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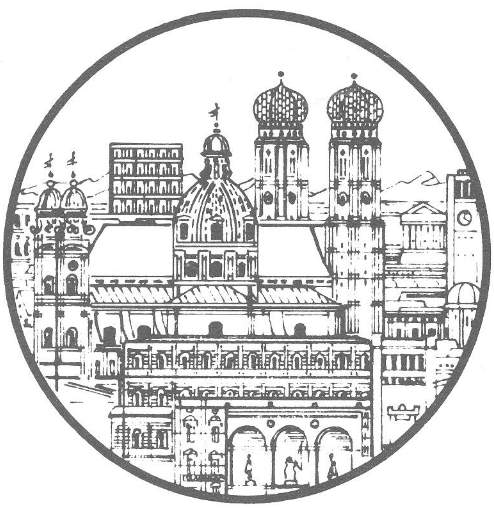

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UPPER CUTOFF IN THE SPECTRUM OF HIGH ENERGY SOLAR PARTICLES DURING CYCLES 19 – 20

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The upper cutoffs, R_m's, of most of the solar proton events recorded by the worldwide network of Neutron Monitors during cycles 19–20 is determined. It is found that R_m varies from an event to another and that its values lay between 3 GV and 20 GV. It is shown that there is no correlation between the amplitude of the events and R_m. The equation which describes the continuous acceleration of the particles is solved for the non-stationary case. The solution shows the existence of a cutoff in the spectrum. The experimental results are discussed by comparing them to parameters liable to represent the acceleration time.

1. Introduction. The existence of an upper cutoff in the solar proton spectrum has been suggested by Heristchi and Trottet (1971). By upper cutoff it is meant an energy or rigidity level beyond which there are no accelerated particles. The authors have shown that the best agreement with the observations, in the low, as well as in the high energy ranges, is obtained with a differential spectrum represented by a power law with an upper cutoff. They have also demonstrated that this upper cutoff remains constant during the whole proton event. Recently, Heristchi and Trottet (1975) found that a power law with an upper cutoff agrees with the direct measurement of the spectrum performed on satellite by Vernov et al. (1973).

In this paper the upper cutoff of the proton events recorded at ground level (G L E) during the solar cycles n° 19 and n° 20 is determined from the records of the worldwide network of Neutron Monitors. Such a cutoff provides us with a directly measurable parameter of the accelerating source for it is almost unaffected by the propagation of particles in the interplanetary medium. The results obtained are discussed in relation to the equations which describe the acceleration of the particles.

2. Experimental results. The upper cutoff is determined from two methods which have been described in details by Heristchi and Trottet (1971) and Heristchi et al (1972). The proton differential spectrum as a function of energy or rigidity is respectively represented by $E^{-\gamma}$ with an upper cutoff E_m or by $R^{-\mu}$ with an upper cutoff R_m. In the first method E_m and γ or R_m and μ are

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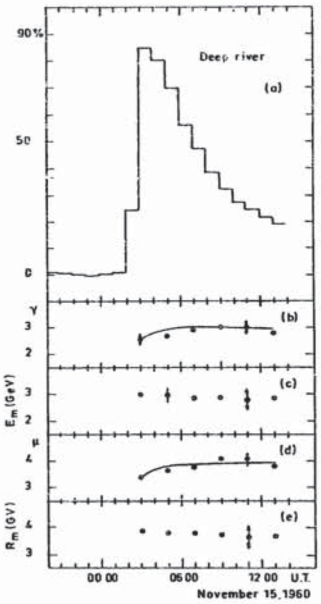

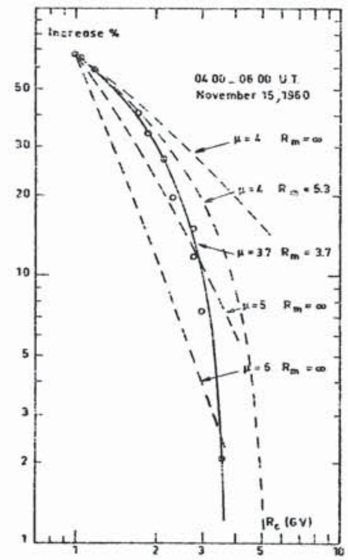

Fig. 1. (a) Recordings by a typical station (b) exponent of the differential energy spectrum. The solid curve is theoretical. (c) upper cutoff in the differential energy spectrum. (d), (e) same as (b) and (c) for rigidity.

Fig. 2. Percent increase in the sea kevek NM's compared with different theoretical curves.

determined by using the increases of the whole of the sea level Neutron Monitors. In the second method, R_m and μ are determined by using the ratios of two pairs of Neutron Monitors Stations.

The methods have been applied to fifteen GLE's occuring during cycles n° 19 and 20. For each event a good concordance is found between the values of γ or μ we obtained and that deduced from balloon or satellite measurements of the spectrum in the energy range 100 to 500 MeV. Figure 1 gives an example of the results obtained for E_m, γ, R_m and μ in the case of november 15, 1960 event. It is shown that the observed temporal variations of γ or μ, agrees with these expected from Krimigis's diffusion model (1965). Moreover, within the errors E_m and R_m remain constant in time. This constancy of E_m or R_m has been observed for other events. So this means that, at rigidities of a few GV, no important deceleration is observed for particles during their propagation in the interplanetary space. Figure 2 shows that the spectrum we have determined agrees well with the experimental points.

Table 1 presents the whole of our results. The second column indicates, for each event, the maximum amplitude registred at sea level (from Shea and Smart, 1973). The examination of the table shows that R_m and E_m vary from one event to another. Moreover R_m does not always vary in the same way as the amplitude of the event. As the observed amplitude depends upon the location of flare on the solar surface, it is only possible to illustrate this by comparing events issued from flare having similar locations, as in the two following examples. For instance the R_m's of November 15, 1960 event and the January 24, 1971 event are roughly the same but the amplitude of the first is several times that of the second. The positions of the corresponding flares on the Sun are respectively 32°W and 50°W which encourages slightly the increase of the second event (Burlaga, 1967). Similar remarks can be made by comparing November 12, 1960 and January 28, 1967 events.

Table 1.

Date	Largest Sea level increase %	E_m (GeV)	R_m (GV)
February 23, 1956	4554 ± 12		20^{+10}_{-4}
May 4, 1960	290 ± 10		7.0 ± 1.0
September 3, 1960	4.5 ± 1		5.0 ± 2.0
November 12, 1960	135 ± 4		4.3 ± 0.5 3.5* ± 1.0
November 15, 1960	160 ± 2	3.0 ± 0.4	4.0 ± 0.8
November 20, 1960	8 ± 1		3.5 ± 1.0
July 18, 1961	23.5 ± 1.4		3.3 ± 0.9
July 7, 1966	2.5 ± 0.3		3.4 ± 0.7
January 28, 1967	21 ± 1	4.5 ± 0.5	5.3 ± 0.7
November 18, 1968	14		5.7 ± 1.5
February 25, 1969	16		5.6 ± 0.9
March 30, 1969	8.8 ± 0.2	3.5 ± 0.9	4.5 ± 0.7
January 24, 1971	26 ± 1	2.8 ± 0.5	4.0 ± 0.6
September 1, 1971	16. ± 0.5	2.3 ± 0.5	3.1 ± 0.6
August 7, 1972	7. ± 1		6.0 ± 1.6

* after correction of geomagnetic cutoffs

3. Theoretical evidences for the existence of an upper cutoff. In this section we will theoretically show the existence of an upper cutoff in the solar proton spectrum. A review of the different processes of acceleration is beyond the scope of this paper. Nevertheless in most of the cases, the balance of the number of particles N of one kind between the time t and t + dt, in the energy or rigidity range E and E + dE per unit of energy or rigidity, is described by the following equation (Ginzburg and Syrovatskii, 1964, p. 296).

$$\frac{\partial N(E,\ t)}{\partial t} + \frac{\partial}{\partial E}\left[N(E,\ t)\ \alpha\ (E,\ t)\right] + \frac{N(E,\ t)}{T(E,\ t)} = q(E,\ t) \qquad (1)$$

α is the energy gain per unit of time and T the characteristic time of confinement of the particles in the medium. These two parameters will be taken independent of time. q(E, t) is a source function which is zero when t is negative. The diffusion of the particles through the medium is neglected.

The general solution of this equation can be easily obtained by taking the Laplace's transform of (1) and by solving the obtained equation with the following conditions : the initial spectrum of the particles N(E, 0) is taken to be zero and the origin of time is choosen at the beginning of the acceleration The inverse Laplace's transform of the obtained solution gives :

$$N(E,\ t) = \frac{1}{\alpha(E)} \int_0^E dE''\ \exp\left[- \int_{E''}^{E} \frac{dE'}{\alpha(E')T(E')}\right] q(E'',\ t-\tau) \qquad (2)$$

with

$$\tau = \int_{E''}^{E} \frac{dE'}{\alpha(E')}$$

Expression (2) may be examined with respect to the values of t − τ. In order to simplify the discussion let q be constant in time and covering a limited energy range from E_{01} to E_{02} let Em_1 be the value of E up to which t − τ is positive for any value of E" and Em_2 be the energy beyond which t − τ is negative for any value of E''. Then equation (2) indicates the existence of three regions :

- when E is smaller than Em_1, $N(E, t)$ is independent of time and the integral is taken over the whole energy range covered by the source. The solution is the same as that obtained in the stationary case. The region $E < Em_1$ will be called region 1.
- when E is between Em_1 and Em_2, $t - \tau$ has positive and negative values depending upon the value of E''. Here the spectrum is a function of time. The integral must be taken for the positive values of $t - \tau$ e. g. from an energy ϵ defined by $t - \int_\epsilon^E \frac{dE'}{\alpha(E')} = 0$. This non stationary solution describes region 2.

  Of course Em_1 and Em_2 increase with time.
- when E is greater than Em_2, $N(E, t) = 0$ because $q = 0$ for $t < 0$. It is region 3.

The existence of region 2 remains if E_{02} becomes infinite but there is no region 3. Moreover region 2 is still present if q varies with t but the region 1 of the spectrum is not stationary.

In order to give some examples of the obtained spectrum, we have applied equation (2) to simple cases by taking $T(E) = T$ and simple forms for α and q. For q we have considered two forms :

S_1) $q(E) = Q$ for $E_{01} \leq E \leq E_{02}$ and $q(E) = 0$ for $E < E_{01}$ and $E > E_{02}$

S_2) $q(E) = Q \exp(E/E_{th})$ for $E \geq E_{01}$ and $q(E) = 0$ for $E < E_{01}$

With $\alpha = a =$ constant, in region 1 the spectrum is an exponential law. For S_1 the limits of region 2 are : $E_{m1} = E_{01} + at$ and $E_{m2} = E_{02} + at$. The width of region 2 is then the same as this of S_1. For $E_r > E_{m1}$, the number of particles drops then rapidly to zero if S_1 is not too wide. In the case of the source S_2, E_{m1} has the same value as in the case of the source S_1, but E_{m2} and consequently the width of region 2 become infinite. However, if E_{th} is small compared to E_{m1}, a sharp cutoff is still present and, for the same choice of the other parameters, the shape of region 2 is quite the same as in the case of S_1.

With $\alpha = bE$ (b = constant), in region 1, the spectrum has the form of a power law the index of which is $\gamma = 1/bT + 1$.

For S_1 we have $E_{m1} = E_{01} \exp(bT)$ and $E_{m2} = E_{02} \exp(bT)$. This indicates that region 2 may be wide. Nevertheless the spectrum clearly differs from the power law of region 1, and this, more rapidly than for S_1 in the low energy part of region 2.

Finally we consider $\alpha = a$ for $E \leq E_1$ and $\alpha = bE$ for $E \geq E_1$ (then $a = bE_1$). For $E > E_1$ the spectrum has the form of a power law in region 1 and the limits of region 2 are :

$E_{m1} = E_1 \exp\left[b(t - (E - E_{01})/a)\right]$ and $E_{m2} = E_1 \exp\left[b(t - (E - E_{02})/a)\right]$. If E_1 is large compared to E_{02} we obtain $E_m = E_{m1} \simeq E_{m2} \simeq (E_1/e) \exp(bt)$. In these conditions, region 2 is very narrow and consequently the upper cutoff is very sharp. Similar results are obtained with S_2. Indeed, though the width of region is infinite the number of particles tends rapidly towards zero when E is greater than E_{m1} if E_1 is large compared to E_{th}.

If the acceleration occurs in two steps, the spectrum obtained at the end of the first step must be accelerated again. Then equation (1) must be solved without source function (q = 0) and with N(E, 0) representing the disponible spectrum. In these conditions the solution is :

$$N = \frac{1}{\alpha(E)} \int^{E} dE'' \, N(E'', 0) \exp\left(-\frac{1}{T}\int_{E''}^{E} dE'/\alpha\right) \delta\left(t - \int_{E''}^{E} dE'/\alpha\right) \qquad (3)$$

δ is the Dirac's function. We obtain for instance :

with $\alpha = a$, $N(E, t) = N(E - a\,t, 0) \exp - \frac{t}{T}$

and with $\alpha = bE$, $N(E, t) = N(Ee^{-bt}, 0) \exp\left[-t\left(\frac{1}{T} + b\right)\right]$

These results show that for $\alpha = a$ region 2 has the same width as in the case of a single acceleration step but that this width grows when $\alpha = bE$. Nevertheless the existence of the upper cutoff remains.

4. Discussion of the acceleration time. The experimental values obtained for E_m or R_m have to be examined in connection with the results of the preceding theoretical study.

The simplest hypothesis to examine consists to assume that all the parameters concerning the accelerative medium, and particularly α, remain the same for all the events. Thus, E_m or R_m is only a growing function of the duration t_{ac} of the acceleration. In these conditions, the knowledge of t_{ac} is sufficient to determine α and other parameters. Several authors (i.e. Ellison et al. 1961) propose that the acceleration of the particles occurs during the flash phase of the Hα flare. We do not find any clear relation between R_m and the duration Δt of this phase. Indeed, in the case of the February 23, 1956 and the July 18, 1961 events, the upper cutoff's of which are respectively 20 GV and 3.3 GV, we obtain respectively Δt = 8 mn and Δt = 18 mn. In the same way, t_{ac} can be derived from the time profiles of the impulsive hard X rays bursts (i.e. Svestka, 1970) or from impulsive micorwave bursts which have equivalent time profiles (i.e. Kundu, 1961). Here again we do not find any correlation between R_m and Δt. Indeed the time profiles of the microwave bursts at 9400 MHz are quite similar, with different amplitudes, in the case of the February 23, 1956 and January 24, 1971 events the upper cutoff's of which are respectively 20 GV and 4 GV. Recently Svestka and Fritzova-Svestkova (1974) remarked that the acceleration of high energy particles is closely connected with the occurence of Type II bursts which according to them indicates an acceleration by shock waves. As we find that E_m remains constant during several hours, the shock front must accelerate particles along a short travel. Consequently, the experimental determination of t_{ac} is not yet easy in this case.

The above discussion shows that either the advanced hypothesis is not valid, either the examined parameters do not show the duration of the acceleration, or the acceleration itself do not occur in a continuous way.

Now we examine the case of α varying from an event to another. In this case we have no criterions to determine t_{ac} from the observations. indeed, even in the simple case $\alpha = bE$, (the other parameters being fixed) for which the choice of t_{ac} is sufficient to calculate α for each event, it is impossible to justify neither the values of α nor the choice of t_{ac}.

Finally the acceleration may not be described by an equation of continuity type as (1). An example of this can be found in the model proposed by

Carlqvist (1969). According to this model E_m shows the effective potential which accelerates the particles to high energies.

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