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Source energy spectra of heavy cosmic ray nuclei as derived from the French-Danish experiment on HEAO-3

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Summary. Cosmic ray energy spectra at the source have been derived from the spectra observed near Earth by the HEAO-3 spacecraft for C, O, Ne, Mg, Si, Ca, and Fe nuclei. The calculations have been performed in the framework of the leaky box model, using for the escape length the values deduced from the secondary B/C and (Sc-Cr)/Fe ratios.

All these source energy spectra look very similar; they are well fit between 1 and 25 GeV/n by a power law in momentum with an exponent $\gamma = -2.41 \pm 0.05$. The modulation parameter used in the calculation is 600 MV, which seems appropriate for the period considered (Oct. 79–June 80). Comparison with data obtained at higher energy, in particular, by the JACEE collaboration suggests a progressive flattening of the $C+N+O$ spectrum when going to the TeV/nucleon region, the exponent being consistent with ~ 2.1 in this latter domain. H and He source energy spectra have been derived from other observations in the framework of the same energy dependent leaky box model. The same spectral index of 2.1 applies to the H spectrum at all energy, from 100 TeV down to a few GeV: no steepening is observed when going towards lower energies. The situation is not clear for the He spectrum due to the spread of the data. These observations might suggest that a soft component of heavy nuclei, with spectral index ~ 2.7 is superposed to a common source spectrum, with spectral index 2.1. More accurate observations between 1 and 1000 GeV/n are needed to confirm this point.

Key words: cosmic rays – energy spectrum

1. Introduction

The French-Danish experiment on board HEAO-3 has registered a large number of high energy particles, the charge and energy of which have been measured with good accuracy. From these data it has been possible to derive the relative composition of cosmic rays from B to Zn and their energy spectrum between 0.8 and 25 GeV/nucleon (hereafter GeV/n) (Engelmann et al., 1983; Juliusson et al., 1983).

For mostly primary nuclei (C, O, Ne, Mg, Si, Ca, and Fe) it is possible to derive the source spectra from the observed spectra if we make some assumptions regarding the propagation characteristics for the radiation in the Galaxy. It is particularly interesting to know whether the source spectra are the same for all nuclei: if not, it would imply contributions from different sources with specific compositions and energy spectra. It is also desirable to know whether the spectral indices found in the energy range covered by our instrument are different from those measured at higher energy and whether these spectral shapes support the predictions of the shock wave acceleration theory.

2. Method of derivation of the spectra at the source

The energy spectra of the most abundant nuclei at Earth have been obtained with good accuracy, as shown in Fig. 1 (Juliusson et al., 1983).

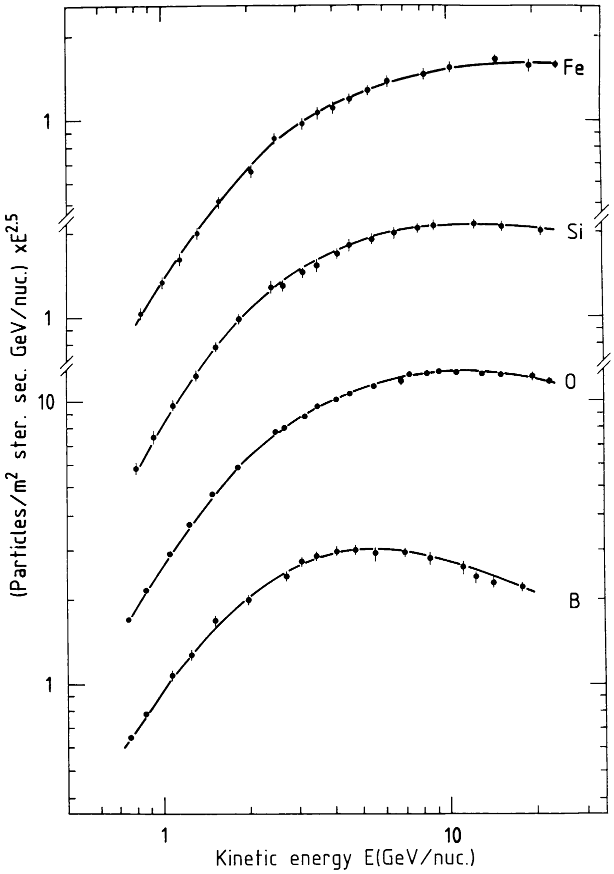

Fig. 1. Examples of energy spectra observed at Earth by our instrument on HEAO-3 for B, O, Si, and Fe nuclei. The spectra have been "flattened" i.e. multiplied by $E^{2.5}$ where E is the kinetic energy per nucleon. The curves are drawn only to guide the eye

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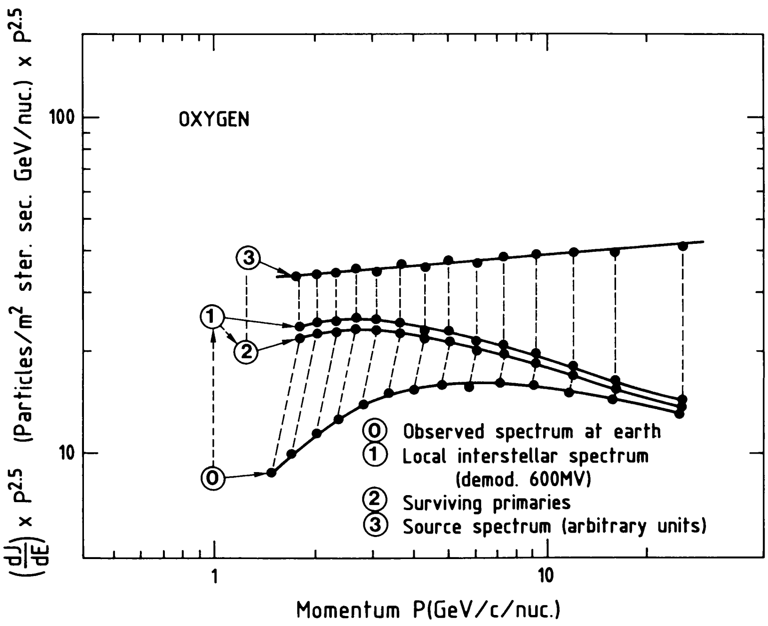

Fig. 2. *Curve 0:* "flattened" oxygen energy spectrum dJ/dE versus momentum per nucleon P. *Curve 1:* spectrum outside the heliosphere after correction for solar modulation. *Curve 2:* spectrum of surviving primaries obtained after multiplication of each flux value of curve 1 by the corresponding correction coefficient for secondary formation plotted in Fig. 3. *Curve 3:* derived source strength (arbitrary units), after allowance for destruction, escape and energy loss by ionization of primaries between source and local interstellar medium

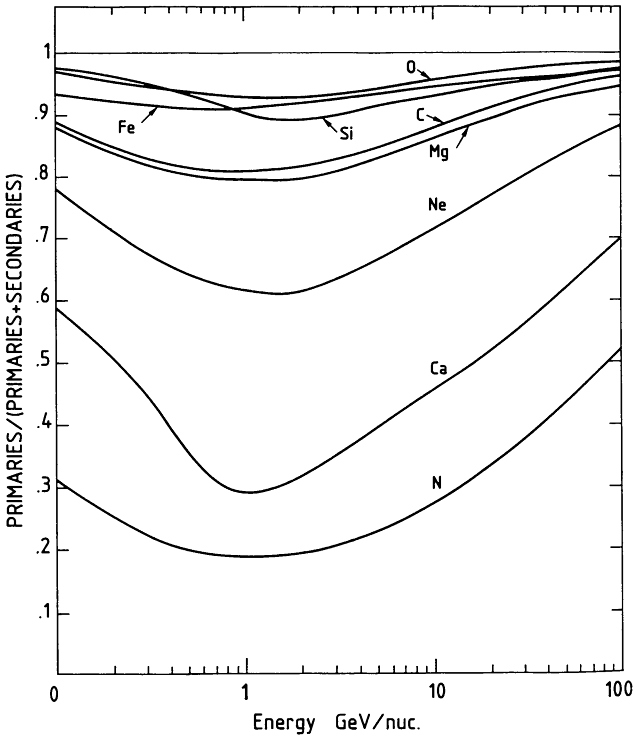

Fig. 3. The proportion of surviving primaries among the cosmic ray nuclei present outside the heliosphere is shown for selected elements. The relative abundances of C, N, O, Ne, Mg, Si, Ca, and Fe nuclei assumed at the source are respectively: 0.844, 0.060, 1.000, 0.125, 0.208, 0.195, 0.0117, 0.181

In this figure the observed spectra have been multiplied by $E^{2.5}$, where E is the kinetic energy per nucleon, in order to make the differences between the curves more apparent. To derive the source spectra, "propagated spectra" have been earlier computed starting from power law source spectra with different indices and for different values of the modulation parameter. These input parameters were varied until the computed spectra for the different elements agreed well with the observed spectra (Koch-Miramond et al., 1983).

In the present approach, we want to derive more precise source spectra by starting from the observed flux values themselves and going backwards to the source in three steps (Fig. 2):

1. We first derive the local interstellar spectra (curve 1 of Fig. 2) by "demodulating" the observed spectra (curve 0), using the "force field solution" (Gleeson and Axford, 1968). For the period of measurement (Oct. 79 to June 80), the modulation parameter ϕ was estimated to lie around 550 MV (Lockwood and Webber, 1979, 1981).

2. Next we correct the demodulated flux values for the nuclei of secondary origin produced in the interstellar medium and obtain the local interstellar flux of the surviving primaries $J(E)$ (curve 2 of Fig. 2).

To get the flux of surviving primaries from the interstellar flux (primaries + secondaries), we must apply a correction factor to remove the secondary formation of the element under consideration. This correction factor has been plotted in Fig. 3 for a few key elements. In this plot, the secondary particles include all particles for which a change of mass has occurred between the source and the solar environment. It is clear from this figure that our analysis procedure will be more precise for O and Fe (and Si to a lesser extent), making these elements particularly suitable for derivation of accurate source spectra.

The correction factor needed in this procedure was obtained by running the propagation program with all formation cross sections equal to zero, but with the total destruction cross section unchanged; the values of the input parameters used in this run were those obtained previously by Koch-Miramond et al. (1983). The source spectrum was assumed to be a power law of the momentum with an index of -2.4; but the correction factors are not sensitive to the exact shape of the source spectrum.

The rigidity dependence of the mean escape length $\lambda_e(R)$ has been derived from our measurement of the secondary/primary ratios B/C and (Sc + Ti + V + Cr)/Fe. (Rigidity has been chosen as the parameter here since it is the most likely parameter governing the propagation and escape of particles in galactic magnetic fields.)

The best fit to these data has been obtained with:

$$\lambda_e(R)=(22\pm2)\cdot R^{-0.60\pm0.04}\,\mathrm{g/cm^2} \quad \text{for} \quad R\geqq 5.5\,\mathrm{GeV}$$

$$\left(\text{i.e. } E>2\,\mathrm{GeV/n} \text{ for } \frac{A}{Z}=2\right),$$

$$\lambda_e(R)=7.9\pm0.7\,\mathrm{g/cm^2} \quad \text{for} \quad 3<R<5.5\,\mathrm{GV}$$

$$\left(\text{i.e. } 0.8<E<2\,\mathrm{GeV/n} \text{ for } \frac{A}{Z}=2\right). \tag{1}$$[1]

of pure hydrogen (Koch-Miramond et al., 1983).

3. Finally, we derive the differential source strength $\frac{dQ}{dE}$ (curve 3 of Fig. 3) from $J(E)$, using the relationship:

$$\frac{dQ}{dE}\propto J(E)\cdot\left(\frac{1}{\lambda_{di}}+\frac{1}{\lambda_e(E)}\right)-\frac{\partial}{\partial E}\left[J(E)\cdot\frac{dE}{dx}\right], \tag{2}$$

where λ_{di} is the pathlength for nuclear destruction of the element i in the interstellar medium. Its value, which is essentially independent of E over our energy range is derived from the mass changing cross section in pure hydrogen given by the formula of Letaw et al. (1983a). $\frac{dE}{dx}$ is the stopping power of the particle in pure hydrogen and is charge and energy dependent. The ionization energy loss term $\frac{\partial}{\partial E}$ is taken into account using the approximation of Letaw et al. (1983b).

The ionization losses lead to a slight increase of the source strengths required to account for the observed fluxes. In the extreme case of iron, we find that this correction amounts to ~16% at 1 GeV/n and ≦2% at 10 GeV/n.

We shall try to approximate the resulting source strength by simple analytical laws. We have used earlier (Perron et al., 1981) a power law in total energy:

$$\frac{dQ}{dE}\propto E_{tot}^{-\gamma}. \tag{3}$$

In fact, if cosmic rays have been accelerated by shock waves, the expected energy spectrum should be a power law of the momentum (see e.g. Axford, 1981; Ormes and Protheroe, 1983)

$$\frac{dQ}{dE}\propto P^{-\gamma}, \tag{4}$$

where E is the kinetic energy per nucleon and P the momentum per nucleon of the particle.

In the present study, we try to fit the data both with this type of spectrum and with a pure momentum (or rigidity) spectrum:

$$\frac{dQ}{dP}\propto P^{-\gamma}. \tag{5}$$

Note that these various laws become equivalent at high energy.

3. Results

The energy spectrum of oxygen as measured by our instrument has been plotted as a function of momentum in Fig. 2, curve 0. The source spectrum 3 is derived from this spectrum by going through the three steps described above. The same procedure has been repeated for different elements and different modulation parameters. In Fig. 4, the *energy* spectra at the source $\frac{dQ}{dE}$ obtained in this way have been plotted as a function of *momentum* for O and Fe nuclei. In the log scales used, a straight line shape is expected if Eq. (4) holds throughout the momentum range considered; it appears to be the case for both types of nuclei for the modulation parameter $\phi=600$ MV.

We can plot likewise the *momentum* spectra at the source $\frac{dQ}{dP}$ as a function of momentum (Fig. 5). Here again a straight line is expected if Eq. (5) holds. It appears to be the case for $\phi=750$ MV.

The type of spectrum corresponding to Eq. (3) (an energy spectrum which is a power law in total energy) can also fit the data over the entire energy range if the modulation parameter is only $\phi=400$ MV.

As mentioned above, the modulation parameter for the period considered lies around 550 MV (from Lockwood and Webber, 1979, 1981), so that the best agreement seems to be given by Eq. (4),

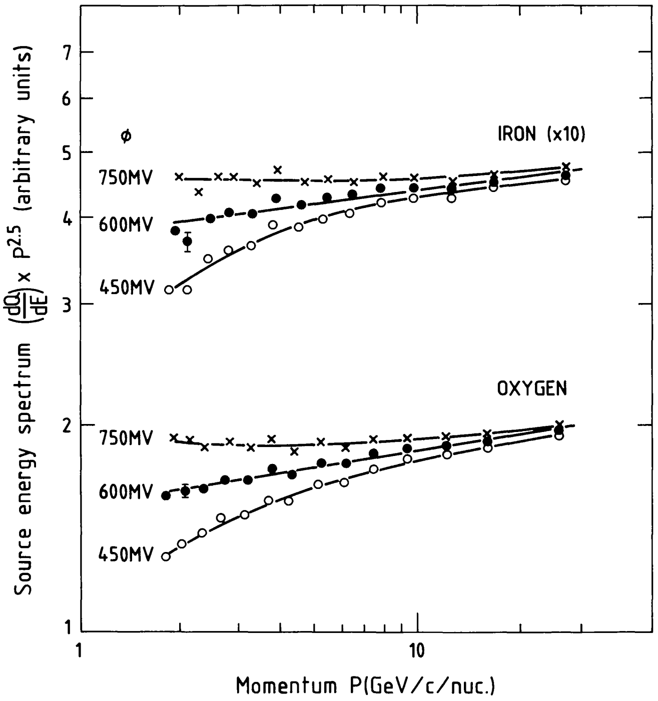

Fig. 4. Kinetic energy spectra of O and Fe nuclei at the source as a function of momentum for different values of the modulation parameter. dQ/dE is in arbitrary units

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[1] This formula is slightly at variance with that derived by Ormes and Protheroe (1983) from balloon and satellite data, including the HEAO-3 data. They tried to cover with a single equation a broader rigidity range down to 1 GV. From the B/C ratio they derive:

$$\lambda_e=a\left[1+\left(\frac{1.88}{R}\right)^2\right]^{-1.5} R^{-0.7\pm0.1}$$

which gives also a good fit to the HEAO-3 data in the rigidity range 3–50 GV for $a=30$. At high energy, this formula leads to a slope for the rigidity dependence of λ of 0.7 ± 0.1, which is consistent within errors with our quoted value of 0.6 ± 0.04

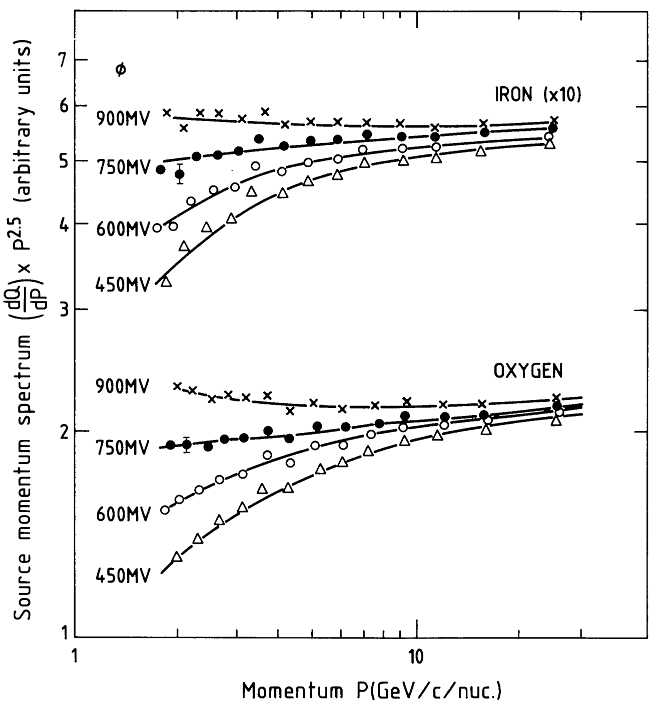


Fig. 5. Momentum spectra of O and Fe nuclei at the source as a function of momentum for different values of the modulation parameter ϕ. dQ/dP is in arbitrary units

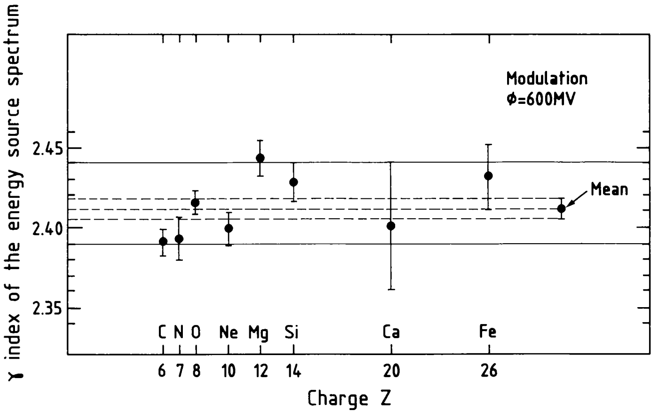


Fig. 6. γ indices of kinetic energy spectra at the source as a function of momentum ($dJ/dE \propto P^{-\gamma}$) for a few elements, for the modulation parameter $\phi = 600$ MV

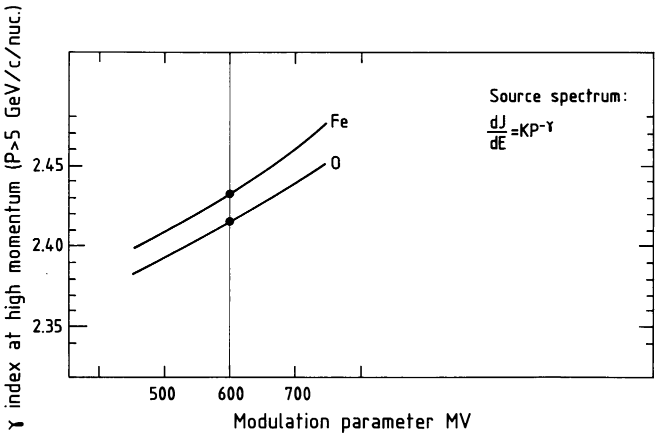


Fig. 7. Variation of the high energy O and Fe spectral indices γ with the modulation parameter ϕ

that is the law directly derived from the shock wave acceleration theory.

Using this Eq. (4) we can compute by a least square fit the indices γ of the source spectra of the different nuclei. The result is shown in Fig. 6 for the main primary elements and a modulation parameter of 600 MV. All elements appear to have very nearly the same γ (including N, for our best estimated source ratio $N/O = 0.06$; Lund, 1984): all individual γ values are within the range 2.39 to 2.44, i.e. 2.415 ± 0.025 (a weighted average of the indices for the various elements would yield 2.411).

Figure 7 shows the sensitivity of the values of γ at high energy ($P > 5$ GeV/c/n) to the choice of the modulation parameter: an error of 100 MV on the adopted value for this parameter leads to an error of 0.015 on the γ value.

The mean γ values obtained by using Eq. (5) with $\phi = 750$ MV and Eq. (3) with $\phi = 400$ MV do not differ appreciably from the one obtained with Eq. (4): they are respectively: 2.44 and 2.42, as compared to 2.416 for the adopted Eq. (4).

The errors quoted above are due to the statistical errors on the flux values and to the spread of the corresponding points only. They do not take into account the error on λ_e, mainly due to the cross section errors on the production of B by spallation of heavier nuclei. If the error on this cross section is ±20%, the propagated error on γ is ±0.05.

We conclude that the energy spectra at the source derived from our data are best fitted by a power law in momentum $\frac{dQ}{dE} \propto P^{-\gamma}$ with $\gamma = 2.41 \pm 0.05$ and a modulation parameter $\phi = 600$ MV.

This value of γ is higher than that derived by Ormes and Protheroe (1983). Their estimate of $\gamma = 2.0 \pm 0.1$ was based on their rigidity dependence of λ_e mentioned above and on the *observed spectrum of protons*. They assumed that the injection spectrum they derived was the same for all nuclei and showed that such a spectrum was in fair agreement with O and Fe observations (at the time of their publication, HEAO-3 spectral data were not available for comparison). Here we focus on the injection spectrum of heavy nuclei ($Z \geq 6$), which may differ from the proton spectrum in a certain energy range, as will be shown in the next section, so we start from the *observed spectra of heavy nuclei.*

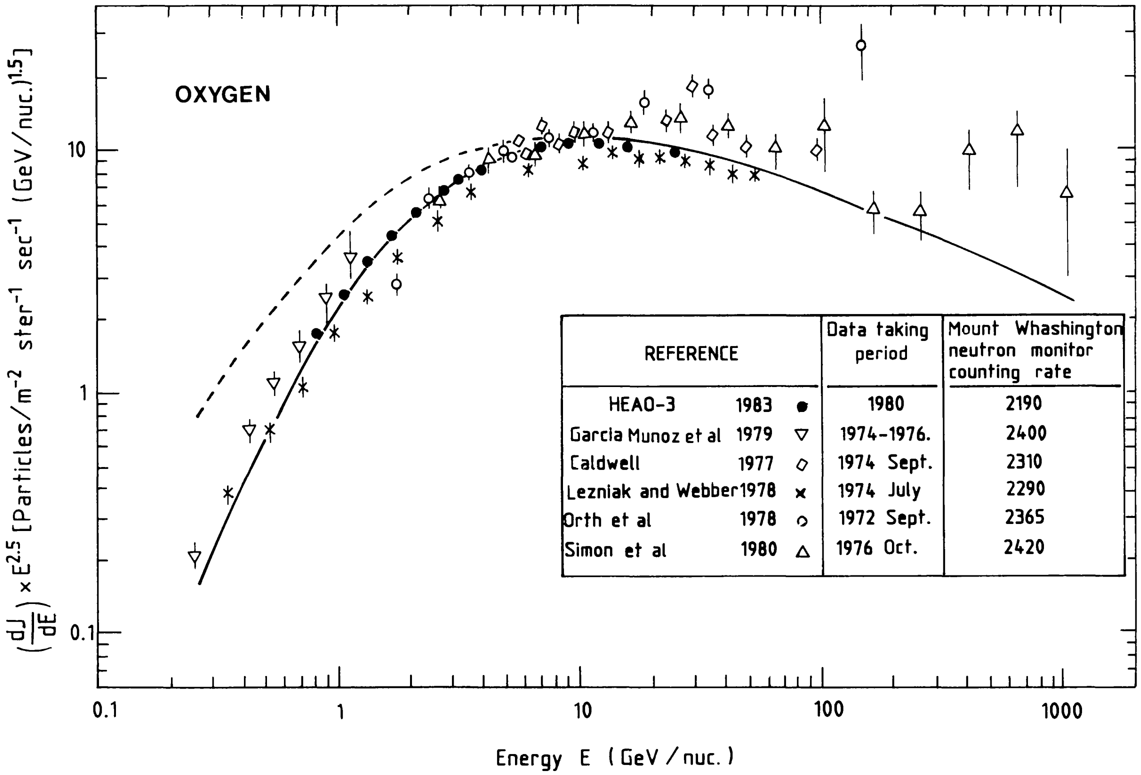
4. Discussion

Is this shape of the source spectra from C to Fe between 1 and 25 GeV/n still valid at high energy?

In Fig. 8, our observed values for the oxygen spectrum are compared with those from other experiments. Our data have been normalized in such a way that the flux at 10 GeV/n is $3.5\,10^{-2}$ m^{-2} s^{-1} sr^{-1} (GeV/n)$^{-1}$. The spread of the points corresponding to different experiments is probably mostly due to possible errors in the effective geometry assumed for each instrument. The source spectrum

$$\frac{dQ}{dE} \propto P^{-2.40}$$

which gives a good fit to the HEAO-3 data is only marginally consistent with the data between 10^2 and 10^3 GeV/c/n [but note that these data are very scattered and come from a single experiment (Simon et al., 1980)]. There are now some data for C+N+O at very high energy (above 10^4 GeV/n) from the JACEE collaboration (Burnett et al., 1984). Their observations are plotted in Fig. 9 together with our data and the available observations at



REFERENCE			Data taking period	Mount Whashington neutron monitor counting rate
HEAO-3	1983	●	1980	2190
Garcia Munoz et al	1979	▽	1974-1976.	2400
Caldwell	1977	◇	1974 Sept.	2310
Lezniak and Webber	1978	×	1974 July	2290
Orth et al	1978	○	1972 Sept.	2365
Simon et al	1980	△	1976 Oct.	2420

Fig. 8. Comparison of the *O* spectra observed by different experimenters. The HEAO-3 data have been normalized in such a way that the flux at 10 GeV/n is 3.5 10^{-2} m^{-2} s^{-1} sr^{-1} $(GeV/n)^{-1}$. A better atmospheric correction has been applied to the Lezniack and Webber's data (Webber, 1984). Indication of the level of modulation at the time of measurement is given by the counting rate of the Mount Washington neutron monitor. *Continuous curve:* propagated spectrum for a source spectrum $dQ/dE \propto P^{-2.4}$ and a modulation parameter $\phi = 600$ MV. *Dashed curve:* same source spectrum with no solar modulation

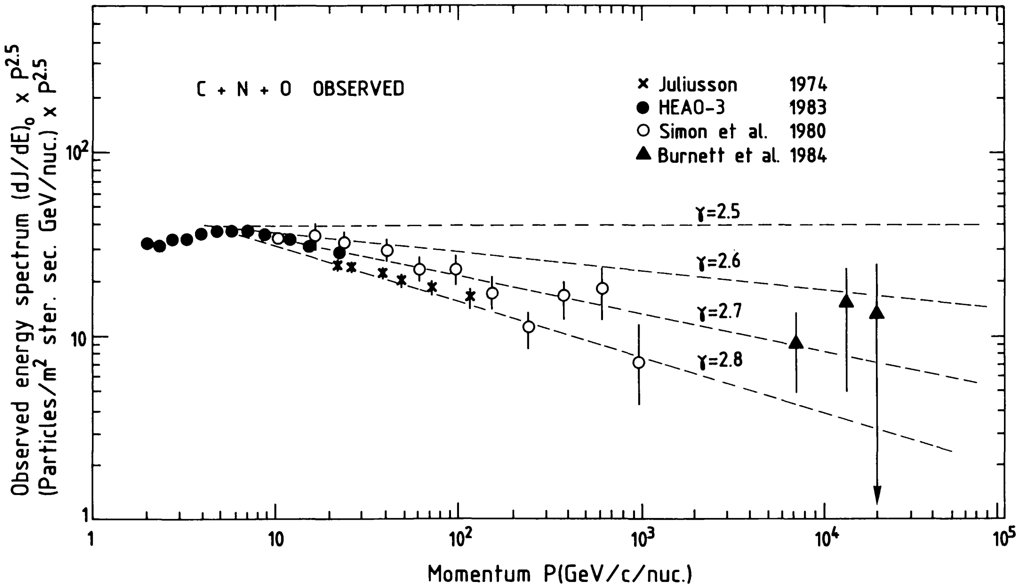


Fig. 9. Energy spectrum of CNO nuclei observed near Earth as a function of momentum *P*. The spectrum has been flattened by multiplication of the differential flux by $P^{2.5}$. The JACEE integral flux measured above an energy E_0 has been plotted at the energy E_0 and converted into differential flux by multiplication by $1.7/E_0$ where we have assumed that the index of the integral spectrum is 1.7. Note also that the error bar corresponding to each point does not include the error on the energy determination of the particle

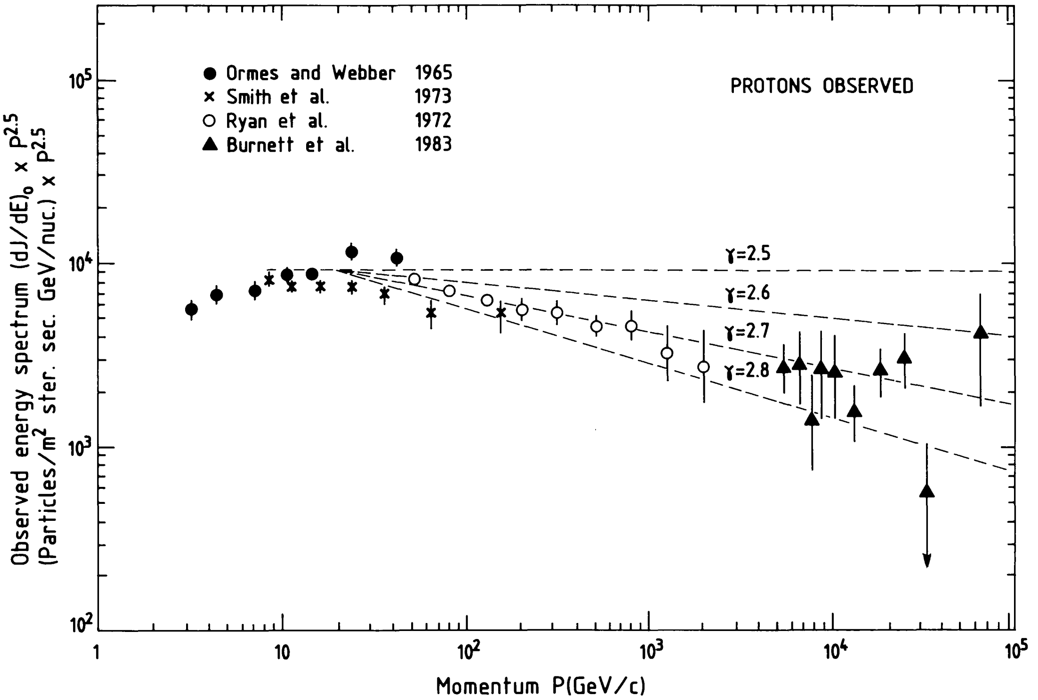


Fig. 10. Energy spectrum of protons observed near Earth as a function of momentum; see legend of Fig. 9

intermediate energies. Above 5 GeV/n the spectral index appears to be 2.7 ± 0.1. The derived source spectrum is plotted in Fig. 12 (curve 3), assuming that the $R^{-0.6}$ dependence of the escape length λ_e continues up to the TeV energy region (this extrapolation is not based on experimental data as there is no measurement of the secondary/primary ratio above ~ 50 GeV/n; (it is only suggested by the constancy of the slope of the observed proton spectrum, see Fig. 10). The general trend of the experimental points seems to favour a flattening of the spectrum toward higher energies, the spectral index decreasing from ~ 2.4 around 10 GeV/c/n to ~ 2.1 above 100 GeV/c/n. Such a trend might be related to the acceleration process: the energy spectrum of particles accelerated by strong shock (Mach number $\geqq 4$) is expected to become flatter when going to higher energy (Ellison and Eichler, 1983). The same kind of energy spectra, a power law with a spectral index slowly varying from 2.3 to 2.1 over four orders of magnitude has been found by Bogdan and Völk (1983) as a result of the changing shock strength during the active lifetime of a supernova remnant.

How do these results compare with those obtained for H and He nuclei? The observed H energy spectrum is shown in Fig. 10, where the data plotted include those from Ryan et al. (1972), who measured above 50 GeV a spectral index of 2.75 ± 0.03. Burnett et al. (1983) from the JACEE collaboration have recently extended this measurement above 5000 GeV and they have found nearly the same slope (2.81 ± 0.13). To derive from this observed spectrum the source spectrum, we work along the same lines as for the heavier nuclei; we take the same variation of the escape length with rigidity and we use for the pathlength for nuclear destruction a value derived from the attenuation cross section calculated by Rasmussen and Peters (1975):

$$\sigma_{dH} = 35(1-\eta^{\delta})\ \text{millibarn},$$

where η is the fraction of energy not lost to pions in $p-p$ collisions ($\eta \cong 0.65$ between 3 and 7 GeV) and δ is the exponent of the integral energy spectrum at the energy considered. This formula leads to $\lambda_d \simeq 150\ \text{g/cm}^2$ for $E \simeq 3$ GeV and $\lambda_d \simeq 90\ \text{g/cm}^2$ for $E \simeq 15$ GeV. These high values of λ_d show that the proton loss is dominated by escape from the galaxy even at a few GeV, so that the exact value of σ_{dH} is not critical. Neglecting the secondary contribution from heavier nuclei, we get the source spectrum plotted in Fig. 12a. It seems that above a few GeV/c a simple power law with an index of 2.11 ± 0.06 can fit all the data if we assume that the same energy dependent leaky box model applies.

The same procedure has been applied to He nuclei (Fig. 11). Here again the slope of 2.83 ± 0.13 measured above 2000 GeV/n by Burnett et al. (1983) is in good agreement with the slope of 2.77 ± 0.05 observed above 10 GeV/n by Ryan et al. (1972). We take the same model for demodulation and variation of the escape length λ_e with rigidity and we take for the nuclear destruction length $\lambda_{d\text{He}} = 17\ \text{g/cm}^2$ (Meyer, 1972). The secondary He contribution from spallation of heavier nuclei is negligible. We end up with the source spectrum plotted in Fig. 12b. In this derivation we have thus assumed that the same energy dependent leaky box model applies to He and to heavier nuclei. It is only recently that a preliminary measurement of the mean escape length of He nuclei above a few GeV/n has been obtained (Jordan and Meyer, 1984). From the observed ratio $^3\text{He}/^4\text{He}$ at 6 GeV/n and the propagation model of Meyer (1974) the authors derive a preliminary value $(\lambda_e)_{\text{He}} \simeq 15\ \text{g/cm}^2$, too large to be consistent with the simple leaky box model. We need to wait for an analysis of the composite instrumental and propagation errors before considering this conclusion as established.

Between 10 and 30,000 GeV/c/n, the best fit of the He source spectrum (cf. Fig. 12b) by a simple power law yields an index 2.17 ± 0.10. An index $\gamma = 2.11$ equal to that which fits best the H points is not easy to reconcile with the data. These data, still quite inaccurate, would be consistent with a change of slope around 100 GeV/c/n.

To summarize this discussion, the H source energy spectrum is well fitted by a single power law with index 2.1 from a few GeV/c/n

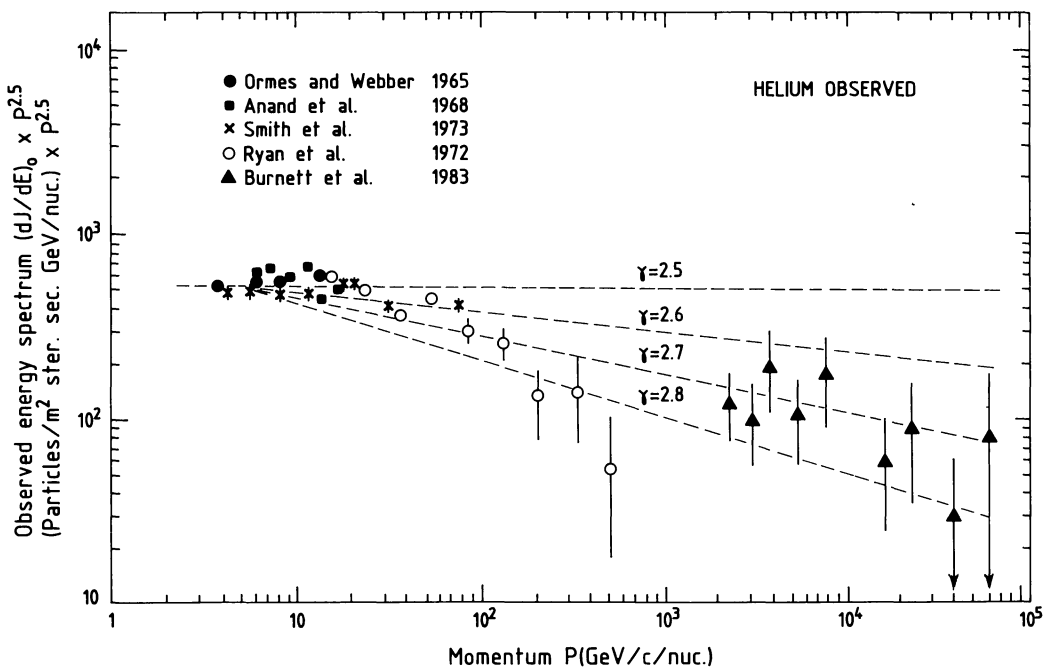


Fig. 11. Energy spectrum of He nuclei observed near Earth as a function of momentum; see legend of Fig. 9

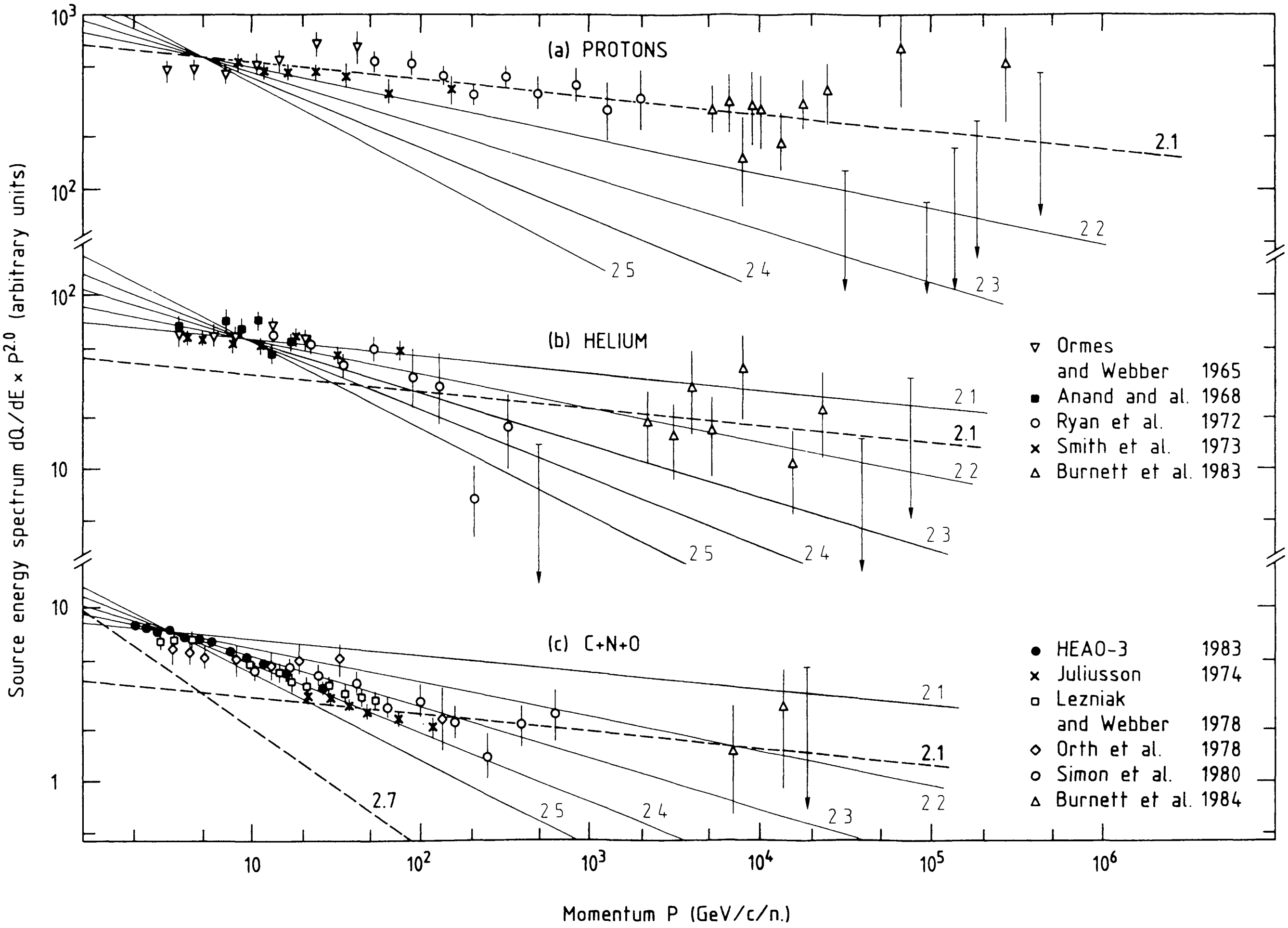


Fig. 12. Differential source strength dQ/dE vs. momentum for (a) protons, (b) He, (c) CNO nuclei. The spectra have been flattened by multiplication by $P^{2.0}$. The proton spectrum is well fitted by a power law with index $\gamma = 2.1$. The slashed lines for He and CNO are an attempt to fit their high energy data with the same spectral index. In the case of CNO nuclei, a soft component ($\gamma \simeq 2.7$) would have to be added to this main component ($\gamma \simeq 2.1$) to account for the low energy observations

up to $\sim 10^5$ GeV/c/n, while that of CNO definitely shows a break somewhere around ~ 50 GeV/c/n. Above that energy, its index could be equal to that of H (i.e., 2.1); at lower energy, it amounts to 2.4. As mentioned above, such a spectral shape might be due to the acceleration process. But it may also be interpreted in terms of the sum of two components with power law spectra: if the harder component is assumed to have the same index as H ($\gamma_{\mathrm{hard}} = 2.1$), then the softer component has an index $\gamma_{\mathrm{soft}} = 2.7$ (Fig. 12c). The measurement uncertainties on the He spectrum do not allow us to tell whether He behaves like H or like CNO.

The difference in the spectral shapes of H and heavy nuclei may be related to the recent antiproton observations. The high observed antiproton/proton radio (Golden et al., 1979; Bogomolov et al., 1979; Buffington et al., 1981) appears to be inconsistent with the value expected from the leaky box model with a $R^{-0.6}$ dependence of λ_e. This may also be the case for the $\mathrm{He}^3/\mathrm{He}^4$ ratio recently measured by Jordan and Meyer (1984). "Thick sources" added to the standard leaky box model can provide this high antiproton flux, but such sources would tend to overproduce positrons and γ rays (Lagage and Cesarsky, 1984). In addition, they would tend to enhance protons relative to heavier nuclei, while protons are observed to be conspicuously underabundant.

5. Conclusions

There is a remarkable similarity between the source spectra which we have derived for the various heavy elements in the cosmic radiation between 1 and 25 GeV/n. There is therefore no evidence in our data for contributions from several distinct sources with different compositions, yielding different spectra for particular elements below 25 GeV/n.

The precise shape of the source spectra derived from our data is slightly dependent on the assumed strength of the solar modulation. Using a modulation parameter ϕ of 600 MV, which is considered the most appropriate for the data taking period, we find that the source energy spectra for the heavy elements are well fit in the 1 to 25 GeV/n range by a single power law in *momentum* $\frac{dQ}{dE} \propto P^{-\gamma}$ with an exponent $\gamma = 2.41 \pm 0.05$. Using other values of the modulation parameter, we arrive at source spectra which may be expressed as single power laws in momentum or in total energy $\left(\frac{dQ}{dE} \propto P^{-\gamma}, \frac{dQ}{dE_{\mathrm{tot}}} \propto E_{\mathrm{tot}}^{-\gamma}\right)$. In all cases the derived values of the spectral index are close to 2.4.

Recent high energy measurement from the JACEE collaboration up to $2\,10^4$ GeV/c/n (Burnett et al., 1984) suggest a progressive flattening of the CNO spectrum above ~ 50 GeV/c/n (assuming that the rigidity dependence of the escape length from the Galaxy $\lambda_e \propto R^{-0.6}$ can be extrapolated to $2\,10^4$ GeV/c/n).

In the framework of the same rigidity dependent leaky box model, we have also derived source energy spectra for hydrogen and helium. The H source spectrum is fitted by a single power law with index ~ 2.1 throughout the energy range, with *no* bending at lower energy similar to the one observed for CNO. The situation is not clear for the He spectrum due to the insufficient accuracy of the data: it might be fitted by a single power law with a slope marginally compatible with that found for H, but the data might also suggest a bending, like that of CNO.

If real, the flattening at high energy of the source spectrum of heavy nuclei can be interpreted as being related to the acceleration mechanism. But such a spectral shape may also suggest a two-component structure for these particles. In this interpretation a soft spectral component ($\gamma \simeq 2.7$) of heavy nuclei ($Z \geqq 6$) might be superposed upon the common spectrum of all cosmic rays ($\gamma = 2.1$ to 2.2).

But irrespective of the interpretation, the observation of a difference of behaviour between the proton and heavier nuclei spectra constitutes by itself an additional piece to the puzzle of the cosmic ray origin.

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