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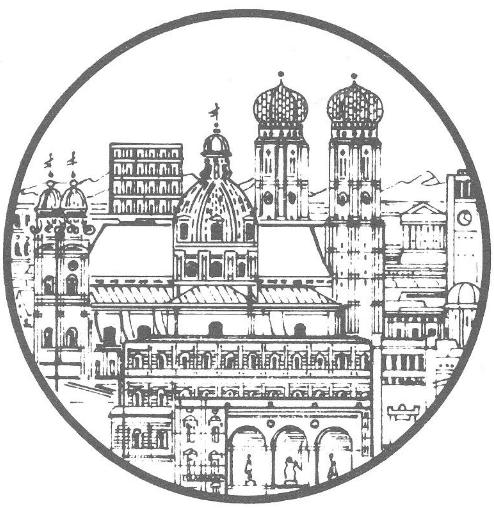

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SOURCE ENERGY SPECTRUM OF PROTONS ACCELERATED IN A HIGH DENSITY MEDIUM

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Velocity-dependent energy spectra are derived by neglecting and including energy losses during Fermi-acceleration of solar protons. The theoretical source spectra are compared with the experimental integral spectra of multi-GeV proton events. The interpretation of our source spectra behavior is based on the existence of two temperature-regimens at the source. Acceleration starting from thermal energies may be inferred for solar events of low-T-regimen. In this case, a small fraction $(10^{-15}-10^{-17})$ of the local plasma particles needs to be picked up by the Fermi-mechanism in order to explain the experimental spectra.

1.- Introduction. The analysis of the spectral distribution of cosmic ray fluxes leads to obtain information about the physical constraints that may be placed on their generation process and the source parameters. Regarding the acceleration process, is at present widely accepted that this is a process of stochastic character, as collisionless magnetohydrodinamic turbulence, thus, we consider a Fermi-statistical type mechamism, since several spectral shapes may be obtained from this kind of process, depending upon the different assumptions regarding both the mean rate of acceleration and the characteristic confinement time in the acceleration region (Wentzel, 1965). The case to be discussed here is for a mean confinement time, τ, and for a rate of energy gain which is proportional to the energy and dependent on the velocity of particles, as

$$\left(\frac{dW}{dt}\right)_F = \alpha\,\beta W = \alpha\left(W^2-(M_c{}^2)^2\right)^{1/2} \tag{1}$$

where β is the velocity of particles in units of the light velocity, α is the parameter of acceleration efficiency, which in the case of the solar source may be considered as roughly constant through the main part of the process (Pérez-Peraza, 1975); $M_c{}^2$ and W are respectively the rest energy and the total energy of particles. In the particular case of solar protons, Heristchi and Trottet (1971) have shown that the best representation through the whole energy domain explored experimentally at present is given by a power law in kinetic energy with a high energy cut off E_m; moreover from the studies of solar proton events of Bryant et al. (1965), it follows that the observed differential intensity and the source spectrum inferred as a power law in energy, are both velocity-dependent. Therefore, we have chosen the acceleration rate (1) because it furnishes the velocity-dependence and the inverse power law in energy such as suggested by these experimental results. We shall compare here the experimental spectra of proton events with the source spectra, in order to make inferences about the physical parameters and the generation process of solar particles at the source. For simplicity we shall assume that modulating effects in interplanetary space do not introduce an important modification in the source spectrum during their propagation to the earth.

2.- The source spectrum. Following Fermi (1949) assumptions, we made the following hypotheses: we assume that N_o particles with similar energy are present in the region where the Fermi-mechanism is operating and a fraction of them are accelerated at the rate (1) while escaping with a mean probability τ^{-1} per second from this region; furthermore, by analogy with radioactive decay the energy distribution is assumed as an exponential distribution in age as follows:

$$N(W)dW = N(t)dt = \frac{N_0}{\tau}\exp(-t/\tau)dt \tag{2}$$

in such a way that neglecting energy loss processes during acceleration and transforming the time dependence into an energy dependence, we immediately obtain from (1) and (2) the following differential energy spectrum

$$N(W)=\frac{N_0}{\alpha\tau}(Mc^2)^{1/\alpha\tau}\left(\frac{1+\beta}{\beta}\right)^{-1/\alpha\tau}W^{-(1+1/\alpha\tau)}=\frac{N_0}{\alpha\tau}(Mc^2)^{1/\alpha\tau}\frac{\{W+(W^2-(Mc^2)^{1/2}\}^{1/\alpha\tau}}{\{W^2-(Mc^2)^2\}^{1/2}} \quad (3)$$

equation (3) thus represents the acceleration spectrum of protons when the velocity dependence is explicity taken into account in the time-energy transformation. When the parameter β is considered outside of the integrating equations, a somewhat different expression for the differential spectrum is obtained (Ramudarai and Biswas 1971)

$$N(W)=\frac{N_0}{\alpha\beta\tau}(Mc^2)^{1/\alpha\beta\tau}W^{-(1+1/\alpha\beta\tau)} \quad (4)$$

We have performed calculations (Pérez-Peraza and Galindo Trejo, 1975) with both spectra (3) and (4) for several different combinations of the product $\alpha\tau$ and shown that the best approach to the experimental curve of the January 28, 1967 event is systematically obtained with expression (3). Transforming (3) to kinetic energy and integrating up to the maximum energy of the accelerated protons, we obtain the integral acceleration spectrum

$$J(>E)=N_0(Mc^2)^{1/\alpha\tau}\{[E+Mc^2+(E^2+2Mc^2E)^{1/2}]^{-1/\alpha\tau}-[E_m+Mc^2+(E_m^2+2Mc^2E_m)^{1/2}]^{-1/\alpha\tau}\} \quad (5)$$

now if acceleration is performed in a high density and high temperature medium, charged particles may probably lose a considerable amount of energy even during the short time-scale of the solar particle acceleration. In order to go deeper into the kind of phenomena which may occur in the solar source, we have investigated the main energy loss processes occurring in astrophysical plasmas, which can strongly affect protons in the energy range of our concern (10^6-10^{10} eV):

(a) Ionization losses in a highly ionized medium, as determined by the following expression (e.g. Ginzburg, 1969)

$$\left(\frac{dW}{dt}\right)_{ion}=\frac{7.62\times10^{-9}}{\beta}\,nL\ \text{(ev/sec)} \quad (6)$$

where n is the concentration of hydrogen ions (and electrons simultaneously) and L is a factor so weakly (logarithmically) dependent on the particle energy, that we have approximated it by its mean value, L=26 for $n=10^{11}$-10^{13} cm^{-3}.

(b) Energy degradation by p-p collisions. For those cases in which rapid protons interact without absorption of the projectil, the average energy loss by nuclear interactions is, according to Ginzburg (1969): $(dW/dt)_{nuc}=-\sigma_{int}cn\beta W$ (eV/sec) where σ_{int} in the case of proton-proton collisions is composed of $\sigma_{in}+\sigma_{el}$. As the inelastic cross section is weakly dependent on energy, it may be approximated to its mean value $\sigma_{in}\simeq$ 26mb, in the energy range covering most of solar protons. Concerning elastic collisions, a reasonable fit of the differential experimental cross-section by an analytical expression has been given by Ramudarai and Biswas (1974). As the isotropic distribution occurs mainly around $\theta=90°$, their expression may be rewritten as $\sigma_{el}=hE^{-2}+jE^{-1}$ (if E≤110 MeV) and $\sigma_{el}=hE^{-2}+f$ (if E >110 MeV) where h=96.09 mb-MeV^2, $j=5.497\times10^3$ mb-MeV and f=46.49 mb; we have thus

$$\left(\frac{dW}{dt}\right)_{p-p}=-cn(h\bar{E}^2+j\bar{E}^1)\beta W\ \text{(if E≤110 MeV)};\ \left(\frac{dW}{dt}\right)_{p-p}=-cn(h\bar{E}^2+f)\beta W\ \text{(if 110<E<285 MeV)}$$

$$\text{and}\ \left(\frac{dW}{dt}\right)_{p-p}=-[\eta+cn(h\bar{E}^2+f)]\beta W\ \text{(if}\geq 285\ \text{MeV) where}\ \eta=cn\sigma_{in} \quad (7)$$

(c) Adiabatic deceleration of the accelerated protons by a plausible expansion of the source, assumed in certain models of the flare phenomenon as an expanding magnetic bottle (e.g. Sakurai 1965; Schatzman 1967). In such a case the energy loss rate may be approximated as

$$\left(\frac{dW}{dt}\right)_{ad} = -\rho\beta^2 W \text{ (eV/sec)} \qquad (8)$$

where $\rho = (4/3)(V/R) \simeq 10^{-3}$; $V \simeq 400$ km/sec is the expanding velocity and $R \simeq 0.3\, R_{sun}$ is the expanded distance. In order to evaluate the modification of the acceleration spectrum (5) by these energy loss processes we have considered three main cases: (1st) when simultaneously with the acceleration, protons lose energy by ionization such that the net energy change rate is determined by (1) and (6) as

$$\left(\frac{dW}{dt}\right) = \alpha\beta W - \frac{b}{\beta} \qquad (9)$$

where $b = 7.62\times10^{-9}\, nL$ for a fixed value of n. It follows from (9) that a net energy gain is effectively fixed on particles only beginning at a certain critical energy, defined by $(dW/dt)=0$, in such a way that transforming (9) to kinetic energy the threshold value for Fermi-acceleration is simply $E_i = b/2\alpha$. Proceeding as the previous case, we obtain from (2) and (9) the following integral spectrum for protons in terms of kinetic energy:

$$J(>E) = N_o e^{\frac{t(E_i)}{\tau}} \left\{ \left[\left| \frac{\varepsilon+E+Mc^2}{Mc^2} \right|^{\frac{-1}{\alpha\tau}} \left| \frac{(E-E_1)+\varepsilon+[E_1(E_1+2Mc^2)]^{1/2}}{(E-E_1)-\varepsilon-[E_1(E_1+2Mc^2)]^{1/2}} \right|^{-p} \exp\left(-\frac{[E_2(-E_2-2Mc^2)]^{1/2}}{\alpha\tau(E_1-E_2)} \tan^{-1}\left(\frac{E(E_2+Mc^2)+Mc^2E_2}{\varepsilon[E_2(-E_2-2Mc^2)]^{1/2}} \right)\right)\right] - e^{\frac{-t(E_m)}{\tau}} \right\} ; \text{with } p = \frac{[E_1(E_1+2Mc^2)]^{1/2}}{\alpha\tau(E_1-E_2)} \text{ and } \varepsilon = [E^2+2Mc^2E]^{1/2} \qquad (10)$$

E_1 and E_2 correspond respectively to $\{[b\pm(b^2+4\alpha^2(Mc^2)^2)^{1/2}]/2\alpha\}-Mc^2$, and $t(E_i)$ and $t(E_m)$ correspond to the solution of (9) evaluated in E_i and the measured value, E_m, respectively. It can be easily seen that the spectrum (10) reduces to (5) when $b=0$. (2nd), we have included losses from p-p collisions so that the net energy change rate from (7) and (9) is:

$$\frac{dW}{dt} = a\beta W - \frac{b}{\beta} - cn(hE^{-2}+jE^{-1}+f)\beta W \quad \text{(eV/sec)} \qquad (11)$$

with $a=\alpha$ (if $E<285$ MeV), $a=\alpha-\eta$ (if $E>285$ MeV), $f=0$ (if $E<110$ MeV) and $j=0$ (if $E>110$ MeV). The critical energy resulting from (11), when $(dW/dt)=0$, is obtained by solving a cubic equation, which depends on α when the medium concentration n is fixed. Proceeding similarly to the previous case, we obtain the following integral spectrum

$$J(>E) = N_o \exp[t(E_i)/\tau] \left\{ \left(\left| \frac{2}{Mc^2}\left[(E^2+2Mc^2E)^{1/2}+E+Mc^2\right] \right|^{-\delta_1} \left| \frac{2(a_1^2-1)(E^2+2Mc^2E)^{1/2}+2a_1E+2Mc^2(a_1-1)}{E+Mc^2(1-a_1)} \right|^{\delta_2} \cdot \left(\exp\left[A_2(1-a_2^2)^{1/2}\operatorname{sen}^{-1}\left(\frac{a_2E+(a_2-1)Mc^2}{|E+(1-a_2)Mc^2|}\right) + A_3(1-a_3^2)^{1/2}\operatorname{sen}^{-1}\left(\frac{a_3E+(a_3-1)Mc^2}{|E+(1-a_3)Mc^2|}\right)\right]\right)^{\delta_3}\right) - \exp\left[\frac{-t(E_m)}{\tau}\right] \right\} \qquad (12)$$

where $\delta_1 = [(Mc^2)^2/Q\tau](a_1A_1+a_2A_2+a_3A_3)$, $\delta_2 = [(Mc^2)^2/Q\tau]A_1(a_2-1)^{1/2}$, $\delta_3 = (Mc^2)^2/Q\tau$, and $Q, A_1, A_2, A_3, a_1, a_2, a_3$ are constants depending on α, b, η, h, j and f which emerge from the integration by partial fractions and take different values throughout the three different energy ranges considered. Spectrum (12) reduces to (10) when nuclear interactions are neglected. (3rd), we have included in (11) adiabatic deceleration of protons such that

$$\frac{dW}{dt} = a\beta W - \frac{b}{\beta} - cn(hE^{-2}+jE^{-1}+f)\beta W - \rho\beta^2 W \quad \text{(eV/sec)} \qquad (13)$$

The complex form of expression (13) prevents an easy integration, so for simplicity we have solved it by numerical integration, and then evaluated the integral spectrum by integrating (2) up to E_m, as in the previous cases.

3. Integral spectrum of solar protons.. The lack of simultaneous measures of proton fluxes through all the energy domain covered by solar protons, during a single event, leads us to create experimental spectra, for some events, from the scanty data available at low energies, by smoothing them with the energy spectra at high energies given by Heristchi et al.(1975). The fluxes utilized in terms of magnetic rigidity can then be described as follows: in the case of the January 28, 1967 event we have considered the integral spectrum given by Heristchi and Trottet (1971) as $\sim R^{-5.1}$, with an upper cutoff at R_m=5.3 GV. For the other five events we have summarized the fluxes used in Table 1. The correspondent upper cutoff parameters (Heristchi et al.1975) are listed in Table 2, in terms of kinetic energy. By transforming the proton fluxes to a kinetic energy scale, we have constructed the experimental spectra illustrated in fig. 1(a) and (b).

TABLE 1. Experimental solar proton fluxes.

Event	0.2GV<R<0.6GV	1.02GV<R<R_m *
18.11.1968	$\sim R^{-5}$ +	$R^{-3.8}$
25. 2.1969	$\sim R^{-2.5}$ x	$R^{-4.3}$
30. 3.1969	$\sim R^{-2.3}$ +	$R^{-2.5}$
24. 1.1971	$\sim R^{-6}$ ‡	$R^{-4.3}$
1. 9.1971	$\sim R^{-3.5}$ +	$R^{-4.1}$

* Heristchi et al.(1975) ‡ West et al.(1972)
x Loockwood et al.(1974) + King (1974)

4. Results. The medium density has been fixed to the typical value $n=10^{13}$ cm^{-3} according to Pérez-Peraza (1975). We have normalized theoretical and the experimental fluxes at the minimum energy for which the experimental data are available, we have listed these normalization energies, E_{nor}, in Table 2. As our expressions directly furnish not the source integral spectra, but $J(>E)/N_0$, we have deduced from this normalization, a factor K_0 which is proportional to the flux N_0 appearing in our equations ($K_0=qN_0$). In order to compare, under the same conditions, each of the theoretical spectra with an experimental curve, we could proceed to fix in advance the value of the acceleration parameters α and τ, which implies making a priori inferences about the physical quantities involved in the acceleration parameters. This would result in obtaining very variable conclusions about the physical processes in the source, depending on the values assumed for α and τ; therefore we proceeded conversely, by determining the appropriate parameters of the source, from the factor $\alpha\tau$ (or α) which represents the experimental curve better. Thus we have determined for each source spectrum the optimum factor $\alpha\tau$ (or α) by imposing the following conditions: $J(>E)_{sour} \equiv J(>E)_{exp}$ at the normalization energy, and $J(>E) \equiv 0$ at the upper cutoff. Table 2 shows the results obtained in this way. The critical energy for acceleration has been determined from the appropriate value of $\alpha\tau$ (or α) in each case. We have taken τ=1, throughout the source spectra in order to be congruent with (5) in drawing conclusions about the source parameters. The critical energy found is, in all cases considered in the range E_i=2.5-10.6 MeV, when $n=10^{13}$ cm^{-3}; the values of E_i obtained from (13) are nearly identical to those obtained from (11). The theoretical spectra calculated from (5)(10)(12) and (13) are illustrated in figs. 1(a) and 1(b). Under the assumption that theoretical spectra approaching near the experimental curves describe better the phenomena occurring at the source, we deduce from fig. 1 that acceleration and adiabatic losses act strongly in events of fig 1(a) than in those of fig 1(b), while ionization acts inversely and p-p collisions act similarly in all events. The source parameters that can be inferred from the $\alpha\tau$ values obtained support the previously deduced (Pérez-

Table 2. The Optimum acceleration parameters $\alpha\tau$ (or α) high energy cutoff, E_m and energy of normalization, E_{nor}.

Event	E_{nor} (MeV)	E_m (GeV)	$\alpha\tau$ Eq(5)	α Eq(10)	α Eq(12)	α Eq(13)
28. 1.1967	10	4.3	0.18	0.19	0.25	0.60
18.11.1968	20	4.8	0.20	0.21	0.26	0.80
25. 2.1969	30	4.7	0.40	0.41	0.46	0.92
30. 3.1969	50	3.1	0.70	0.71	0.75	1.0
24. 1.1971	40	3.3	0.34	0.35	0.39	0.69
1. 9.1971	30	2.3	0.21	0.22	0.27	0.71

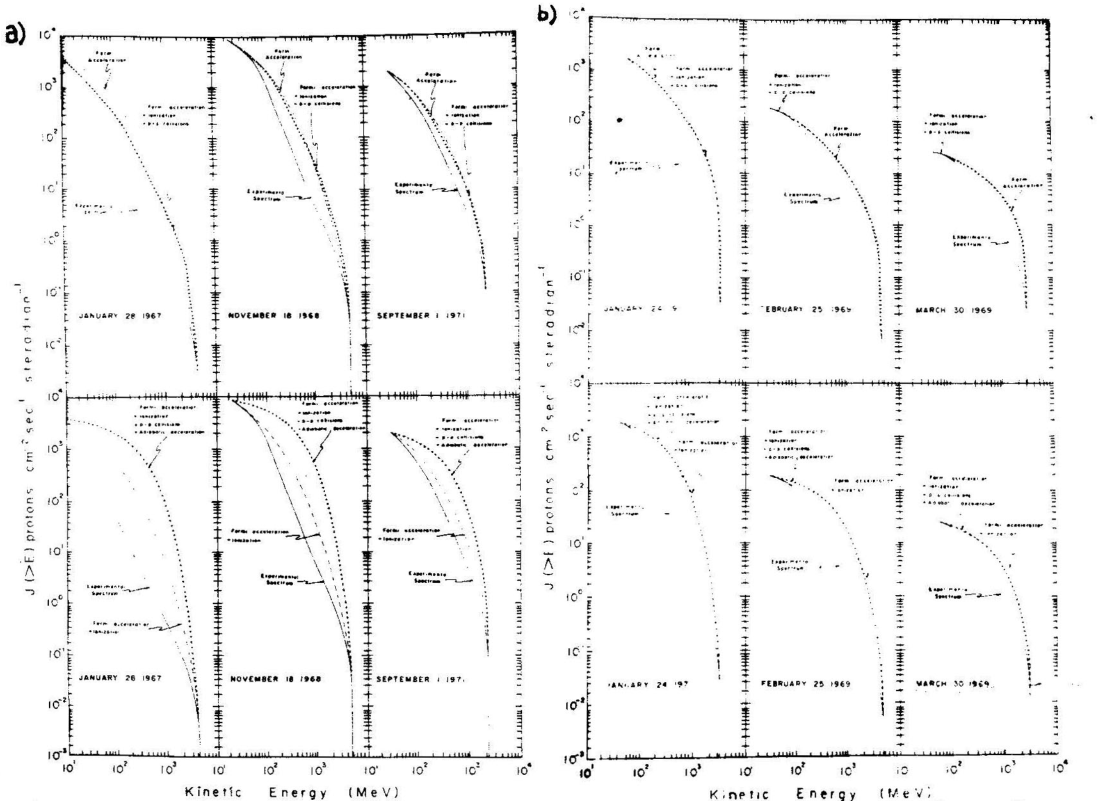

Fig 1. Theoretical source spectra and experimental spectra for: 1(a) 28.1.1967, 18.11.1968 and 1.9.1971 events,and 1(b) 24.1.1971, 25.2.1969 and 30.3.1969 events.

Peraza and Galindo Trejo 1975):$\tau \simeq 0.4-2.5$ sec and $\alpha \simeq 0.4$ sec^{-1} corresponding to a turbulence scale of $\sim$1 km and hydromagnetic velocities with H=500G and $n=10^{11}-10^{13} cm^{-3}$.

5. <u>Discussion</u>. Physical processes occurring in a dense medium,as the Sun's atmosphere,are undoubtedly very diverse,and we do not claim to have included all loss processes for charged particles,but only perhaps the more important occurring during their acceleration durability. In fact,although Čerenkov losses are included in (6)we have ignored other losses from collective effects;however,loss energy by plasmaperturbations seems to be negligible for protons of E>23MeV (Friedman 1969). Also we have not considered energy losses appearing for instance by viscosity and Joule dissipation as suggested by Syrovatskii(1961).Moreover we have not examined here local modulation of protons at the source by energy losses processes after acceleration,either during a post-acceleration step in a closed magnetic structure (Pérez-Peraza 1972)or while traversing the dense medium of the atmosphere to attain the interplanetary medium (Syrovatskii and Shmeleva 1972),which seems to be a fundamental assumption in explaining non-thermal electromagnetic radiation from flares. Nevertheless,we think that this research permits us to fix ideas about the processes of solar particles generation:that is, in order to evaluate the importance of each of the four processes considered,we could have compared at different energy values,the rates (1)(6)(7)and(8) and have drawn general conclusions about the behavior of our theoretical spectra. But contrary to this assumption we have seen in sec 4,that no general conclusions of this kind can be drawn,but our source spectra of fig 1(a) behaves differently from those of fig 1(b). Nevertheless,our results may be well interpreted on the basis of the parameter temperature: that is, we argue that there exist two main temperature regimens in solar flare conditions;a high and a low one. Therefore in those events occurring in low-temperature regions,

On the Overabundance of Heavy Nuclei in the Generation Process of Solar Cosmic Rays

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The feature of non-thermodynamic equilibrium of solar flare regions is used to explain the enhancement of heavy nuclei in some solar cosmic ray events. Particle acceleration occuring in low temperature regions ($T \simeq 10^4 - 10^5$ °K) is associated with heavy nuclei enhancements. The enhacement factor decreases while increasing temperature, in such a way that non-enhancement is predicted when acceleration occurs in high temperature regions ($T \simeq 10^7 - 10^8$ °K). In low-T-regions, energy losses are negligible, so that acceleration conditions from thermal energies are more easily satisfied for high-Z-nuclei. The enhancement factor Q by rapport to local abundances is determined as:

$$Q(E,Z) = F\left(\begin{smallmatrix}\text{pref.}\\ \text{accel.}\end{smallmatrix}\right) \cdot F\left(\begin{smallmatrix}\text{pref.}\\ \text{escape}\end{smallmatrix}\right) \cdot F\left(\begin{smallmatrix}\text{charge}\\ \text{interch.}\end{smallmatrix}\right) \cdot F\left(\begin{smallmatrix}\text{local mod.}\\ \text{post-accel.}\end{smallmatrix}\right) \cdot F\left(\begin{smallmatrix}\text{inter.}\\ \text{mod.}\end{smallmatrix}\right)$$

such that the energy and charge dependence of the overabundance of heavy nuclei observed in the 17.4.1972 and 4.8.1972 events is well explained by this expression, when:

1) The acceleration spectrum, which depends on the medium concentration, the temperature, the mean confinement time, τ, and the high energy cutoff, E_m, is calculated with either ($T = 10^5$ °K; $n = 10^{13}$ cm^{-3}) or ($T = 10^4$ °K; $n = 10^{12}$ cm^{-3}), $\tau = 0.1 - 0.5$ sec^{-1} and $E_m \simeq$ the high energy for which experimental fluxes are available.
2) A thin geometry in the source is assumed in the preferential escape function.
3) The charge interchange function is proportional to the ratio of electron capture to electron loss, with the Coulombian and radiative capture given respectively as ($\sigma_c \propto Z^5 v^{-12}$; $\sigma_r \propto Z^5 v^{-5}$) and Coulombian electron loss as ($\sigma_\ell \propto Z^{0.3} v^{-3}$). Photoionization is negleted.
4) Particles are decelerated by ionization and energy degradation from nuclear interactions when the acceleration has ceased, before escape into the interplanetary space.
5) A solar wind model of interplanetary modulation is assumed.

Eventhough Q is weakly sensible to the two last functions, the presence of a state of ionization, at low energies, higher than that predicted by a Z*-effective state, may be explained from the post-acceleration step of ionization. Also, secondary isotope production may be explained by nuclear interactions of the high-energy accelerated nuclei with nuclei of the medium. Furthermore, the fact that Q(E,Z) is little affected by these functions, may be interpretated as meaning that modulation acts roughly the same on different low-energy nuclei in the range $2 \leq Z \leq 26$.