# The composition of galactic cosmic rays[1]

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Recent measurements of low-energy galactic cosmic rays obtained on sounding rockets and satellites exhibit a composition different from that obtained for intermediate and high-energy radiation obtained at balloon altitudes. In particular the ratio of light to medium nuclei is observed to be 0.2–0.3 in the 50–100 MeV/nucleon interval as compared with values near 0.5 in the 200–500 MeV/nucleon region. Lower values of the ratios C/O, N/O, F/O, and odd-$Z$/even-$Z$ are also found. In the light of these new measurements and of new measurements on the fragmentation cross sections for cosmic-ray nuclei in interstellar space, an attempt has been made to calculate the composition expected if similar source spectra are assumed. It is found that neither passage through a fixed amount of material nor an equilibrium condition (exponential path-length distribution) is adequate to explain the observed features. The effects of including other mechanisms such as rigidity-dependent escape from the galaxy and Fermi acceleration in interstellar space are evaluated.

## I. INTRODUCTION

Virtually all of the quantitative theories contrived to explain the energy-dependent composition of the galactic cosmic radiation involve the progagation of the radiation through interstellar material. If this process occurs, at least two mechanisms must affect the cosmic-ray composition and energy spectra; these are fragmentation produced in nuclear reactions with the material (assumed to be mostly hydrogen) and ionization energy loss. Additional processes which might affect the energy dependence of the relative composition include Fermi-type acceleration in collisions of the cosmic-ray nuclei with magnetic irregularities on clouds and rigidity-dependent loss from the galaxy.

In this work we examine two extreme models of the propagation process, that in which the amount of interstellar material through which the radiation propagates is constant, and the equilibrium model in which the supply of particles is balanced by their loss through the various mechanisms mentioned above. These two models lead to delta-function and exponential probability distributions for the path-lengths traversed, respectively.

The present reexamination of cosmic-ray propagation is occasioned especially by the existence of new measurements on the fragmentation cross sections, which are, in some instances, quite different than those previously assumed.

The assumptions made about the cosmic-ray source are that the spectrum of all species emitted has the same shape and that the emitted fluxes of Li, Be, and B are negligible relative to that of oxygen. Other abundances have been treated as adjustable parameters.

Our calculations propagate individual elements from He through O and the charge groups $9 \leqslant Z \leqslant 19$ and $Z > 20$. Having obtained the abundances of the individual species at earth as a function of energy/nucleon we sum to find the energy-dependent ratio of light ($3 \leqslant Z \leqslant 5$) to medium ($6 \leqslant Z \leqslant 8$) nuclei. We make the approximation that the charge-to-mass ratio of all species considered is $\frac{1}{2}$.

## II. THEORY

The theory of energy-dependent propagation of cosmic rays through interstellar space has been described recently by Fichtel and Reames (1966). The transport equation used in that work is

$$(1)\quad \mathrm{d}[w_i(E)j_i(E, X)]/\mathrm{d}X + w_i(E)j_i(E, X)/\Lambda_i(E) = w_i(E)\textstyle\sum_{k>i} j_k(E, X)/\Lambda_{ki}(E),$$

where $j_i(E, X)$ is the flux per unit energy/nucleon of $i$-type particles of energy/nucleon $E$ after propagation through $X$ g/cm$^2$ of

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material, and $w_i(E) = \mathrm{d}E/\mathrm{d}x$ for these particles.

For the equilibrium case we begin with the equation of Ginzburg and Syrovatskii (1964) for the general energy-dependent number density of $i$-type cosmic rays, which we write as

$$(2)\quad \frac{\partial N_i}{\partial t} - \nabla\cdot(D_i\nabla N_i) + \frac{\partial}{\partial E}(b_i N_i) - \frac{1}{2}\frac{\partial^2}{\partial E^2}(d_i N_i) = Q_i - \frac{N_i}{\tau_i} + \sum_{k>i}\frac{N_k}{\tau_{ki}}.$$

Since we are concerned with the equilibrium case, $\partial N/\partial t = 0$. We also assume that there are no spatial variations or second-order energy effects so that the second and fourth terms in (2) are zero.

To write eq. (2) in terms of fluxes and convert $t$ to $x$, we let $J_i \sim \beta N_i$, $b_i = \mathrm{d}E/\mathrm{d}t \sim \beta\mathrm{d}E/\mathrm{d}x = \beta w_i(E)$, and $\Lambda_i \sim \beta\tau_i$, since $\mathrm{d}x = \beta\rho c\mathrm{d}t \sim \beta\mathrm{d}t$. With these substitutions eq. (2) becomes

$$(3)\quad \partial[w_i(E)J_i(E)]/\partial E + J_i(E)/\Lambda_i(E) = Q_i(E) + \textstyle\sum_{k>i} J_k(E)/\Lambda_{ki}(E).$$

It is easy to show that the solutions of eqs. (1) and (3) are related by

$$(4)\quad J_i(E) = \int_0^\infty j_i(E, X)\mathrm{d}X$$

and that

$$(5)\quad Q_i(E) = j_i(E, 0),$$

where the integral in eq. (4) runs over all $X$ for *constant* $E$. It is thus possible to obtain equilibrium solutions by integrating over those obtained for differing amounts of material, i.e. over increasingly "older" spectra, at constant energy.

In addition to the ionization energy loss we have investigated the effect of including a small amount of Fermi acceleration (Fermi 1949, 1954). This acceleration has been included directly in the $\mathrm{d}E/\mathrm{d}x$ term, i.e.

$$(6)\quad w_i = \mathrm{d}E/\mathrm{d}X\ (\text{ionization}) + \alpha W = -(Z_i^2/M_i)f(\beta) + \alpha W,$$

where $W$ is the total energy/nucleon.

In eq. (6) $\alpha$ has been chosen in the range 0–0.03 cm²/g. These values are several orders of magnitude smaller than that necessary to produce the observed slope of the particle spectra with this acceleration alone, and are more nearly in accord with values estimated from measurements on magnetic clouds in interstellar space.

The final effect included is a rigidity-dependent escape from the galaxy using the equilibrium model. Actually an escape of this kind should be included as a boundary condition on eq. (2), since it will, in general, couple energy and spatial dependences. Following the example of Cowsik *et al.* (1966), however, we have included this effect as a volume loss term $\Lambda_e = K/R$, normalized to 3 g/cm² at 8 GV.

## III. FRAGMENTATION CROSS SECTIONS

Our previous work (Fichtel and Reames 1966) did not account for a number of new measurements on the fragmentation of nuclei in proton reactions. Significant among these is the first measurement of the production of the stable isotopes $^6$Li and $^7$Li in proton reactions with $^{12}$C and $^{16}$O (Bernas *et al.* 1965). Other data not included in older summaries have been measured for $^{12}$C(p, x)$^7$Be (Williams and Fulmer 1967), and for production of $^{15}$O, $^{13}$N, $^{11}$C, and $^7$Be in $^{16}$O(p, x) reactions (Albouy *et al.* 1962). Recent summaries of measurements have also been made (Bertini *et al.* 1966; Bernas *et al.* 1967).

From these measurements and from the theoretical work of Bertini *et al.* and Bernas *et al.* we have attempted to make a better estimate of the fragmentation cross sections. The results for the production of Li and B from various species are shown in Fig. 1.

It is interesting to note that the high-energy cross section for the production of stable Li isotopes from $^{12}$C(p, x) reactions is almost a factor of two lower than that estimated previously (Badhwar *et al.* 1962). This result is not entirely surprising since the previous result was based on measurements from neutron bombardment, these being the only data available at that time. Differences in the results from p and n reactions on the same target leading to the same product are expected (Bernas *et al.* 1967). No violation in

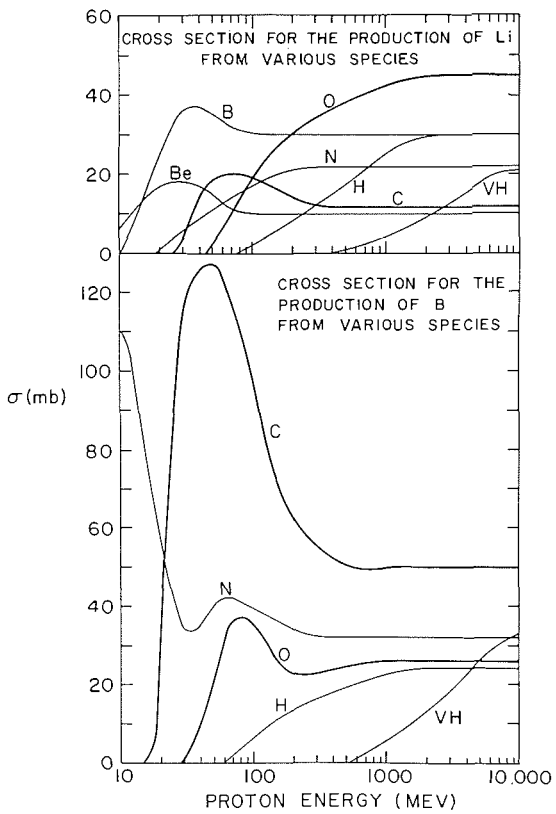


FIG. 1. Cross sections for the production of the dominant light nuclei in the fragmentation of various heavier species.

isotopic spin conservation need be involved to produce such differences.

Errors in the final Li abundance from errors in the cross sections probably do not exceed 25%. In the case of boron production, Fig. 1 shows that most of the B results from fragmentation of carbon and in fact comes from the $^{12}C(p, pn)^{11}C(\beta^{+}\nu)^{11}B$ reaction and decay. Since the more-poorly-known reactions contribute less to the total boron production, the error in the latter is probably also not more than 20–30%.

## IV. RESULTS AND DISCUSSION

The resultant L/M ratio calculated using the two different models and various mechanisms described is shown with the data in Fig. 2. Data are taken from the summary of Reames and Fichtel (1967). Clearly no striking agreement exists between the theory and the measurements. Most of the previous agreement has been destroyed by the use of the new cross-section measurements. The dominant cross sections are flat or rising with energy in the same energy region where the L/M ratio appears to be reaching a maximum and then decreasing with energy.

The inclusion of Fermi acceleration ($\alpha \neq 0$) generally affects the L/M ratio only at low energies. Effects associated with the crossover from acceleration to deceleration (occurring at different $E$ for different species) are too weak to be observed.

Equilibrium spectra fail to explain the data unless a rigidity-dependent loss from the galaxy is assumed. We are somewhat reluctant to accept such a loss mechanism for a number of reasons. First, the L/M ratio predicted decreases at high energies in proportion to the loss term (e.g. like $K/R$); apparently no such effect is observed. Second, the high-energy spectrum emitted by the source must be flatter with energy for losses as strong as $R^{-1}$; if the observed spectrum goes as $R^{-2.5}$, the source spectrum must go as $R^{-1.5}$ to account for a $K/R$ loss. This means that the source must emit many orders of magnitude more energy in cosmic rays than previously believed.

In all the results plotted in Fig. 2 we have used a differential rigidity spectrum proportional to $R^{-2.5}$ except in the case of the equilibrium spectrum with the $K/R$ loss described above. Numerous other spectral shapes have been used in our calculations, but give equally poor agreement.

The general inadequacy of the present theories may arise from any of several sources: (1) propagation through interstellar space may not be the dominant process for producing light nuclei and/or they may be emitted directly by the source; (2) the cross sections used here may not be appropriate, and cross sections for processes other than $p + {}^{12}C$ or $p + {}^{16}O$ may dominate the production of light nuclei; (3) the observed features of the galaxy are considerably more complicated than expressed in either of the models considered here; the path-length distribution might be a more complicated function of $X$ and $E$. We tried to avoid treating the path-length as a totally phenomenological parameter.

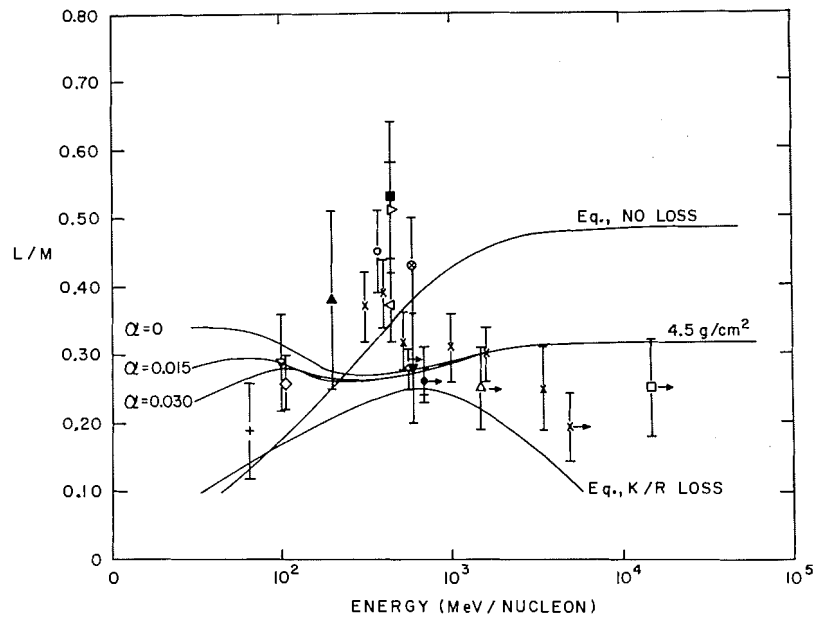


FIG. 2. Energy dependence of the L/M ratio. Curves labeled Eq. are calculated from equilibrium (steady state) theory, with and without loss from the galaxy; other curves are for passage through 4.5 g/cm² of material with varying amounts of Fermi acceleration (see text). Data are taken from the compilation in Reames and Fichtel (1967).

In view of the poor agreement of the theories with the L/M data we do not present other ratios which have been calculated with these individual-element abundances obtained from the theories.

## REFERENCES

ALBOUY, G., COHEN, J. P., GUSAKOW, M., POFFE, N., SERGOLLE, H., and VALENTIN, L. 1962. Phys. Letters, **2**, 306.

BADHWAR, G. D., DANIEL, R. R., and VIJAYALAKSHMI, B. 1962. Progr. Theoret. Phys. Kyoto, **28**, 607.

BERNAS, R., EPHERRE, M., GRADSZTAJN, E., KLAPISCH, R., and YIOU, F. 1965. Phys. Letters, **15**, 147.

BERNAS, R., GRADSZTAJN, E., REEVES, H., and SCHATZMAN, E. 1967. Ann. of Phys. (to be published).

BERTINI, H. W., GUTHRIE, M. P., PICKELL, E. H., and BISHOP, B. L. 1966. Oak Ridge Natl. Lab. Rept. ORNL-3884.

COWSIK, R., PAL, YASH, TANDON, S. N., and VERMA, R. P. 1966. Tata Institute of Fundamental Research Rept. NE-66-18.

FERMI, E. 1949. Phys. Rev. **75**, 1169.

——— 1954. Astrophys. J. **119**, 1.

FICHTEL, C. E. and REAMES, D. V. 1966. Phys. Rev. **149**, 995.

GINZBURG, V. L. and SYROVATSKII, S. I. 1964. The origin of cosmic rays (Macmillan Co., New York).

REAMES, D. V. and FICHTEL, C. E. 1967. Phys. Rev. **162**, 1291.

WILLIAMS, I. R. and FULMER, C. B. 1967. Phys. Rev. **154**, 1005.