nucleon corresponds to a galactic confinement time of $\sim 3 \times 10^6$ years at an average interstellar hydrogen density of ~ 1 atom/cm^3. The measurements of the composition at higher energies, however, are compatible with a continuous decrease of the confinement time, starting already at energies around 1 GeV/nucleon. It turns out that an energy dependence of the confinement time in form of a simple power law $\tau = \tau_0 E^{-\alpha}$ for $E \geq 1$ GeV/nucleon with

$\alpha \approx 1/3$ and $\tau = 3 \times 10^6$ yrs at 1 GeV/nucleon would yield a possible fit to the experimental data (see Fig. 3). As a consequence of this hypothesis all measured cosmic ray spectra at high energies are expected to be steeper than the source spectra. On the other hand, cosmic ray composition measurements at lower energies point toward an energy independent confinement time around and below 1 GeV/nucleon, and therefore a local interstellar spectrum which follows the source spectrum. Assuming a power law spectrum at the sources one may expect a break in the spectral slope in this energy region which, however, would be difficult to observe due to the effects of solar modulation.

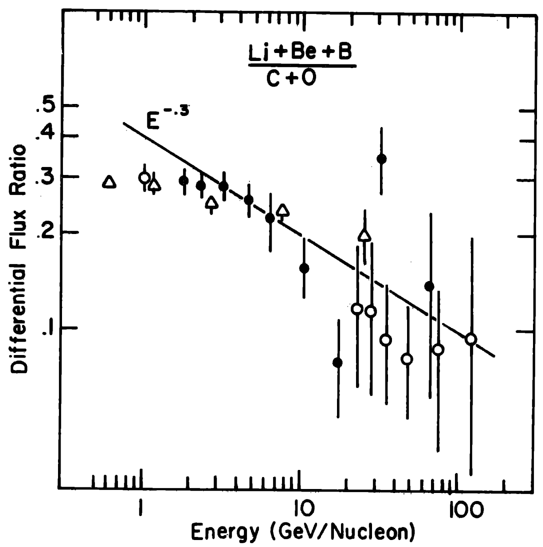

Fig. 3. The ratio Li+Be+B / C + O as a function of energy. The line represents the expected ratio if $\tau = \tau_0 E^{-0.3}$ above 1 GeV/n.

If we accept this picture, we are led to new conclusions with respect to the electron spectrum. Let us write the continuity equation for electrons in the most simplified version:

$$P E^{-\gamma} = \frac{N(E)}{\tau(E)} - \frac{\partial}{\partial E}\left(\kappa E^{2} N(E)\right) , \quad \tau(E) = \tau_0 E^{-\alpha}$$

where $PE^{-\gamma}$ = source spectrum, N (E) = observed spectrum, $\partial/\partial E\,(\kappa E^{2} \cdot N)$ = energy loss term. This would yield the solutions

$$N(E) = \begin{cases} P\tau_0 E^{-(\gamma+\alpha)} & E \ll E_c \\ \frac{P}{\kappa(\gamma-1)} E^{-(\gamma+1)} & E \gg E_c \end{cases} ; \quad E_c = \left(\frac{1}{\tau_0 \kappa (\gamma-1)}\right)^{\frac{1}{1-\alpha}}$$

The observed spectrum of electrons would be, like the spectra of the primary nuclei, steeper (index $-(\gamma+\alpha)$) than the source spectrum(index $-\gamma$) at energies below the "break energy" E_c. The steepening due to synchrotron - and Compton - losses around E_c would be, depending on the value of α, less pronounced than one unit in the spectral index, and, most importantly, the break point E_c would shift to significantly higher energies than expected for $\alpha = 0$. For instance, with the customary assumptions about interstellar magnetic fields and photon densities, and with $\alpha = 1/3$, E_c would shift from ~ 300 GeV to ~ 5000 GeV. This high value of E_c is far beyond the energy regime covered by existing measurements of electrons.*

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* Similar considerations were recently pointed out by R. Ramaty to one of us (E. J.).

It is interesting that a steepening of the electron spectrum has not as yet been clearly established and might be absent up to energies of around 1000 GeV.

Therefore it is tempting to explain the electron data with the aid of the described hypothesis. A fairly slight energy dependence τ (E), for instance with α = 0.15, would already have the effect of abscuring completely the much discussed steepening of the electron spectrum over the whole energy range in which measurements presently exist.

3. Conclusions. This discussion shows that we are unable to decide in favor of any one of the described models. The amount of unknown assumptions exceeds in each case the available observational material, and still other possibilities to explain the data may exist. In any case, the extragalactic model (b) seems to be the most speculative hypothesis, and is probably the most difficult one to disprove experimentally.

However, we wish to point out that more decisive answers can be expected from future experiments. Relative abundances of cosmic rays, measured at still higher energies, with greatly improved statistical accuracy, and possibly combined with measurements of the isotopic composition, appear to be the most sensitive test for the existence of discrete nearby sources. On the other hand, better accuracy of the electron data at high energies, and an extension of the electron measurements by, maybe, another decade in energy (up to ~ 10,000 GeV) will be of crucial importance for models invoking energy dependent confinement times.

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References .

B. Cartwright (1973), Astrophys. Letters (in press).

E. Juliusson, P. Meyer and D. Müller (1972), Phys. Rev. Letters 29, 445.

E. Juliusson (1973) Proceed. of this conference, paper 248.

E. Juliusson and P. Meyer (1973), Astrophys. Letters (in press)

P. Meyer and D. Müller (1971) Proc. 12th Intern. Conf. on Cosmic Rays, Hobart 1, 117.

D. Müller (1973), Proceed. of this conference, paper 249.

J. F. Ormes and V. K. Balasubrahmanyan (1973), Nature 241, 95.

R. Ramaty and R. E. Lingenfelter (1971), Phys. Rev. Letters 27, 1309.

M. J. Ryan, J. F. Ormes and V. K. Balasubrahmanyan (1972), Phys. Rev. Letters 28, 985.

L. S. Shen and C. Y. Mao (1971), Astrophys. Letters 9, 169.

L. H. Smith, A. Buffington, G. F. Smoot, L. W. Alvarez and W. A. Wahlig (1973), Ap. J. 180, 987.

W. R. Webber, J. A. Lezniak, J. C. Kish and S. V. Damle (1973), Nature 241, 96.