SOURCE SPECTRAL INDEX OF HEAVY COSMIC RAY NUCLEI

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1. Introduction. From the energy spectra of the heavy nuclei observed by the French-Danish experiment on HEAO-3, we have derived the source spectra of the mostly primary nuclei (C, O, Ne, Mg, Si, Ca and Fe) in the framework of an energy dependent leaky box model (Engelmann et al. 1985). The energy dependence of the escape length was derived from the observed B/C and sub-iron/iron ratios and the presently available cross sections for C and Fe on H nuclei (Koch-Miramond et al., 1983). A good fit to the source energy spectra of all these nuclei was obtained by a power law in momentum with an exponent $\gamma = -2.4 + 0.05$ for the energy range 1-25GeV/n (Engelmann et al. 85). Comparison with data obtained at higher energy suggested a progressive flattening of these spectra.

In the present paper we want to derive more accurate spectral indices by using better values of the escape length based on the latest cross section measurements (Webber 1984, Soutoul et al. this conference). Our aim is also to extend the analysis to lower energies down to 0.4GeV/n (kinetic energy observed near earth), using data obtained by other groups. The only nuclei for which we have a good data base in a broad range of energies are O and Fe , so the present study is restricted to these two elements.

2. Derivation of the source spectra. We work along the same lines as in Engelmann et al. 1985. We first derive the interstellar spectrum by "demodulating" the observed spectrum, using the "force field approximation" (Gleeson and Axford, 1968) ; then we correct the demodulated flux values for the nuclei of secondary origin produced the interstellar medium and for the energy loss suffered by the particles during their propagation. We get the interstellar flux of the "surviving" primaries J(E), which is related to the source strength dQ/dE by the relationship :

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

where λ_{di} is the pathlength for nuclear destruction of the element i in the interstellar medium and λ_e is the escape length, the value of which is derived in a companion paper (Soutoul et al., 1985). $\partial/\partial E$ is the ionization energy loss term and dE/dx is the stopping power of the particle in pure H.

When applying this step by step procedure, we are faced with two difficulties : i) if the modulation correction is too large, the uncertainty on its value will lead to a large uncertainty in the interstellar flux value. To keep this kind of error at a relatively low level, we select among the published data those registered in such conditions (energy range, modulation level) that the modulation

correction on the flux values does not exceed 35%. When this condition is fulfilled an error of 0.10 GV on the modulation parameter around a mean value of 0.40GV leads to a maximum error of 10% on the flux value corrected for modulation.   ii) For the flux value registered by a particular experiment at a given energy, there are two major causes of errors : the statistical error and a systematic error due to the uncertainties on the exposure factor of the instrument and on the atmospheric corrections for balloon experiments. If we renormalize the data in order to put certain flux values from different experimenters in agreement we introduce a subjective feeling in the choice of these flux values. To avoid this problem we do not try to derive from the data the absolute flux values but merely the spectral indices measured by each experimenter in given energy ranges.

3. Data base used in this study.   Our data base is listed in Table I

Reference	Date of measurement	Mont Washington neutron monitor count rate	Modulation parameter ϕ GV	Type of particle	Selected energy range
Webber 85[1]	1974, July	2290	0.50	0,Fe	0.95-6
Webber 85[1]	1977, Sept.	2360	0.35	0,Fe	0.65-6
Webber 85[1]	1974,77,78	2300	0.50	0,Fe	10.5-112
HEAO-3[2]	1979 Oct. to 1980 June	2190	0.60	0,Fe	1.3-25
Juliusson 74	1971-72 Sept	2350	0.40	0	23-76
Orth & al.78	1972 Sept	2350	0.40	0,Fe	2.4-11
Maehl & al77	1973 Aug.	2350	0.40	0,Fe	0.85-2.25
Caldwell 77	1974 Sept	2310	0.50	0	5.5-95
Minagawa 81	1975 Sept	2404	0.30	Fe	1.5-8.0
Simon & al80	1976 Oct.	2420	0.30	0,Fe	2.5-630

(1) These data consist of revisited flux values obtained in several balloon flights and published in Lezniak and Webber 1978 and Webber 1983. More accurate atmospheric corrections have been applied.
(2) Juliusson et al., 1983 ; Engelmann et al., 1985.

The modulation parameter ϕ characterising the conditions prevailing at the time of each experiment can be correlated to the counting rate of the Washington neutron monitor (Lockwood and Webber 1979, 1981).
The interstellar energy spectra dJ/dE of O and Fe derived from these selected data after demodulation have been plotted in Fig. 1 as a function of the momentum of the particle.

4. Results.   As can be seen in Fig. 1, the differences between the experimental points obtained at the same energy are much larger than the errors quoted by the authors. As mentioned above this is probably due to errors on the geometry and efficiency of the experiments and on the atmospheric corrections. So we consider separately each experiment, and for some of them we devide the energy range they cover into several energy intervals. For each experiment and energy domain we derive the spectral index γ of the source strength assumed to follow the law :
$$dQ/dE = KP^{-\gamma} \quad\quad\quad (2)$$
where P is the momentum of the particle in GeV/c/n. The values of the γ index for O and Fe have been plotted as a function of momentum in

Fig.2 and 3 respectively.
For O the data seem to be consistent with a constant γ index above 4GeV/c/n with a weighted mean value γ_o=2.29+0.03 (Note that the HEAO results are significantly above the average ; excluding these data would lead to a weighted mean γ_o=2.22+0.04). Below 4GeV/c/n, the index seems to increase when the momentum decreases, up to $\gamma_o \simeq 2.9$ at 1.5GeV/c/n. For Fe we find for the weighted mean a value of γ_{Fe}=2.36+0.05 which is nearly the same as that found for O at high energy. But the increase observed for O at low energy does not seem present for Fe, although the large error bars and the scarcity of the points at low energy prevent us from drawing any definite conclusion.
The quoted errors on γ are due to the errors on the flux values and to the spread of the corresponding points. If we include in addition the error on λ_e due to cross section errors on the production of B by spallation of heavier nuclei and of Fe secondaries by spallation of Fe, we get the final values λ_o(H.E.)=2.29+0.06 and λ_{Fe}=2.36+0.07. Therefore a unique power law in momentum does not hold for the O source spectrum. What about a power law in total energy, which we have used earlier (Perron et al., 1981)?:
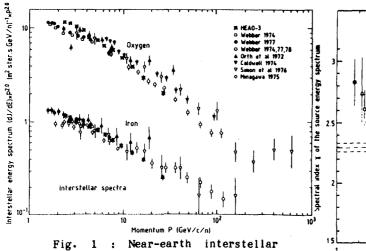
$$dQ/dE = K' E_{Tot}^{-\gamma'} \qquad (3)$$

The γ' index values from the experimental data have been plotted as a function of the kinetic energy for O nuclei in Fig. 4. The weighted mean γ value above 3 GeV/n is again 2.29+0.03 and the same type of increase is observed when going towards lower energies.
It is worthwhile to stress that this type of increase cannot be due to an error in the modulation correction (unless the modulation theory is grossly in error). An error of +0.1GV around an average value of 0.4GV for the modulation parameter would lead to an error of +0.07 on the spectral index around 1GeV/n, i.e. about 10 times less than the index variation observed between 1 and 3GeV/n (interstellar kinetic energy).

4. Conclusion. We find, at least for O nuclei an apparent increase of the γ index of the source spectrum below 3GeV/n. Is this low energy steepening of the spectrum real ? As discussed above, the careful selection of the data used in this study should prevent the demodulation to be responsible for this result. As concerns the partial cross sections from which the escape length is derived, the uncertainty in their values may introduce an error on the source abundances. If some energy dependences were left on the cross section errors, these would propagate into an error on the source spectral index. It is precisely in the energy region where the γ index is changing (0.8 to 3GeV/n) that the cross sections were measured with the best accuracy (Webber,1984). From the quoted errors, we calculate that a possible energy dependence on σ could be responsible at maximum for an apparent slope of 0.05, far smaller than the observed γ variation.
This apparent increase of the source spectrum at low energy can be brought together with the flattening of the CNO source spectrum observed in the TeV energy region (Engelmann et al. 1985). It is in agreement with our suggestion that a soft component with a source spectral index around 2.7 may be superposed on a common source spectrum, including H and He, with a spectral index $\gamma \simeq 2.1$. In the few GeV/range, both components would contribute to the observed flux of heavies, leading to a spectral index around 2.3 .

Fig. 1 : Near-earth interstellar spectra of O and Fe nuclei, derived from experimental data corrected for the effect of solar modulation. The differential energy flux values have been plotted as a function of the momentum P. The spectra have been "flattened" by multiplication by $P^{2.0}$.
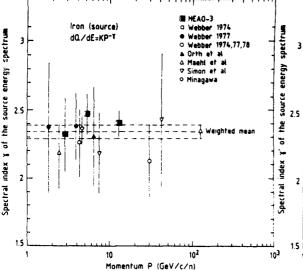

Fig. 2 : Oxygen source spectral index γ plotted as a function of momentum P, assuming for the spectral shape a power law in momentum.
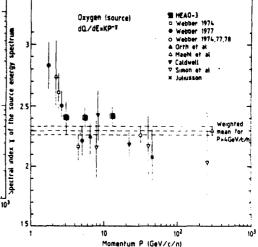

Fig. 3 : Iron source spectral index plotted as a function of momentum, assuming for the spectral shape a power law in momentum.
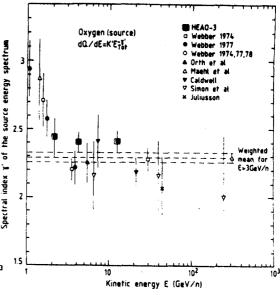

Fig. 4 : Oxygen source spectral index γ plotted as a function of kinetic energy, assuming for the spectral shape a power law in total energy.

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