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IMPLICATIONS OF *HEAO 3* DATA FOR THE ACCELERATION AND PROPAGATION OF GALACTIC COSMIC RAYS

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ABSTRACT

We reexamine the energy dependence of the mean escape length of cosmic rays from the Galaxy in the light of recent measurements of cosmic-ray abundances from the Danish-French experiment on *HEAO* 3. On comparing these data with results of our propagation calculations, we find that the energy dependence is steeper than previously thought. The boron to carbon, nitrogen to oxygen, and $21 \leqslant Z \leqslant 25$ to iron ratios at energies above 2.8 GeV per nucleon are best fitted with 95% confidence by a rigidity dependence $R^{(-0.7 \pm 0.1)}$.

This, coupled with the absence of structure in the proton spectrum to 10^{14} eV, implies that 1 GeV per nucleon cosmic rays do not diffuse more than a few hundred parsecs from their sources during their 10^7 year lifetime. Further, if the source spectrum is produced by shock acceleration, the shocks must be strong (compression ratio 4 or certainly greater than 3.5). The shapes of the observed energy spectra are well fitted by this source spectrum. We also agree with earlier conclusions by the University of Chicago group concerning the impact of their data from *IMP* on the decrease in the path length at lower energies (< 1 GeV per nucleon). We discuss implications for the shape of the cosmic ray path length distribution at short path lengths and on the galactic wind model for the loss of cosmic rays from the Galaxy by convection.

Subject headings: cosmic rays: abundances — cosmic rays: general — galaxies: internal motions — particle acceleration — shock waves

I. INTRODUCTION

Highly accurate new data on the relative abundances of cosmic-ray nuclei (boron through nickel) in the energy range 0.9 to 15 GeV per nucleon are now available (Engelmann *et al.* 1981). These data have been obtained on the Danish-French collaborative experiment (Bouffard *et al.* 1982) flown on board the *HEAO 3* satellite which was launched on 1979 September 20. At the same time, new, more accurate measurements of some of the cross sections upon which an interpretation of these data must be based have been made and are available (Webber and Brautigam 1982; see also survey of total cross section measurements by Letaw, Silberberg, and Tsao 1983). Using these new data and earlier low-energy measurements, we have reexamined the nature of cosmic-ray acceleration and propagation.

The energy dependence of the secondary-to-primary ratios allows us to determine the energy dependence of the mean escape length, λ_e. We shall use this, together with the measured proton energy spectrum, to infer the source spectrum, i.e., the spectrum of cosmic rays after acceleration. The result will be discussed in terms of predictions of shock acceleration models (Axford, Leer and Skadron 1977; Bell 1978*a*, *b*; Blandford and Ostriker 1978, 1980). The energy dependence of the mean escape length inferred from the data at low energies has previously been shown by the University of Chicago group (Garcia-Munoz *et al.* 1979) to require a reduction in λ_e with decreasing energy below ~ 1 GeV per nucleon. We find this reduction is more rapid than can be accounted for in dynamical halo models. Using the inferred source spectrum and energy dependence of λ_e, we will show that the observed energy spectra of primary species can be satisfactorily accounted for.

II. SOURCE SPECTRA

Cosmic-ray energy spectra must reflect the mechanism by which they have been accelerated. The range from 100 MeV nuc^{-1} to 1 GeV nuc^{-1}, in which particle energies transition from the nonrelativistic to the relativistic regime is particularly crucial in this regard as, at these energies, the effects of the various mechanisms differ and are reflected in the predicted spectral shapes. In this section we shall discuss the shape of the spectra predicted by shock acceleration models over the whole energy range accessible to observation of the galactic cosmic rays.

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At energies where individual cosmic-ray species may be identified, it is customary to measure their flux as a function of kinetic energy per nucleon, T. Previous analyses of the solar modulation have shown that the demodulated spectrum outside the heliosphere must lie somewhere between a power law in total energy and a power law in rigidity with exponent -2.7. These spectra cannot be distinguished at high energy. Extensive analyses by the University of Chicago group (Garcia-Munoz, Mason, and Simpson 1975*a*, *b*), taking account of solar modulation and assuming energy independent propagation, give a best source spectrum $dJ/dT \propto (T + 400 \text{ MeV per nuc})^{-2.6}$ at energies below a few GeV per nucleon. This spectrum is plotted in Figure 1. However, this is only an empirical fit to the data, and it would be desirable to find a theoretical justification for this shape.

The shock acceleration mechanism gives a definite prediction for the shape of the source spectrum. This, along with our current understanding of the propagation of cosmic-ray nuclei, allows us to predict the interstellar energy spectra of cosmic-ray nuclei. We summarize here the relevant discussion of acceleration of cosmic rays by shocks (see review paper by Axford 1981).

A plane shock of infinite extent will produce a density of particles N which is a power law in momentum p,

$$dN = kp^{-(2+\varepsilon)}dp\,, \tag{1}$$

where the exponent depends upon the strength of the shock. Defining r as the ratio of the velocities of the shocked and the unshocked materials, V_1 and V_2, respectively, then

$$\varepsilon = \frac{4-r}{r-1}\,. \tag{2}$$

For strong shocks, $r = 4$, hence $\varepsilon = 0$.

The acceleration mechanism involves momentum rather than rigidity. This is because the relative motion of the shocked and unshocked material provides a momentum increment each time a particle crosses the shock boundary, even though the scattering mechanism which keeps the particle near the shock front may be a rigidity-dependent phenomenon due to the magnetic turbulence. A power law results, the high-energy particles having traversed the shock many times.

In the event of acceleration by more than one shock, the spectrum will be determined by the strongest shock. Axford (1981) shows that shocks which are strong enough to produce the cosmic-ray spectrum occupy only a small volume of space, so it is unlikely that the observed particles have been subjected to more than one strong shock during their lifetimes.

The maximum energy to which particles can be accelerated will depend upon how long they can be trapped near the shock front. While the power law produced is *independent* of the scattering mechanism (hence not a rigidity process), the energy at which the trapping mechanism begins to break down will be rigidity dependent. One of two factors will ultimately limit the rigidity to which particles can be accelerated: (*a*) the gyro-radius of the particles could be so large that the shock no longer looks planar; (*b*) the particles could fail to be trapped near the shock front (diffusion coefficients tend to rise with increasing rigidity) for a sufficiently long time (the higher the energy, the longer the acceleration time required). In either case, the mechanism will break down at constant rigidity. Current estimates for the maximum rigidity that can be obtained by acceleration in supernova shocks are less than 10^6 GV c^{-1} (Cesarsky and Lagage 1981).

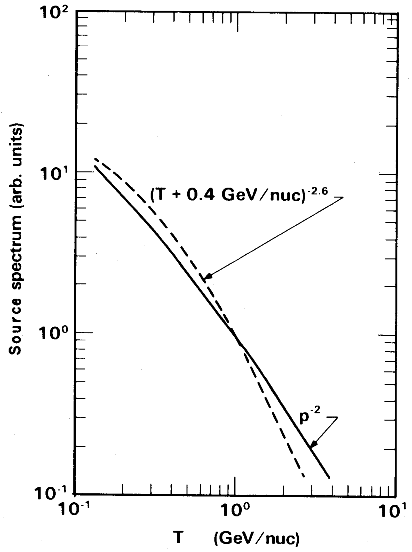

FIG. 1.—Comparison between source spectra inferred from low-energy cosmic-ray data (Garcia-Munoz, Mason, and Simpson 1975*a*, *b*) and that expected from acceleration with strong shocks (see text).

As a function of kinetic energy per nucleon, the cosmic-ray energy spectrum per unit volume at production (eq. [1]) becomes:

$$dN = kp^{-(2+\varepsilon)}(A/\beta c)\,dT, \tag{3}$$

where A is the atomic mass number of the nucleus and βc is the particle velocity.

Converting from particle density N to flux J we obtain:

$$dJ = kp^{-(2+\varepsilon)}(A/4\pi)\,dT. \tag{4}$$

We compare in Figure 1 this source spectrum expected for strong shocks ($\varepsilon \ll 1$) with that obtained from the low-energy data as discussed earlier. From 100 MeV nuc^{-1} to 1 GeV nuc^{-1} the spectra agree within 30% when normalized at 1 GeV nuc^{-1}.

The spectrum $(T+400)^{-2.6}$ has been used to interpret cosmic-ray propagation data (Garcia-Munoz *et al.* 1981*a* and references therein). This spectrum, when propagated in an energy *independent* manner, gives a reasonable fit to the demodulated spectra. However, it must be modified for energy dependent propagation effects in order to derive a source spectrum. Webber (1981) came to a similar conclusion and showed that the source spectrum at high rigidity should be of the form $dJ/dT \propto R^{-(2+\varepsilon)}$. We use the source spectrum given in equation (4) to interpret the data at all rigidities.

III. PROPAGATION EFFECTS

The cosmic-ray spectra outside the heliosphere will be affected by the propagation of the particles from their source through the interstellar medium. For secondary nuclei, which are produced by interactions in the interstellar material, the source spectra will be similar to the equilibrium spectra of the primaries. Above a few GeV per nucleon, the spectra of secondaries are observed to be steeper than of primaries (see, e.g., Ormes and Freier 1978). In the leaky box model (see Cowsik *et al.* 1967) or in a diffusion picture (see Ginzburg and Ptuskin 1976), higher energy particles must leak out of the Galaxy more easily (faster) in order to produce equilibrium spectra that are steeper than source spectra (as reflected in the steeper spectra of secondary nuclei).

Assuming for the moment that the mean escape length can be represented as a power law of particle rigidity, $\lambda_e \propto R^{-\delta}$, the observed spectrum at energies above a few GeV per nucleon will be

$$\left(\frac{dJ}{dT}\right)_{\text{observed}} \propto \left(\frac{dJ}{dT}\right)_{\text{source}} R^{-\delta} \propto R^{-(2+\varepsilon+\delta)} \qquad (5)$$

whenever escape losses are dominant over other possible loss mechanisms. For protons, the interaction length in interstellar matter, λ_{int}, is about 60 g cm^{-2} (i.e., $\lambda_{\text{int}} \gg \lambda_e$) so interaction losses can be ignored, and the high energy proton spectrum can be used to determine $2+\varepsilon+\delta$. Proton spectral measurements (Ryan, Balasubrahmanyan, and Ormes 1972; Gregory *et al.* 1981; Tasaka *et al.* 1982) up to 10^5 GV c^{-1} rigidity (10^{14} eV) give $2+\varepsilon+\delta = 2.70 \pm 0.05$. We will infer the slope of the injection spectrum of primary species after obtaining δ from the energy dependence of ratios of secondary to primary nuclei in the cosmic rays in the next section.

a) *Mean Escape Length at High Energy*

In the early seventies it was discovered that the mean escape length decreases monotonically with energy above a few GeV per nucleon (Smith *et al.* 1973; Juliusson and Meyer 1973). On the other hand, at low energies the mean escape length becomes constant (Protheroe, Ormes, and Comstock 1981, and references therein) or even decreases (Garcia-Munoz *et al.* 1981*b*). The new *HEAO 3* data cover the energy range 0.9–15 GeV per nucleon and are of very high statistical accuracy. The available data on the energy dependence of the boron-to-carbon ratio from this experiment are plotted in Figure 2. We also show data obtained on both satellites and balloons. The satellite data at low energy (Garcia-Munoz *et al.* 1979) are from *IMP*, and the higher energy data (Engelmann *et al.* 1981) are from the *HEAO 3* cosmic-ray experiment for which the quoted statistical errors are less than ±2%. Note how rapidly the *HEAO 3* data fall with energy above 1 GeV per nucleon. The balloon data are from a variety of observations with individual references listed (original compilation: Garcia-Munoz *et al.*

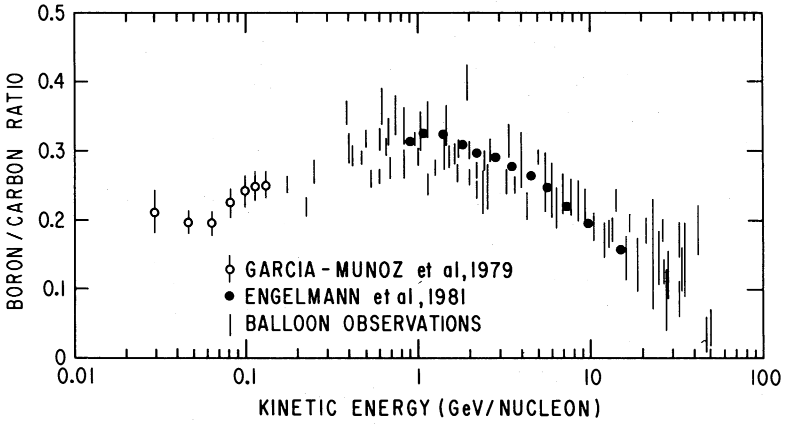

FIG. 2.—Boron-to-carbon ratios measured by *HEAO 3* and *IMP* satellites are compared with a survey of balloon observations: Arens and Ormes 1975; Buffington, Orth, and Mast 1978; Byrnak *et al.* 1977; Caldwell and Meyer 1977; Dwyer 1978; Fisher *et al.* 1976; Garcia-Munoz *et al.* 1979, 1981*a*; Hagen, Fisher, and Ormes 1977; Juliusson 1974; Julliot, Koch, and Petrou 1975; Lezniak and Webber 1978; Lund *et al.* 1975; Maehl *et al.* 1977; Orth *et al.* 1978; Simon *et al.* 1980; Smith *et al.* 1973 (and see reanalysis of Orth *et al.* 1978); Webber, Damle, and Kish 1972; Webber *et al.* 1977.

1981*b*, with additions). They are shown in order to indicate the general agreement between these and the new more accurate satellite observations. This agreement is important because of a potential problem with the *HEAO 3* data. In order to avoid triggering on delta rays with high Z nuclei, a compromise had to be made in flash tube triggering efficiency for low Z nuclei. As a result, not every low Z nucleus produced a recognizable track in the flash tube array (Rotenberg *et al.* 1981). Because of this inefficiency, lithium and some of the beryllium data cannot be used. At the quoted accuracies, it is possible that an energy dependent bias in the flash tube efficiency could affect the boron-to-carbon ratio. Both the agreement with the balloon data and, as we shall see later, other secondary to primary ratios which are not subject to this bias show this is probably not the case.

To determine the mean escape length as a function of energy, we have performed a propagation calculation for the leaky box model which takes into account nuclear interactions, radioactive decay, ionization energy losses, and solar modulation. Details of the method of calculation are given in our earlier work (Protheroe, Ormes, and Comstock 1981). In the present calculation we have used source elemental abundances derived from the *HEAO 3* data (Perron *et al.* 1982). We assumed the isotope ratios at the source to be as in solar material (Cameron 1980), except for C, O, Ne, Mg, and Si for which we used those obtained by Wiedenbeck and Greiner (1981). For source abundances of the sub-iron group (Sc–Mn) we have taken the local galactic abundances (Meyer 1979). We have used energy dependent total cross sections calculated from formulae of Letaw, Silberberg, and Tsao (1983). For spallation cross sections, we have used the semiempirical formulas (Silberberg and Tsao 1973*a*, *b*, 1977*a*, *b*, *c*; Tsao and Silberberg 1979). The semiempirical cross sections for spallation of iron have been normalized to the recent measurements of Webber and Brautigam (1982) at 980 MeV per nucleon.

Since the spallation and total interaction cross sections are expected to be almost independent of energy above ~ 2.3 GeV nuc^{-1} (Silberberg and Tsao 1977*a*), by comparing the results of our propagation calculations with the secondary-to-primary ratios observed above this energy from the *HEAO 3* experiment, we should be able to determine δ very well. We can also determine the normalization of λ_e but, for this, we must take into account a systematic error due to uncertainties in spallation cross sections. For example, the measurements for iron fragmentation cross sections of high statistical accuracy (3–4%) at 660 MeV nuc^{-1} and 980 MeV nuc^{-1} (Webber and Brautigam 1982) indicate substantial energy dependence in the cross sections which are not matched by a comparable accuracy in the semiempirical relationships used to calculate cross sections at all other energies. Furthermore there are no measurements of comparable accuracy at energies above 1 GeV nuc^{-1} and for many of the other relevant partial cross sections. Because of these limitations, we estimate the uncertainty in the normalization for λ_e due to cross sections uncertainties to be of the order of 10%. Previous estimates of the uncertainties are even larger (30%, Raisbeck 1979; 15%, Webber and Brautigam 1982).

In this section, we shall restrict our analysis to the high-energy data (2.8–15 GeV nuc^{-1}) to probe the asymptotic behavior of λ_e, avoiding biases introduced at low energies by solar modulation effects, strong energy dependence of cross sections, and velocity dependent propagation effects. For a source spectrum appropriate to acceleration by strong shocks, i.e., $dJ/dT \propto p^{-2}$, we have calculated the energy dependence of secondary-to-primary ratios for two possible forms of the energy variation of λ_e:

$$\lambda_e = \Lambda_R R^{-\delta_R}, \tag{6}$$

and

$$\lambda_e = \Lambda_T T^{-\delta_T}. \tag{7}$$

We show in Figure 3 the results of a comparison of these propagation calculations with various secondary-to-primary ratios obtained from the *HEAO 3* data over the restricted energy range 2.8–15 GeV nuc^{-1}. The results

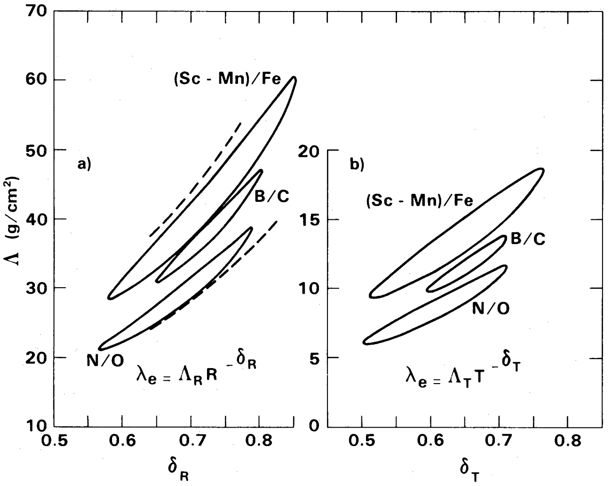

FIG. 3.—Comparison of boron-to-carbon, sub-iron-to-iron, and nitrogen-to-oxygen ratios observed from 2.8 to 15 GeV nuc^{-1} by *HEAO 3* with results of the present propagation calculations. The figure shows the goodness of fit when the parameters of eq. (6) (part *a*) or equation (7) (part *b*) are varied. The closed curves are contours of constant χ^2 corresponding to 95% probability. In section *a*, the dashed lines show the effect on the fit to the boron-to-carbon ratio of assuming a 10% uncertainty in the cross section for spallation of carbon to boron. Care must be taken in interpreting the normalization constants, which assume the rigidity (energy) dependence extends to lower rigidity (energy). The value of λ_e at 5 GeV nuc^{-1} is 6 g cm^{-2}, consistent with previous analyses.

are given, for three important secondary-to-primary ratios, in the form of the χ^2 contour plot in the $(\Lambda-\delta)$-plane. For clarity, only the contour corresponding to the 95% confidence interval has been plotted. From this figure, it is clear that for these almost purely secondary-to-primary ratios (i.e., B/C, N/O, Sc–Mn/Fe), the *HEAO 3* data give a best value of δ somewhat higher than previously realized. From all those ratios, we find $\delta_R \approx 0.7 \pm 0.1$ for the rigidity dependent fit (eq. [6]) and $\delta_T \approx 0.63 \pm 0.1$ for the kinetic energy per nucleon dependent fit (eq. [7]). There is sufficient internal consistency between calculations and the different ratios that we see no reason to question the boron-to-carbon ratio from *HEAO 3* as published.

Previous estimates based on balloon data (see data survey references) of the boron-to-carbon and other secondary-to-primary cosmic-ray ratios placed δ_T in the range 0.3–0.5. Two problems may have resulted in these lower values of δ_T. First of all, the data were of much poorer statistical significance, and so the structural features were not so pronounced. Second, the data in the atmosphere at high energy are subject to large atmospheric corrections. The latter problem is not present in the *HEAO 3* observations. As to the former problem, when we attempted fitting the *HEAO 3* data over a wider energy range, consistently poor χ^2 values resulted. Perron *et al.* (1981) in their analysis of the *HEAO 3* Be and B data suggest larger values of δ would fit better, and it is clear from the figures in their paper that they too obtain poor fits with $\delta = 0.5$ variation. If one were to ignore the quoted errors and include data at lower energies in the fit, lower values of δ_T could easily be obtained. Kinematic effects make δ_R larger than δ_T in this energy range. While kinetic energy has often been used because it is the observer's variable, magnetic scattering is a phenomenon in which rigidity is the more natural variable and so we presume that is the correct physical variable.

From the results of our propagation calculation, as shown in Figure 3, we find that the best value of Λ as obtained from the ratio of iron-secondaries to iron is about 10% higher than that obtained from the boron-to-carbon ratio. This is consistent with a slightly truncated pathlength distribution, for example as expected in the nested leaky box model (Cowsik and Wilson 1973). It would imply about 8% of λ_e could be in the source region. Unfortunately, this conclusion cannot be reached because of previously mentioned uncertainties in spallation cross sections. To illustrate this point the acceptable range of Λ_R, obtained from the boron-to-carbon data allowing for a 10% uncertainty in the partial cross sections, has been added to Figure 3*a* and includes the region between the two dashed lines. The "best" values of Λ_R obtained from the three secondary-to-primary ratios shown in Figure 3*a* appear to be entirely consistent if uncertainties in spallation cross sections of ~10% are taken into account. For further discussion of truncated pathlength distributions, see Protheroe, Ormes, and Comstock (1981) and Garcia-Munoz *et al.* (1981*a*).

Care must be taken in interpreting the normalization constants given in Figure 3. The fits are valid at 2.8 GeV nuc^{-1} and above, and the normalization constants apply to much lower energy (rigidity). From the B/C contour in Figure 3*b* and equation (7), one can readily show that the value of λ_e at 5 GeV nuc^{-1} is about 6 g cm^{-2}, consistent with previous analyses.

b) *Mean Escape Length at Low Energies*

Before interpreting the abundances of the lower energy nuclei in terms of the propagation of cosmic rays in the interstellar medium, we must allow for the effects of solar modulation. We use the simple force field approximation (Gleeson and Axford 1968) to calculate modulated spectra (observed spectra) from interstellar spectra. Throughout the remaining work, we will adopt a deceleration parameter $\phi = 600$ MeV appropriate to near solar maximum conditions (Urch and Gleeson 1973). This corresponds to a mean energy loss of 300 MeV nuc^{-1} for nuclei with $A/Z = 2$.

The variation of λ_e with energy below a few GeV per nucleon is difficult to determine reliably. This is because the precise energy dependence of many of the important spallation cross sections is not measured as a function of energy and because the secondary-to-primary ratios are altered by solar modulation. It is clear, however, that the escape length must flatten off or decrease with decreasing energy below a few GeV per nucleon. This is indi-

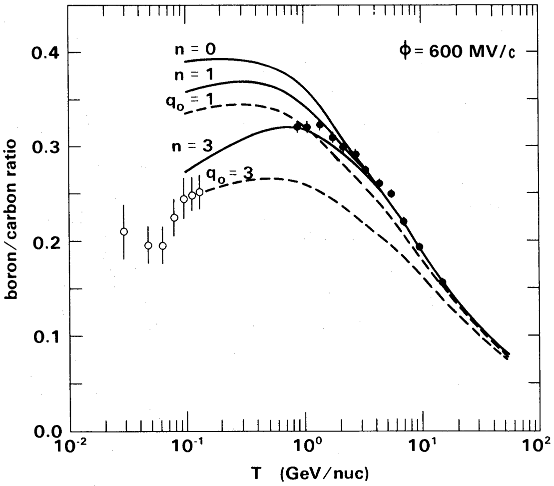

FIG. 4.—Boron-to-carbon ratio (replotted from Fig. 2). Dashed curves show predicted energy dependence for diffusion/convection model (q_0 is defined in eq. [9]). Solid curves show prediction for variation of λ_e with energy given by eq. (10). The solid curves are not based on any model but on attempts to find empirical fits. The modulation parameter assumed is $\phi = 600$ MV c^{-1}.

cated in Figure 4 where we plot the energy dependence of the boron-to-carbon ratio obtained from the satellite experiments. In the figure we show the result (solid curve labeled $n = 0$) of extrapolating the rigidity dependence of λ_e derived in § III*a* (from the high energy data) to lower energies where the calculated boron-to-carbon ratio is seen to lie significantly above the data. We will now discuss the deviation of λ_e from a simple power law in rigidity.

A power law rigidity dependence of the mean escape length, $\lambda_e \propto R^{-\delta}$, is expected in diffusion models (e.g., Ginzburg and Ptuskin 1976) for a rigidity dependence of the diffusion coefficient of the form

$$\kappa = \kappa_0 \beta R^{\delta}. \qquad (8)$$

This does not give the required flattening or reduction in λ_e at low energies. Jones (1979) and Freedman *et al.* (1980), following the suggestions of Jokipii (1976) and Owens and Jokipii (1977), realized that if the cosmic rays were convected outward in the halo, at some low energy the escape length would turn over because the time to escape would become independent of particle velocity, and hence the escape length would be proportional to velocity. The relative importance of convection and diffusion may be given in terms of a parameter q_0 (Kóta and Owens 1980) given by

$$q_0 = V_{\text{conv}} s / \kappa_0 , \qquad (9)$$

where s is the size of the halo propagation region. In Figure 4, we show (*dashed lines*) results for a dynamical halo model calculated for $q_0 = 1$ and 3 such that in the diffusion dominated regime (high energies) the variation of λ_e with rigidity is as determined above (eq. [6]). These results indicate that the rapid reduction in λ_e required by the low-energy data (Garcia-Munoz *et al.* 1979) cannot be reproduced by the slower variation produced by the dynamical halo model.

In order to parameterize how rapidly λ_e must decrease at low energies, we will compare the low-energy observations of secondary-to-primary ratios and the spectral shape with a mean escape length which involves a power of the particle velocity. The form we adopt is

$$\lambda_e = \Lambda \left[1 + (R_0/R)^2 \right]^{-n/2} R^{-\delta}, \qquad (10)$$

where $R_0 = 1.88$ GV/c. For nuclei with $A/Z = 2$, this corresponds to

$$\lambda_e = \Lambda \beta^n R^{-\delta}, \qquad (11)$$

where βc is the particle velocity. We have taken $\delta = 0.7$ and $\Lambda = 35$ g cm^{-2} of interstellar matter, consistent with the high energy boron/carbon data. We show in Figure 4 results for $n = 1$ and 3. For the degree of solar modulation assumed here, we find a reasonable fit may be obtained for $n = 3$ although lower indices would apply if the modulation were less than we have assumed here.

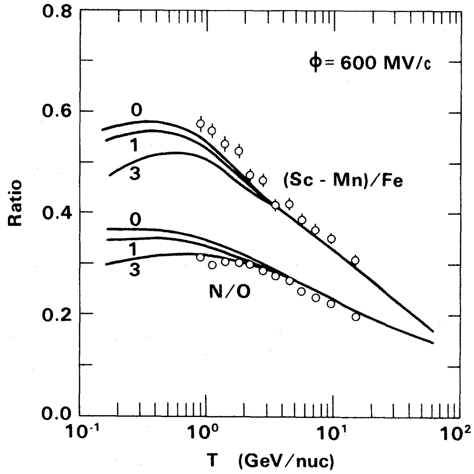

FIG. 5.—Energy dependence of nitrogen/oxygen and sub-iron/iron ratios (data from *HEAO 3* experiment). Curves give prediction for variation of λ_e with energy according to eq. (10) (numbers attached to curves give value of n).

We now show in Figure 5 how the escape length parameterized in this way agrees with the observed nitrogen-to-oxygen and sub-iron-to-iron ratios. Nitrogen is present at the cosmic-ray source, and so the observed ratio is not expected to be as steep as the boron-to-carbon ratio. The energy dependence of the nitrogen-to-oxygen ratio is in good agreement with the result for $n = 3$ while that of the sub-iron-to-iron ratio does not require such a marked flattening in λ_e as the boron-to-carbon ratio or the nitrogen-to-oxygen ratio. The reason for this is at present unknown, but it might be due to variations in the iron spallation cross sections with energy.

c) *Spectra and Solar Modulation*

We will now see how well the predicted interstellar spectra agree with those observed. In the previous section we found that the mean escape length varied steeply with energy, and that $\delta_R = 0.7 \pm 0.1$, implying a source spectrum of the form $dJ/dT \propto R^{-2}$ as expected from shock acceleration by strong shocks. We now can calculate the spectra of cosmic-ray nuclei expected outside the heliosphere.

In Figure 6 we have plotted (*open circles*) the energy spectrum of protons observed at high energies (Ryan *et al.*; this spectrum is consistent with the more recent results: Gregory *et al.* 1981; Tasaka *et al.* 1982) and at low energies we show three estimates of the interstellar proton spectrum derived after taking into account solar modulation (Morfill, Völk, and Lee 1976; Fisk, 1976;

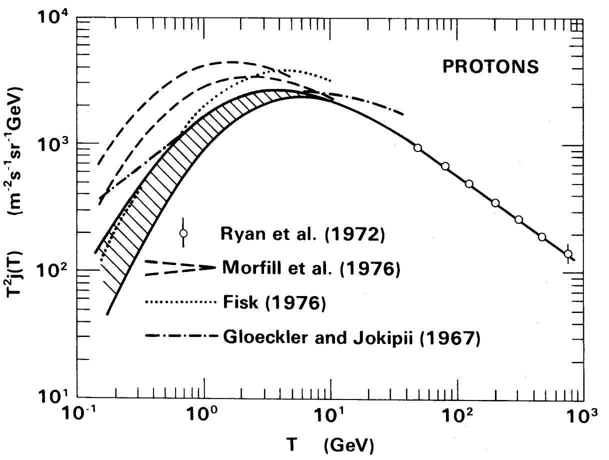

FIG. 6.—Interstellar proton spectrum. Three estimates of low energy demodulated spectrum and high energy measurements are given. The hatched area corresponds to our prediction for a p^{-2} injection spectrum and a variation of λ_e with energy given by eq. (10) with n in the range 1–3.

Gloeckler and Jokipii 1967). We have plotted (*solid lines*) the energy spectrum of protons we expect (normalized to the high-energy data) for a variation of mean escape length with rigidity as given by equation (10). The cross hatched region represents the variation over the range $1 \leqslant n \leqslant 3$. We find general agreement with the demodulated spectra at low energies (i.e., the general features are reproduced).

Because of the competition between nuclear interaction and escape, the energy spectra of primary nuclei are expected to be somewhat flatter than of protons even up to several hundred GeV per nuc. Again, in Figure 7, we have plotted the energy spectra of oxygen and iron observed by Simon *et al.* (1980) and Orth *et al.* (1978) which are indeed flatter than the spectrum observed for protons (Fig. 6). We have added to Figure 7 the spectral shapes expected from our propagation calculation which are seen to be in good agreement with the data. The normalization of these curves is determined by the source abundances; we have made no attempt here to optimize those abundances.

IV. CONCLUSIONS

We have used the highly accurate new data on secondary-to-primary ratios from the Danish-French experiment on *HEAO 3*, to determine the energy dependence of the mean matter traversed by cosmic rays in the Galaxy. The final results are shown in Figure 8. We have found that above 2.8 GeV nuc^{-1}, the variation with energy may be as steep as $\lambda_e \propto R^{-0.7}$ which would imply that primary cosmic rays may be produced with a p^{-2} spectrum as expected for acceleration by a first-order Fermi mechanism in strong shocks.

A turnover in λ_e at lower energies proportional to the cube of the particle velocity is required to fit both the lower energy *HEAO 3* ratios and the observations around 100 MeV nuc^{-1} of the boron-to-carbon ratio made with the *IMP* experiment (Garcia-Munoz *et al.* 1979). As they stated in that paper, if the solar modulation is as strong as generally believed (200–300 MeV nuc^{-1} energy loss), the turnover at about 1 GeV nuc^{-1} is very rapid, i.e., much more rapid than can be accounted for by the dynamical halo model.

A slight truncation of the pathlength distribution may be indicated by the *HEAO 3* data as well as by the *IMP* data. For example, in the nested leaky box model about

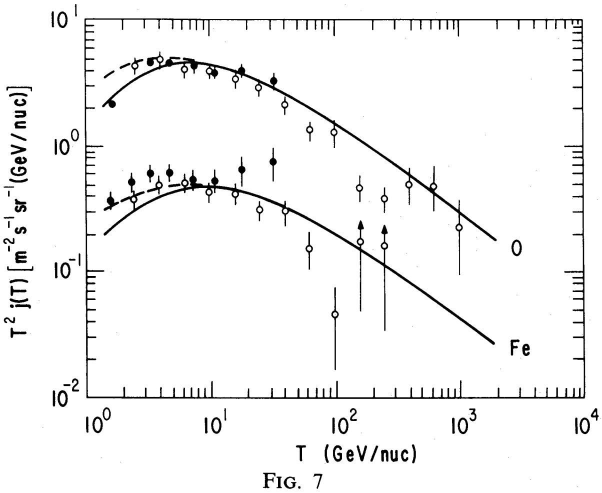

FIG. 7

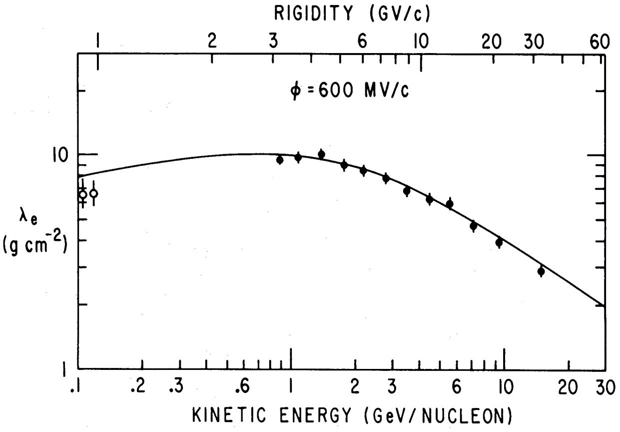

FIG. 8

FIG. 7.—Observed iron and oxygen energy spectra (*open circles*: Simon *et al.* 1980; *full circles*: Orth *et al.* 1978; *dashed lines*: predicted interstellar spectra; *solid lines*: modulated spectra [model as in Fig. 6]).

FIG. 8.—Summary of the derived mean escape length as a function of energy. The curve is the empirical fit based on eq. (10) with $n = 3$. The best escape length derived from each individual *HEAO 3* data point and those of *IMP* above 100 MeV nuc^{-1} are shown based on $\phi = 600$ MV c^{-1} modulation parameter.

8% of the mean matter traversed could be around source regions. However any conclusion is premature because of uncertainties in spallation cross sections. Now that cosmic-ray data are available with a statistical accuracy approaching 2%, it is important to measure the energy dependence of the major spallation and total cross sections to a similar accuracy so that more explicit conclusions can be drawn.

The steep rigidity dependence of the escape length derived here has some important consequences regarding the distance cosmic rays can propagate under the assumption of their diffusive storage in the Galaxy. Given an age of the cosmic rays and the assumption that this age corresponds to the escape time from a given storage volume, one can derive an upper limit to the size of that storage volume based on the fact that the cosmic-ray age must be greater than the speed of light crossing time for the region. Since there is no observed structure (e.g., change of slope) in the proton spectrum up to 10^5 GeV c^{-1} (Gregory *et al.* 1981; Tasaka *et al.* 1982), we conclude that the rapid decrease of λ_e with rigidity continues up to this energy. The lifetime of cosmic rays is proportional to the escape length. Extrapolating from the 10^7 year age (Wiedenbeck and Greiner 1980; Garcia-Munoz, Simpson, and Wefel 1981) at 1 GeV c^{-1} using the $R^{-0.7}$ dependence derived in this paper, the age at 10^5 GeV c^{-1} is about 3000 years and the size of the "storage region" must be less than 1 kpc. Since particles which diffusively propagate must strongly satisfy this inequality, the cosmic rays we observe locally probably come from within a few hundred parsec and are lost (i.e., have a low probability of returning to the solar system) once they diffuse very far from the disk of the Galaxy. If the escape law were $R^{-0.5}$, as previously believed, this size limit would be an order of magnitude larger.

We have also shown that the *HEAO 3* data cannot be fitted in detail by the combination of diffusive and convective losses postulated by the dynamical halo model. This statement is even stronger if we try to fit the *IMP* data at the same time. This is consistent with the conclusion about the scale size of the storage volume in the following sense. The convection picture discussed above and compared with data in this paper is assumed to be due to a large-scale galactic wind. Such a wind might reduce the probability that particles can return to the disk from the halo, but the effect of such winds may be unobservable locally because of the small region sampled by the cosmic rays observable at the solar system. However, a conclusion that the dynamical halo model cannot fit the observations must be tempered with the realization that the predictions themselves are subject to the uncertainties introduced by the simplifying theoretical assumptions. Our conclusion is the same as that of the Chicago group: the only way the observed decrease in the boron-to-carbon ratio below 1 GeV nucleon^{-1} can be fitted is if the modulation parameter is assumed to be very small ($\phi \leqslant 100$ MV c^{-1}, for $n = 0$), a result inconsistent with our current understanding of solar modulation.

The injection spectrum derived here may be inconsistent with the observations based on the electron spectrum. Recent observations (Nishimura *et al.* 1980; Prince 1979; Mauger 1981) of the electron spectrum at high energy (> 30 GeV) give a spectral exponent $\gamma = 3.2$ or 3.3. The simplest interpretation is that this asymptotic high energy slope should be one power steeper than the injection spectrum just due to the energy dependence of synchrotron losses, indicating a source spectrum of slope 2.2 or 2.3, consistent with the previously quoted rigidity dependence of the escape length ($R^{-0.5}$), but inconsistent with our result ($R^{-0.7}$). An alternative explanation, however, is that the propagation time from the nearest source is sufficiently high (perhaps due to an absence of nearby sources) that the electron spectrum we see at Earth is steeper. Such a steepening would be consistent with a slight truncation in the path length distribution. This will be explored further in a subsequent paper.

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REFERENCES

Arens, J. F., and Ormes, J. F. 1975, *Phys. Rev.*, **D12**, 1920.

Axford, W. I. 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **12**, 155.

Axford, W. I., Leer, E., and Skadron, G. 1977, *Proc. 15th International Cosmic Ray Conference*, **2**, 273.

Bell, A. R., 1978*a*, *M.N.R.A.S.*, **182**, 147.

______. 1978*b*, *M.N.R.A.S.*, **182**, 443.

Blandford, R. D., and Ostriker, J. P. 1978, *Ap. J.* (*Letters*), **227**, L49.

______. 1980, *Ap. J.*, **237**, 793.

Bouffard, M., Engelmann, J. J., Koch, L., Lund, N., Rasmussen, I. L., Peters, B., and Soutoul, A. 1982, *Ap. Space Sci.*, **84**, 3.

Buffington, A., Orth, C. D., and Mast, J. S. 1978, *Ap. J.*, **226**, 355.

Byrnak, B., Lund, N., Rasmussen, I. L., and Rotenberg, M. 1977, *Proc. 15th Internat. Cosmic Ray Conference* (Plovdiv), **1**, 219.

Caldwell, J. H., and Meyer, P. 1977, *Proc. 15th Internat. Cosmic Ray Conference* (*Plovdiv*), **1**, 243.

Cameron, A. G. W. 1980, Center for Astrophysics preprint no. 1357.

Cesarsky, C. J., and Lagage, P. O. 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **9**, 250.

Cowsik, R., and Wilson, L. W. 1973, *Proc. 13th Internat. Cosmic Ray Conference*, **1**, 500.

Cowsik, R., Yash Pal, Tandon, S. N., and Verma, R. P. 1967, *Phys. Rev.*, **158**, 1238.

Dwyer, R. 1978, *Ap. J.*, **224**, 691.

Engelmann, J. J., *et al.* 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **9**, 97.

Fisher, A. J., Hagen, F. A., Maehl, R. C., Ormes, J. F., and Arens, J. F. 1976, *Ap. J.*, **205**, 938.

Fisk, L. A. 1976, *J. Geophys. Res.*, **81**, 4646.

Freedman, I., Giler, J., Keasrsey, S., and Osborne, J. L. 1980, *Astr. Ap.*, **82**, 110.

Garcia-Munoz, M., Guzik, T. G., Margolis, S. H., Simpson, J. A., and Wefel, J. P. 1981*a*, *Proc. 17th Internat. Cosmic Ray Conference*, **9**, 195.

Garcia-Munoz, M., Guzik, T. G., Simpson, J. A., and Wefel, J. P. 1981*b*, *Proc. 17th Internat. Cosmic Ray Conference*, **2**, 192.

Garcia-Munoz, M., Margolis, S. H., Simpson, J. A., and Wefel, J. P. 1979, *Proc. 16th Internat. Cosmic Ray Conference (Kyoto)*, **1**, 310.

Garcia-Munoz, M., Mason, G. M., and Simpson, J. A. 1975*a*, *Ap. J. (Letters)*, **201**, L145.

———. 1975*b*, *Ap. J.*, **202**, 265.

Garcia-Munoz, M., Simpson, J. A., and Wefel, J. P. 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **2**, 72.

Ginzburg, V. L., and Ptuskin, V. S. 1976, *Rev. Mod. Phys.*, **48**, 161.

Gleeson, L. J., and Axford, W. I. 1968, *Ap. J.*, **154**, 1011.

Gloeckler, G., and Jokipii, J. R. 1967, *Ap. J. (Letters)*, **148**, L41.

Gregory, J. C., *et al.* 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **9**, 154; and submitted to *Phys. Rev. Letters.*

Hagen, F. A., Fisher, A. J., and Ormes, J. F. 1977, *Ap. J.*, **212**, 262.

Jokipii, J. R. 1976, *Ap. J.*, **208**, 900.

Jones, F. C. 1979, *Ap. J.*, **229**, 747.

Juliusson, E. 1974, *Ap. J.*, **191**, 331.

Juliusson, E., and Meyer, P. 1973, *Ap. Letters*, **14**, 153.

Julliot, C., Koch, L., and Petrou, N. 1975, *Proc. 14th Internat. Cosmic Ray Conference (Munich)*, **12**, 4118.

Kóta, J., and Owens, A. J. 1980, *Ap. J.*, **237**, 814.

Letaw, J. R., Silberberg, R., and Tsao, C. H. 1983, *Ap. J. Suppl.*, **51**, 309.

Lezniak, J. A., and Webber, W. R. 1978, *Ap. J.*, **223**, 676.

Lund, N., Rasmussen, I. L., Peters, B., and Westergaard, N. J. 1975, *Proc. 14th Internat. Cosmic Ray Conference (Munich)*, **1**, 257.

Maehl, R. C., Ormes, J. F., Fisher, A. J., and Hagen, F. A. 1977, *Ap. Space Sci.*, **47**, 163.

Mauger, B. 1981, Ph.D. thesis, New Mexico State University.

Meyer, J. P. 1979, *Proc. 16th Internat. Cosmic Ray Conference*, **2**, 115.

Morfill, G. E., Völk, H. J., and Lee, M. A. 1976, *J. Geophys. Res.*, **81**, 5841.

Nishimura, J., *et al.* 1980, *Ap. J.*, **218**, 394.

Ormes, J. F., and Freier, P. S. 1978, *Ap. J.*, **222**, 471.

Orth, C. D., Buffington, A., Smoot, G. F., and Mast, T. 1978, *Ap. J.*, **226**, 1147.

Owens, A. J., and Jokipii, R. J. 1977, *Ap. J.*, **215**, 677.

Perron, C., *et al.* 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **9**, 118.

Prince, T. A. 1979, *Ap. J.*, **227**, 676.

Protheroe, R. J., Ormes, J. F., and Comstock, G. M. 1981, *Ap. J.*, **247**, 362.

Raisbeck, G. M. 1979, *Proc. 16th Internat. Cosmic Ray Conference*, **14**, 146.

Rotenberg, M., Rasmusson, J. L., Engelmann, J. J., Masse, P., and Rio, Y. 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **8**, 112.

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

Silberberg, R., and Tsao, C. H. 1973*a*, *Ap. J. Suppl.*, **25**, 315.

———. 1973*b*, *Ap. J. Suppl.*, **25**, 335.

———. 1977*a*, *Ap. J. Suppl.*, **35**, 129.

———. 1977*b*, *Ap. J. Suppl.*, **35**, 137.

———. 1977*c*, *Proc. 15th Internat. Cosmic Ray Conference*, **2**, 84.

Simon, M., Spiegelhauer, H., Schmidt, W. K. H., Siohan, F., Ormes, J. F., Balasubrahmanyan, V. K., and Arens, J. F. 1980, *Ap. J.*, **239**, 712.

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

Tasaka, S., *et al.* 1982, *Phys. Rev.*, **D25**, 1765.

Tsao, C. H., and Silberberg, R. 1979, *Proc. 16th Internat. Cosmic Ray Conference*, **2**, 202.

Urch, J. H., and Gleeson, L. J. 1973, *Ap. Space Sci.*, **20**, 117.

Webber, W. R. 1981, *Proc. 17th Internat. Cosmic Ray Conference*, **2**, 63.

Webber, W. R., and Brautigam, D. A. 1982, *Ap. J.*, **260**, 894.

Webber, W. R., Damle, S. V., and Kish, J. 1972, *Ap. Space Sci.*, **15**, 245.

Webber, W. R., Lezniak, J. A., Kish, J., and Simpson, G. A. 1977, *Ap. Letters*, **18**, 125.

Wiedenbeck, M. E., and Greiner, D. E. 1980, *Ap. J. (Letters)*, **239**, L139.

———. 1981, *Phys. Rev. Letters*, **46**, 682.

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