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Preliminary Report on Cosmic Ray Intensity during Magnetic Storms in July 1959

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Preliminary Report on Cosmic Ray Intensity during Magnetic Storms in July 1959 (*).

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Summary. The cosmic ray intensity variation during three magnetic storms of July 1959 is analyzed. Data from neutron monitors at Mina Aguilar (4 000 m o.s.l. at 12° S geomagnetic latitude), Buenos Aires (0 m o.s.l., 23° S) and Ellsworth (0 m o.s.l., 67° S) were used. A method is described which gives detailed information on the variation of the primary cosmic ray spectrum during magnetic storms. This method is applied to the present case, giving the following results: the shape of the primary variation spectrum responsible for the three July storms was approximately the same as that of the May 1959 storm. During the recovery of the second storm, an injection of considerable intensity of low energy particles was found. The time dependence of this extra flux is determined. During the slow recovery after the last storm, the primary variation spectrum changes its shape in a similar way as in the May storm recovery. The correlation of these effects with geomagnetic activity is shown.

1. – Introduction.

The analysis of two or more superposed cosmic ray storms is of considerable interest. The question arises of whether or not there is a linear superposition of effects, that is, to what extent do mechanisms, causing superposed cosmic ray storms, interfere mutually. The answer to this question would give valuable information on the hydromagnetic properties of the cosmic ray modulating solar plasma beams (¹).

There are many alternative ways to explain the superposition of cosmic ray storms, depending on the model chosen for the explanation of the single

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(*) Paper presented to the Antarctic Symposium, Buenos Aires, November 1959.

(¹) W. R. Piggott and C. W. Allen: *VIII Rapport de la Commission pour l'étude des relations entre les phénomènes solaires et terrestres* (1957), p. 77.

storm modulation mechanism ([2-6]). If we take, for instance, Dorman's theory ([5]), we may explain qualitatively the occurrence of two successive magnetic storms with overlapping cosmic ray effects, as the action of two solar plasma beams being emitted from two points of active regions which are ejecting particles into a common region of solid angle. These beams impinge on the earth, causing magnetic disturbances and cosmic ray modulation. In the region of plasma superposition, there may be a linear addition of cosmic ray effects or not according to the degree of mutual interaction between frozen magnetic fields and currents of both streams. A linear addition would be attained in the limit of none interaction; deep changes in the modulating effect would occur in the case of strong interaction (if for instance one beam «sweeps away» the other, or if unstability is achieved, causing turbulence in the fringe region). In the first case, almost no change in the *shape* of the primary spectrum should be expected; merely the «amplitude» of the variation spectrum should change. In the second case, however, considerable changes in the primary spectrum might be produced.

It is interesting to note that the interaction of superposed plasma beams is expected to be stronger, the more the translational velocities of the two streams differ (*i.e.*, the greater is their relative velocity ([*])). If we take the lag between the flare and the sudden commencement of the magnetic storm as a measure of the mean velocity of particles in the stream, we conclude that our July streams are of successively increasing velocity: $1.1\cdot 10^8$ cm/s; $1.5\cdot 10^8$ and $2.2\cdot 10^8$ cm/s.

If on the other hand, we consider theories in which turbulent fields intervene ([4,6]), linear superposition of effects in two or more overlapping cosmic ray storms may preferably occur. Finally, theories in which the cosmic ray modulation is not merely localized inside the perturbing region, but extends out into the hydromagnetically «quiet» space ([2]), may again give only linear addition of effects.

2. – The primary variation spectrum during cosmic ray storms.

Different forms have been suggested for the primary variation spectrum of a cosmic ray storm ([5]). We will use Dorman's notation, writing $\delta D/D$ for the relative (%) variation spectrum. $D(E)$ is the reference differential primary

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([2]) E. A. Brunberg and A. Dattner: *Tellus*, **6**, 254 (1954).

([3]) Y. Sekido and M. Wada: *Rep. Ions. Res. Japan*, **9**, 174 (1955).

([4]) P. Morrison: *Phys. Rev.*, **101**, 1397 (1956).

([5]) L. I. Dorman: *Izv. AK. Nauk SSSR, Ser. Fiz.*, **20**, 24 (1956) and *Cosmic Ray Variations* (English Translation).

([6]) E. N. Parker: *Phys. Rev.*, **110**, 1445 (1958).

([*]) The shorter would be the time available for the magnetic lines of force of one beam to diffuse into the other.

spectrum taken from a quiet prestorm period. We shall assume for $\delta D/D$ the form

$$\frac{\delta D}{D} = \begin{cases} \delta k(t)\cdot E^{-\gamma} & \text{for} \quad \varepsilon_\lambda < \varepsilon < \varepsilon_0 \\ 0 & \text{for} \quad \varepsilon > \varepsilon_0 . \end{cases} \tag{1}$$

In the most general case, the three parameters δk, γ and ε_0 are time dependent. (ε_λ is the geomagnetic cut-off which we suppose to be constant). Now, as the exponent γ is mainly fixed by the modulation mechanism as a whole, we expect it to be fairly constant, unless the type of the mechanism is changed. The same applies to the upper cut-off ε_0, although a certain time dependence might be expected even during the action of one and the same modulation mechanism. For some theories, $\varepsilon_0 = \infty$.

We shall make the assumption that, for a given type of modulation mechanism, γ and ε_0 are constant in time; the main contribution of cosmic ray intensity time dependence is given by $\delta k(t)$ (depending on the earth's position in the beam, magnetic and electric field intensities, stream density, etc.). We shall call δk the «amplitude» of the variation spectrum. With the form of variation spectrum (1), the superposition of two effects obeying to the same modulation mechanism, would be given by the linear superposition of the amplitudes. If, instead, two *distinct* modulation mechanisms are superposed, we would have

$$\frac{\delta D}{D} = \delta k_1(t)\cdot E^{-\gamma_1} + \delta k_2(t)\cdot E^{-\gamma_2} , \tag{2}$$

with two cut-offs ε_{01} and ε_{02} for the first and the second terms, respectively. Finally, a sudden change of the mechanism at the time t_0 would be expressed by a spectrum like (2), with the condition

$$\begin{cases} \delta k_1(t) = \text{constant} & \text{for } t > t_0 , \\ \delta k_2(t) = 0 & \text{for } t < t_0 . \end{cases} \tag{3}$$

Let us now take the relative intensity variation recorded by a monitor at a given latitude (cut-off ε_λ)

$$\delta I = \frac{\delta N}{N} = \int_{\varepsilon_\lambda}^{\varepsilon_0} \frac{\delta D}{D} W_{\varepsilon_\lambda}(E)\cdot \mathrm{d}E ,$$

W_{ε_λ} is the coupling function for the given monitor at the given place. With a variation spectrum of the form (1), we have

$$\delta I = \delta k(t)\int_{\varepsilon_\lambda}^{\varepsilon_0} E^{-\gamma} W_{\varepsilon_\lambda}(E)\cdot \mathrm{d}E = \Gamma\cdot\delta k(t)\,; \tag{4}$$

Γ is a coefficient which depends on the monitor, its location and the two parameters γ and ε_0.

If we now consider two monitors « a » and « b », located at different latitudes, we can define a two dimensional vector $\delta\boldsymbol{I}$ of components $\delta I_a = \Gamma_a\cdot\delta k(t)$ and $\delta I_b = \Gamma_b\cdot\delta k(t)$. Eq. (4) shows that the direction of this vector is *constant in time* for a variation spectrum of type (1). Notice that the vector $\delta\boldsymbol{I}$, at a given instant t, is the sum of successive vectors $\Delta\boldsymbol{I} = \delta\boldsymbol{I}(t+\Delta t) - \delta\boldsymbol{I}(t)$ which represent the variation during a recording interval Δt (for instance, hourly or bihourly). The direction of these difference vectors should be constant, too. From the statistical point of view, all this means that δI_a and δI_b should be correlated linearly (*), the coefficient of regression being

$$\alpha_{ab} = \frac{\Gamma_a}{\Gamma_b} = \frac{\int_{\varepsilon_{\lambda_a}}^{\varepsilon_0} E^{-\gamma}\cdot W_a\cdot \mathrm{d}E}{\int_{\varepsilon_{\lambda_b}}^{\varepsilon_0} E^{-\gamma}\cdot W_b\cdot \mathrm{d}E}\,. \tag{5}$$

Any deviation from this linear correlation should be due to a change in the modulation mechanism.

We have calculated α_{ab} for the pairs of neutron monitors Ellsworth-Mina Aguilar and Buenos Aires-Mina Aguilar. We used the coupling functions given by DORMAN, (7) normalized to our geomagnetic cut-offs. These coupling functions are shown in Fig. 1. The resulting α values are given in Fig. 2 as a function of the upper

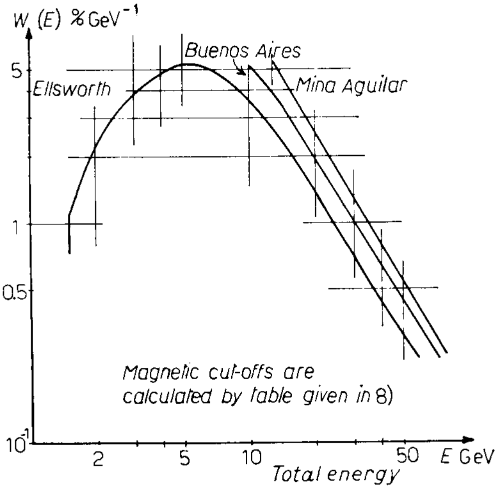

Fig. 1. – Coupling functions for neutron monitors at Mina Aguilar, Buenos Aires and Ellsworth, calculated using curves given in (8).

(*) This is of course also true for two monitors of different coupling function operating at the same place.

(7) L. I. DORMAN: *Cosmic Ray Variation* (English Translation), p. 117.

(8) J. J. QUENBY and W. R. WEBBER: *Phil. Mag.*, 4, 90 (1959).

cut-off, and for some plausible γ values. Using at least two pairs of stations of significantly different coupling functions, one may be able to determine γ and ε_0.

So far we have discussed the case of a single spectrum (1). Suppose now that a different, additional modulation mechanism starts its action at $t = t_0$. This means that after that instant, an additional term $\delta k_2(t) \cdot E^{-\gamma_2}$ appears in the variation spectrum. Therefore, after t_0, our two dimensional vector $\delta \boldsymbol{I}$ becomes the sum of two independent vectors

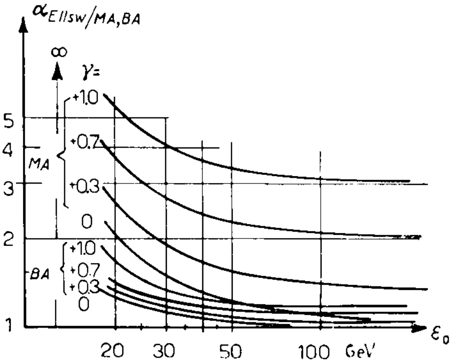

Fig. 2. – Ratio $\alpha_{ab} = \Gamma_a / \Gamma_b$ (eq. (5)) for the pairs of stations Ellsworth-Mina Aguilar and Buenos Aires-Mina Aguilar, as a function of the upper cut-off ε_0, and for different γ values.

$$\delta \boldsymbol{I} = \delta \boldsymbol{I}_1 + \delta \boldsymbol{I}_2 \tag{6}$$

of components

$$\left| \begin{aligned} \delta \boldsymbol{I}_1 &= (\delta k_1(t)\,\Gamma_{a_1};\ \delta k_1(t)\,\Gamma_{b_1})\,, \\ \delta \boldsymbol{I}_2 &= (\delta k_2(t)\,\Gamma_{a_2};\ \delta k_2(t)\,\Gamma_{b_2})\,, \end{aligned} \right. \tag{6$'$}$$

where

$$\Gamma_{a,b_2} = \int\limits_{\varepsilon_{\lambda a,b}}^{\varepsilon_{02}} E^{-\gamma_2} \cdot W_{a,b} \cdot \mathrm{d}E\,.$$

The important fact is that the direction of both vectors is *constant in time*. The linear correlation between δI_a and δI_b would be disturbed after t_0, and the difference vectors $\Delta \boldsymbol{I}$ would no longer be parallel after that time Fig. 3.

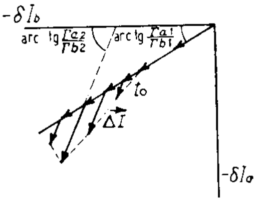

Fig. 3.

If we know *a priori* the *direction* of both vectors $\delta \boldsymbol{I}_1$ and $\delta \boldsymbol{I}_2$, we can easily determine the time dependence of both vectors independently given by $\delta k_1(t)$ and $\delta k_2(t)$. If, however, we only know the *direction* of *one* of them, say $\delta \boldsymbol{I}_1$, we are still able to determine the time dependence of the other (but not that of the first): if $\alpha_1 = \Gamma_{a_1}/\Gamma_{b_1}$ is the slope of $\delta \boldsymbol{I}_1$, we have, according to (6) and (6′),

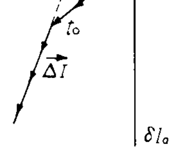

Fig. 4.

$$\delta I_a - \alpha_1\, \delta I_b = \delta k_2(t)\,[\Gamma_{a_2} - \alpha_1 \Gamma_{b_2}]\,. \tag{7}$$

As the first member is obtained from experimental data, we can determine the amplitude $\delta k_2(t)$ up to a constant factor $\Gamma_{a_2} - \alpha_1 \Gamma_{b_2}$. Again, if we have records from at least three stations, Γ_{a_2}, Γ_{b_2} and therefore γ_2, ε_{02}, as well as $\delta k_2(t)$ may be determined. In particular, if $\varepsilon_{\lambda_a} < \varepsilon_{02} < \varepsilon_{\lambda_b}$, we have $I'_{b_2} = 0$ and the difference $\delta I_a - \alpha_1 \delta I_b$ gives just δI_{a_2}, the contribution of process 2 to the intensity at station « *a* ».

Finally, if rather than a superposition, there is a sudden change in the modulation mechanism at $t = t_0$, we deduce from (3) (3′), (6) and (6′) that the *difference vectors* ΔI *merely change their direction* remaining again parallel to each other after $t = t_0$ Fig. 4.

3. – Experimental results.

The scope of this preliminary report is to give a qualitative analysis of the main behaviour of cosmic ray intensity during July 1959, recorded by three neutron monitors, located at Mina Aguilar, Buenos Aires and Ellsworth, Antarctica (*). Unfortunately, data from our Ushuaia monitor (0 m o.s.l., at

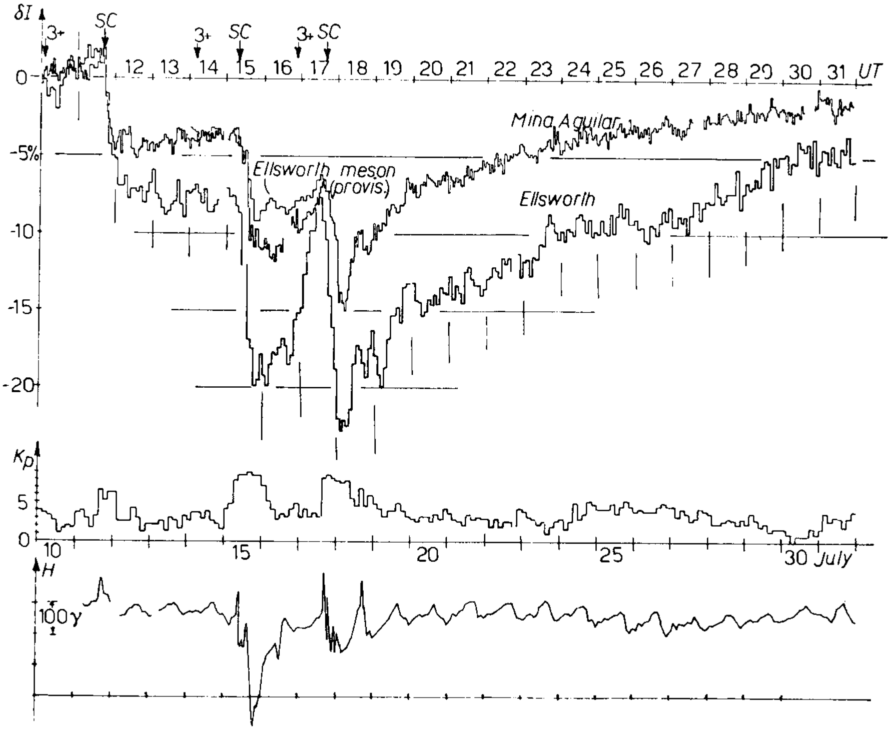

Fig. 5. – Percentage nucleon intensity variations recorded at Mina Aguilar (4 000 m, 12° S geom. lat.) and Ellsworth (sea level, 67° S). Meson cubical elescope data of the latter station (corrected for pressure only) are shown for comparison in the interval July 14-17th. K_p values, and the horizontal component of the magnetic field recorded at Pilar (Argentina), are represented at the bottom.

(*) The Ellsworth monitors are operated in collaboration with the Instituto Antártico Argentino and the University of California.

43° S geomagnetic latitude) had to be rejected due to unreliable performance during that month.

Fig. 5 shows the hourly and bihourly percentage intensity at Mina Aguilar and Ellsworth, respectively, referred to an average level during the quietest days preceding the first storm (July 6-9). Buenos Aires percentage intensity is not represented; it is remarkably coincident within 1% with the Mina Aguilar curve during the whole period. K_p indices and the horizontal component of geomagnetic field recorded at Pilar Observatory (*) are shown at the bottom. Many interesting features are revealed at first sight, one of the most remarkable being the strong increase recorded at Ellsworth some hours before the third storm set on (July 17-th). For the same time interval, strong increases of low energy particle intensity at high altitude have been reported (9). It is worth to try to get as much information as possible on the changes in shape and intensity of the primary cosmic ray spectrum.

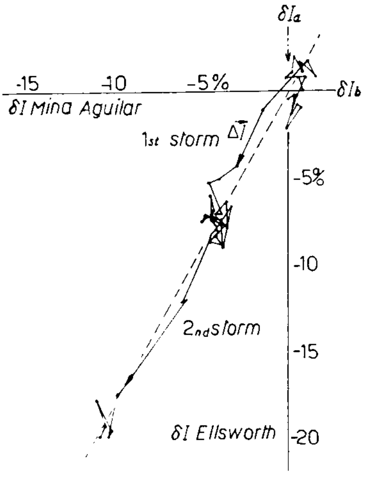

Fig. 6. – δI vectors (eqs. (4)-(6′)) of the pair of stations Ellsworth and Mina Aguilar, for the first and second storm (10th-17th July). The broken line is a best fit with $\alpha = 1.80$.

We applied the method described in the preceding chapter to the pairs of stations Mina Aguilar-Ellsworth and Mina Aguilar-Buenos Aires. In Fig. 6, δI_{MA} is plotted *vs.* δI_{ELLS} for the period July 10 to 16 (0400 UT); bihourly ΔI vectors are indicated. The total δI vector is obtained joining each angular point with the origin. The mean slope during this period is

$$\alpha_{\text{ELLS-MA}} = 1.80 \pm 0.10 \, .$$

Scattering of points is mainly due to daily variation, in addition to statistical fluctuations. Unfortunately, we have no reliable Ushuaia data in order to estimate the exponent γ and the upper cut-off ε_0 of the primary variation spectrum during these days. Buenos Aires and Mina Aguilar monitors have coupling functions (Fig. 1) too close to each other; indeed, the experimental α value for this pair of stations comes out

$$\alpha_{\text{BA-MA}} = 0.95 \pm 0.10$$

for the whole July period. Nevertheless, we can at least derive certain limits

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(*) 31° 40′ S - 63° 53′ W geographic coordinates.

(9) H. GHIELMETTI: private communication on Iowa Conference.

for γ and ε_0 from our experimental α values (Fig. 2). We obtain

$$0 < \gamma < 0.60 ,$$

with the corresponding limits for ε_0:

$$\text{for } \gamma = 0 , \quad \varepsilon_0 = 23 \text{ GeV} ; \qquad \text{for } \gamma = 0.6 , \quad \varepsilon_0 = \infty .$$

The value $\alpha_{\text{ELLS-MA}} = 1.8$ is slightly higher than that found for the same pair of stations during the May 1959 storm (1.65 ± .10). For the first stage of that storm (10) we find using data from Mina Aguilar, Buenos Aires, Ushuaia, Ellsworth, and Mt. Wellington:

$$\gamma = 0.48 \pm 0.06 , \qquad \varepsilon_0 \simeq \infty .$$

Taking into account limits of error, we may tentatively state that during the first stage of the July storms (11th-16th), the primary variation spectrum has a γ value comprised between 0.4 and 0.6.

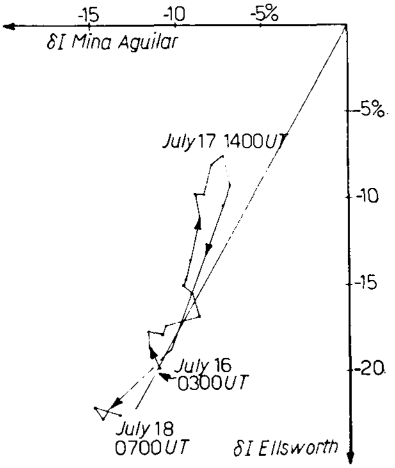

Fig. 7. – δI vectors for the 17th of July, showing the additional flux of low energy particles (see for instance eqs. (6) and (6′) and Fig. 3). The $\alpha = 1.80$ lines is drawn for reference.

Fig. 7 gives the behaviour of the ΔI vectors during the recovery after the second storm, till the big decrease of the third storm. A clean departure from the «normal» behaviour (11) (indicated by the $\alpha = 1.80$ line) suggests the superposition of a different type of primary variation spectrum, which represents an injection of low energy particles (*). Unfortunately, again due to our lack of information from intermediate latitudes (Ushuaia), we are not able to tell about the shape of the additional particles' spectrum. However, we can determine its time dependence according to (7). In Fig. 8 we have represented the «reduced» Mina Aguilar percentage intensity $\alpha_1 \delta I_{\text{MA}}$ ($\alpha_1 = 1.80$), together with the Ellsworth intensity. The difference $\delta I_{\text{ELLS}} - \alpha_1 \delta I_{\text{MA}} = \delta k_2(t)(\Gamma_{\text{ELLS}} - \alpha_1 \Gamma_{\text{MA}})$ is plotted below. If $\Gamma_{\text{MA}} = 0$ (*i.e.*, the additional flux has a cut-off $\varepsilon_{02} < 13$ GeV,

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(10) J. R. MANZANO, J. G. ROEDERER and O. R. SANTOCHI: *Nuovo Cimento*, **18**, 136 (1960).

(11) H. CARMICHAEL and J. F. STELJES: *Phys. Rev. Lett.*, **3**, 392 (1959).

(*) One may think, as an alternative, of an extremely fast recuperation of the low energy flux. However, any conventional mechanism could hardly explain a collapse of the modulating process for low energies, while it is still acting on high energy particles.

or $\gamma_2 \gg 1$ (*)), this difference gives directly $\delta I_{2\text{ELLS}}$, the contribution of the additional flux, in % of Ellsworth reference intensity. In this case, $\alpha_1 \, \delta I_{\text{MA}} =$

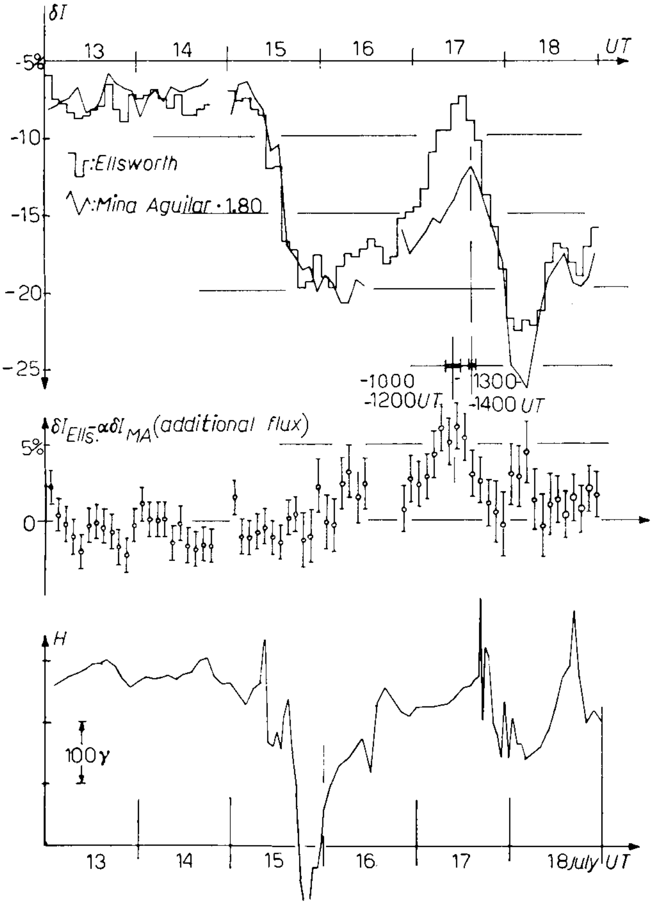

Fig. 8. – Top: Ellsworth percentage intensity and the « reduced » Mina Aguilar intensity (eq. (7)). Center: additional flux (in % at Ellsworth), with statistical errors. Bottom: horizontal component at Pilar.

$= \delta I_{1\text{ELLS}}$, the contribution at Ellsworth of the Forbush decrease modulation mechanism. Note the time difference between the maximum of the additional flux and the onset of the third storm. For the sake of comparison, we again plotted the horizontal field intensity.

(*) The steep increase found at high altitudes supports this hypothesis. Furthermore, a brief preliminary inspection of cubic telescope data from Ellsworth, which do not reveal any additional increase (see Fig. 3), suggests that ε_0 had to be less than ($8 \div 10$) GeV (the cut off of meson coupling function).

In Fig. 9, the ΔI vectors from 24 hour moving average intensity values are shown for the recovery period after the third storm. We took 24 hour moving average in order to eliminate the considerable daily variation in this period. Taking into account the discussion of Sect. 2, we realize that during the recovery period, the shape of the primary variation spectrum was changing with respect to that of the previous decreasing period. The general behaviour of the curve in Fig. 9 may be interpreted as a much slower recovery of low energy particles than that of the higher energy region. In other words, the primary variation spectrum decreased its γ (or increased its upper limit ε_0, or both) during the recovery period. It is interesting to note that this general behaviour is much the same as that of the May storm recovery (^{10}). Finally, as to the «fine structure» of the curve in Fig. 9, notice the peculiarity of the days 24, 25 and 26, during which the intensity at Ellsworth stood still while Mina Aguilar (and Buenos Aires) were steadily recovering. Around these days, the horizontal magnetic field intensity decreased, while the K_p index and the amplitude of daily variation increased. The daily variation is shown in Fig. 10, as it was estimated from the difference of 12 and 24 hours moving averages (^{12}).

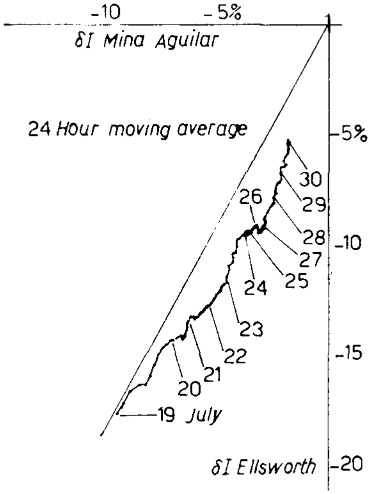

Fig. 9. - δI vectors of Ellsworth and Mina Aguilar, using 24 h moving averages. The gradual departure from the $\alpha = 1.80$ line after the 19th of July shows a gradual change in the shape of the primary variation spectrum, indicating that low energy particles recover slower than high energy ones.

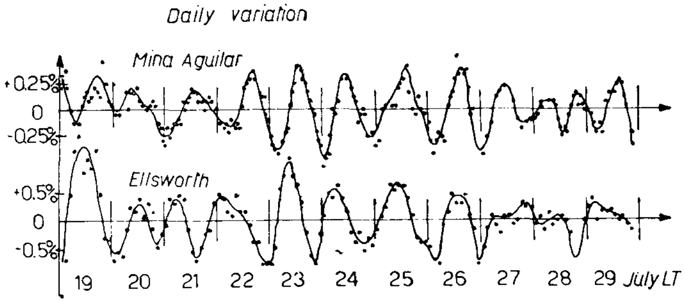

Fig. 10. - Daily variation at Mina Aguilar and Ellsworth, calculated from 24 h and 12 h moving averages (^{12}).

(^{12}) J. F. Steljes: *Nuovo Cimento*, **4**, 857 (1959).

15 minutes interval data have not yet been analyzed; a more careful quantitative analysis using meson telescope data (cubical at Ellsworth and Buenos Aires, narrow directional at Buenos Aires) is in progress.

4. – Conclusions.

From the preceding results we deduce that there was no appreciable change in the primary variation spectrum for the three successive Forbush decreases. This may be interpreted as an indication of a linear superposition of cosmic ray modulation effects during the July 1959 disturbances. On July 17th, an injection of low energy particles, probably with a steep energy spectrum occured. At the final stage, low energy particles recovered slower than high energy particles.

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RIASSUNTO (*)

Si analizza la variazione dell'intensità dei raggi cosmici durante le tre tempeste magnetiche del Luglio 1959. Si sono utilizzati i dati dei rivelatori di neutroni di Mina Aguilar (4000 m s.l.m., 67° S di latitudine geomagnetica), Buenos Aires (0 m s.l.m., 23° S) ed Ellsworth (0 m s.l.m., 67° S). Si descrive un metodo che fornisce dettagliate informazioni sulla variazione dello spettro dei raggi cosmici primari durante le tempeste magnetiche. Questo metodo viene applicato al caso presente, ottenendo i seguenti risultati: la forma dello spettro di variazione dei primari, cui è dovuta la tempesta del Luglio, era quasi uguale a quella della tempesta del Maggio 1959. Durante la ripresa dopo la seconda tempesta si è riscontrata una iniezione di intensità considerevole di particelle di bassa energia. Si determina la dipendenza dal tempo di questo flusso aggiuntivo. Durante la lenta ripresa dopo l'ultima tempesta, lo spettro di variazione dei primari cambia la sua forma in maniera simile alla ripresa dopo la tempesta di maggio. Si mostra la correlazione fra questi effetti e l'attività geomagnetica.

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