H. GHIELMETTI, etc.
1960, Gennaio
*Il Nuovo Cimento*
Serie X, Vol. 15, pag. 87-98

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# Solar Flare Effects on Cosmic Ray Intensity

BOLOGNA
TIPOGRAFIA COMPOSITORI
1960

# Solar Flare Effects on Cosmic Ray Intensity.

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(ricevuto il 24 Settembre 1959)

**Summary.** — In order to look for small cosmic ray increases associated with the development of solar flares, data from two neutron monitors located in the Southern Hemisphere were analysed. Solar flares of magnitude 2 or greater were selected, and the analysis was carried out for the detectors being located within the morning impact zones. The behaviour of nucleonic intensity, corrected for superposed daily variation, did not show any significative increase over the « zero hour ». This result contrasts with that of Firor, but agrees with the more recent paper by Towle and Lockwood. However, in the present work and for one station, there appears a significative peak if another type of correction is applied. Furthermore, another significative increase arises several hours after the onset of solar flares, closely peaked around the time of maximum in the mean daily variation. Data examined were extracted from records of the University of Tasmania at Mount Wellington (Hobart, Tasmania) and Mawson (Antarctica). The period investigated covers from July 1957 to August 1958.

## 1. - Introduction.

One of the most outstanding features of the large increases in cosmic ray intensity associated with important chromospheric outbursts on the sun, is that both events do not occur at comparable rates. Since the beginning of continuous recording of cosmic ray intensity there were only few instances of large cosmic ray increases, while the frequency of important solar flares is several times greater.

If one assumes that the intensity increases are due to a sudden production of high energy particles on the sun or near it, the fact that not every solar flare is accompanied by a rise in cosmic rays intensity might be explained by one or several of the following arguments:

*a*) The physical process occurring on the sun during the development of a solar flare has, in each case, a different effectiveness for particle acceleration. The resultant spectrum of the additional solar radiation changes in shape and total number of particles.

*b*) The accelerating mechanism being the same in each flare of similar magnitude, the electromagnetic conditions around the sun are different in each case. Only in few opportunities the accelerated particles would be able to reach the space beyond the solar atmosphere.

*c*) Electromagnetic conditions in interplanetary space are different in each case. Again, only in few instances the conditions would be favorable for particles to reach the earth.

*d*) Solar particles arrive at the earth in any case, but special conditions are required for the position of detectors, relative to the source, in order to show any increase in the recorded intensity.

The first calculated trajectories of particles initially travelling in the direction of the earth-sun line, already showed that argument *d*) is valid (1,2). In order to reveal a solar originated increase, the detector must be located within one of the impact zones (3). This however does not explain the rarity of reported increases, even less if one takes into account that the number of simultaneously operating observatories has increased substantially.

To find out whether *a*) or *b*) or both hold, it seems necessary to be sure of the true mechanism operating on the sun during a solar flare and of the correlated changes in magnetic fields around the sun. As to argument *a*), there are several plausible mechanisms proposed to explain how charged particles may be accelerated to cosmic ray energies during a solar flare (4); the point is to elucidate if physical conditions are reproduced for different flares, so that one accepted mechanism could operate with the same effectiveness in each case.

The « tunnel » theory of FORBUSH *et al.*, (5) that fits into *b*), is probably one of the few known arguments that might explain the scarcity of increases. Indeed, « tunnel » formation in a proper superposition of the sun's general field and the magnetic field of a sunspot would occur with a rare chance. However, new evidence about the permanent solar magnetic moment suggest that tunnels should arise more frequently than formerly supposed. Almost

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(1) A. EHMERT: *Zeits. f. Naturfor.*, **3a**, 264 (1948).

(2) A. SCHLÜTER: *Zeits. f. Naturfor.*, **6a**, 613 (1951).

(3) J. W. FIROR: *Phys. Rev.*, **94**, 1017 (1954) (and references therein).

(4) S. F. SINGER: in *Progress in Cosmic Ray Physics*, edited by J. G. WILSON, vol. 4, (Amsterdam, 1958), p. 313 (and references therein).

(5) S. E. FORBUSH, P. S. GILL and M. S. VALLARTA: *Rev. Mod. Phys.*, **21**, 44 (1949).

every sunspot with a magnetic field of at least 1000 gauss is expected to give rise to a magnetic tunnel (⁶). If this were the case, intensity increases should be expected after almost every solar flare, although the size of the increase cold be different from case to case, due to changes in energy spectra.

There is clear evidence that interplanetary magnetic fields influence the additional flux of charged particles arriving at the earth (⁷). If this influence is the predominant one, it would be expected a difference in cosmic ray behaviour during solar flares in epochs of high or low solar activity. About the time of maximum solar activity, the increased number of magnetized beams and clouds ejected by the sun would prevent with a greater chance the arrival of solar particles at the earth.

Therefore it seems important to clarify whether a cosmic rays increase, no matter how small, is associated with every solar flare. The experimental difficulty lies in the fact that very small increases are masked by statistical fluctuations and by other superposed cosmic ray intensity variations.

DOLBEAR, ELLIOT and DAWTON (⁸) analysed data of a counter telescope, looking for increases associated with radio fade-outs accompanying solar flares. They found an increase of 0.3 percent, although impact zones were not taken into account. Near 1954 solar cycle minimum, analysing nucleonic component data at Climax, FIROR found an increase near 1 percent associated with solar flares of importance 1 + or greater, when the station was within a proper impact zone. In a similar analysis recently made by TOWLE and LOCKWOOD (⁹), no increase $\geqslant 0.25\%$ was found, even for flares of importance 2 or greater (*). This result correspond to data obtained near 1957 solar maximum.

The task of the present work is to investigate the behaviour of nucleonic intensity recorded by two neutron monitors located in the Southern Hemisphere, during solar flares occuring at maximum solar activity.

## 2. - Sources of data.

In the present analysis, data reported by the University of Tasmania (**), since the beginning of the International Geophysical Year, were utilized. They correspond to two neutron monitors located at Mount Wellington (Hobart,

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(⁶) L. I. DORMAN: *Cosmic Ray Variations* (Translation from Russian prepared by Technical Documents Liaison Office, Wright-Patterson Air Force Base, Ohio, 1957).

(⁷) P. MEYER, E. N. PARKER and J. A. SIMPSON: *Phys. Rev.*, **104**, 768 (1956).

(⁸) D. W. N. DOLBEAR, H. ELLIOT and D. I. DAWTON: *Journ. Atm. Terr. Phys*, **1**, 187 (1950).

(⁹) L. C. TOWLE and J. A. LOCKWOOD: *Phys. Rev.*, **113**, 641 (1959).

(*) This paper was known to the authors only when the present work was finished.

(**) We are very indebted to Prof. N. R. PARSONS for sending us the data.

Tasmania) and Mawson (Antarctica). Both stations supply pressure corrected hourly intensity values with standard deviations about 0.55 % or better.

Geomagnetic co-ordinates for the two stations are: 51.7 °S, 225.2 °E (Mt. Wellington), and 73.1 °S, 103.0 °E (Mawson); and geomagnetic time (10) is given by: $t+10.4$ h and $t+2.3$ h, where $t$ is universal time (UT), in hours.

The epoch considered, around solar maximum, extends from July 1957 to August 1958.

## 3. – Selection criteria.

3'1. *Selection of solar flares.* – As it was shown by FIROR (3), the size of cosmic ray intensity increases during solar flares is correlated with flare magnitude. Due to this evidence, and to the fact that the maximum solar activity over the period considered *a priori* assures a reasonable number of events, we analysed only those solar flares of reported importance 2 or greater, confirmed by several observatories (11).

3'2. *Geomagnetic co-ordinate system.* – To locate the position of the detectors and to determine the variable position of the sun, the conventional geomagnetic system, in the centered dipole approximation, was utilized. Although the question of the effective co-ordinate system for cosmic rays is still open (12,13), PFOTZER showed that the conventional geomagnetic system was the better one to give account of the relative increases in cosmic ray intensity at several stations during the second phase of the cosmic ray disturbance following the solar flare of February 23, 1956 (14).

The geomagnetic latitude $\Phi_S$ of the source was determined using suitable curves deduced from McNish graphs (10).

3'3. *Impact zones.* – In order to locate the source position, the sun was considered as a point source, despite of the fact that evidence from large cosmic ray increases has shown that it acts as a finite source of considerable angular aperture $(15° \div 30°)$ (3).

With the geomagnetic latitude $\Phi$ of the station and using Firor's graphs (curves 3 and 4 in ref. (3)) we determined both, the range in $\Phi_S$ for which the

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(10) A. G. McNISH: *Terr. Magn. and Atm. Elec.*, **41**, 37 (1936).

(11) *Solar-Geophysical Data*, Part B (U. S. Dept. of Commerce, National Bureau of Standards, Central Radio Propagation Laboratory, Boulder Colorado, 1957, 1958).

(12) J. A. SIMPSON, F. JORY and M. PYKO: *Journ. Geophys. Res.*, **61**, 11 (1956).

(13) J. A. SIMPSON, K. B. FENTON, I. KATZMANN and D. C. ROSE: *Phys. Rev.* **102**, 1648 (1956).

(14) G. PFOTZER: *Suppl. Nuovo Cimento*, **8**, 220 (1958).

detector could be in an impact zone, and the range in geomagnetic time (*) corresponding to the center $\theta_c$ of this zone. Only the morning impact zones were considered, and as usual they were supposed to be four hours in width. If at the moment of the flare the detector was located within one of them, the event was classified as of type A. If the detector was at least one hour away from the edges of the zones (complementary region) the event was classified as of type B.

For Mawson (73° S) it was found that only the « 09 » impact zone is of importance. Effects are to be expected when $\Phi_s$ lies between 20° S and 35° S, roughly corresponding to particles of magnetic rigidities $M$ between 1 and 3 GV. The center of the zone lies between 0930 and 1000 hours, in geomagnetic time.

For Mt. Wellington (52° S), effects are expected when the station is within the two morning impact zones: « 09 » and « 04 ». For the first one, we have roughly: $0° \leqslant \Phi_s \leqslant 20°$ N ($5 \leqslant M \leqslant 10$ GV) and $0630 \leqslant \theta_c \leqslant 0930$ hours. For the second one, 20° S $\leqslant \Phi_s \leqslant$ 20° N ($2.5 \leqslant M \leqslant 5$ GV) and $\theta_c$ ranges between 2330 and 0630 hours.

It must be noted that, in general, only « 09 » and « 04 » impact zones have been taken into account ($^{3,9}$), in view of the greater relative increases to be expected in them. However, this is true only when the source is on the geomagnetic equator and the additional particles have a flat spectrum. The relative increases at the top of the atmosphere may be considerably different for certain $\Phi_s$, as it has been shown by LÜST ($^{15}$). On the other hand, we must realize that the magnetic rigidity of the particles able to reach a particular point changes with $\Phi_s$. As the effectiveness of a detector deeply immersed in the atmosphere depends on primary energy, the superposition of events occurring at distant epochs (different $\Phi_s$), greatly affects the reliability of the method used to reveal such small increases.

3·4. *Procedure of analysis.* – Data were analysed according to the method of superposed epochs ($^{16}$). As « zero hour » we chose the interval containing the time of the first optical observation of the solar flare. The analysis was carried out for an interval extended from 6 hours before « zero hour » (preflare interval) to 12 hours after.

For each station, and each type of impact zone, hourly averages per column and percent deviations from the hourly mean over the preflare interval were

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(*) The approximate relation $\theta = t + (\Lambda - 69)/15$ for geomagnetic time ($t$ = UT; $\Lambda$ geomagnetic longitude) was considered good enough for the present purposes ($^{10}$).

($^{15}$) R. LÜST: *Phys. Rev.*, **105**, 1827 (1957) (and references therein).

($^{16}$) C. CHREE: *Phil. Trans.*, A **213**, 245 (1913); A **212**, 76 (1913).

calculated (*). Table I shows the number of events considered in each set of data. Standard errors of the percent deviations were in any case better than 0.15 %.

TABLE I.

| Station | Type of impact zone | No. of events | Range of $\Phi_S$ | Range of $M$ | Range of $\theta_c$ | Date of analysed events |
|---|---|---|---|---|---|---|
| Mawson | « 09 » | 16 | 20° S ÷<br>÷ 35° S | (1 ÷ 3)<br>GV | 0930 ÷<br>÷ 1000 | 1957: Oct., Nov., Dec.<br>1958: Jan., Feb. |
|  | Compl. Region | 20 |  |  |  |  |
| Mt. Wellington | « 09 » | 16 | 0° ÷<br>÷ 20° N | (5 ÷ 10)<br>GV | 0630 ÷<br>÷ 0930 | 1957: Aug., Sep., Oct.<br>1958: Mar., Apr., Aug. |
|  | Compl. Region | 100 |  |  |  |  |
|  | « 04 » | 20 | 20° S ÷<br>÷ 20° N | (2.5 ÷ 5)<br>GV | 2330 ÷<br>÷ 0630 | 1957: Aug., Sep., Oct., Nov., Dec.<br>1958: Jan., Mar., Apr., Jun., Aug. |
|  | Compl. Region | 69 |  |  |  |  |

## 4. – Corrections.

It is obvious that the investigation of different time variations of cosmic ray primary intensity is made difficult due to their superposition; when attention is focused on one of them, it is not always easy to eliminate completely the influence of the others. In our case, we assumed that the most important additional variation to be considered is the daily variation, which masks the small effect looked for.

4.1. *Superposed daily variation.* – Data from Mawson were corrected with a daily variation averaged on five months around the main events; those from Mt. Wellington were corrected with a mean variation deduced from eleven months (see Table I).

As a check of this procedure, data from Mawson were tentatively grouped into months and corrected with a mean daily variation deduced from each month. No difference was found with respect to the use of an over all mean daily variation.

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(*) A more reliable procedure, taking the percent deviations of hourly values from pre-flare mean in each single event, and then averaging these deviations over corresponding columns, showed no significative difference. This is due to the fact that hourly averages in each case do not differ in more than 5 % from the over all hourly mean.

4·2. *Correction with « preceding day » daily variation.* – It is well known that daily variation suffers very irregular day to day changes, specially during times of increased solar activity. Furthermore, the appearence of an important solar flare generally means that a very disturbed area on the visible hemisphere on the sun has been acting since some days before. Days surrounding that of a flare are characterized by high geomagnetic activity and therefore by a daily variation different of the mean, showing significative increases in the amplitude of higher harmonics. For this reason, the weakest point in the usual correction arises in the use of a mean daily variation taken over a long period covering the intervals of the flares.

In order to take this into account, another way of correction was applied: data of each day preceding the occurrence of a flare (included in the former analysis) were superposed, taking in each case the same hours as in the nineteen hours interval around the flare. The percent deviations per column were subtracted from raw data. The resulting deviations were supposed to be free of daily variation effect, showing the true variation due to the additional radiation coming from the sun, if any.

As it will be shown below, there appears a significative difference in final results, if one applies correction *a*) or *b*).

## 5. – Results.

Table I gives details concerning analysed cases. In spite of the relatively large number of solar flares of importance 2 or greater during the considered period (*), the restrictions imposed decrease greatly the number of acceptable data.

Hourly deviations have a standard error of 0.15 % or better; after correction *a*) the error is almost the same; correcting according to *b*) it increases to 0.20 % or better. Notwithstanding, an increase of about 1 % should be reliably detected.

Final results are presented in Figs. 1-8. Fig. 1 shows the mean daily

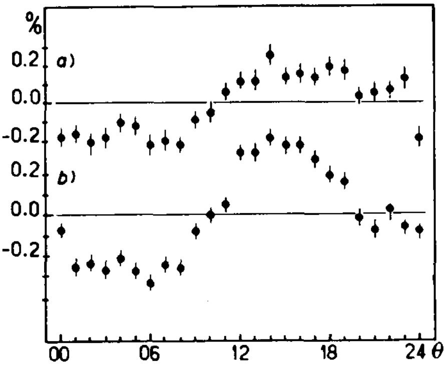

Fig. 1. – Mean daily variation of cosmic ray intensity at Mawson *a*) and Mt. Wellington *b*), calculated over several months around the selected solar flares (see Table I).

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(*) During the last quarter of 1957 the relative sunspot number reached its highest value since many solar cycles.

variation during the period analysed (Mawson: curve *a*), Mt. Wellington: curve *b*)). Despite of the high flare activity in this epoch, no significative increase during morning hours is found, in contrast to Firor's results for daily variation of days of high flare activity index, obtained near the last solar minimum. However, flare activity index was not explicitly taken into account in the present case, so that these curves cannot be considered as evidence of no increase during morning hours.

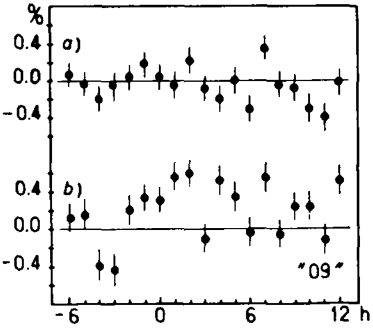

Fig. 2. – Cosmic ray intensity at Mawson (in the « 09 » impact zone) six hours before and twelve-hours after the onset of 16 solar flares. *a*) Corrected for mean solar cycle, *b*) corrected for « preceding day » effect.

Fig. 2 shows final results for Mawson in « 09 » impact zone, raw data being corrected with both above mentioned methods: mean daily variation *a*), and « preceding day » *b*). No statistically significative increase at « zero hour » is observed.

Figs. 3 and 4 show corrected deviations for Mt. Wellington in « 09 » and « 04 » impact zones, respectively. In both figures, *a*) corresponds to data corrected with mean daily cycle, and *b*) to those corrected with the « preceding day » method. Fig. 3 *c*) shows data after correction taking into account intensity variation from the day preceding and day following the occurrence of each flare. Here the correction applied results from hourly averages deduced by adding the total pairs of days embracing each flare, over the same intervals in UT corresponding to the flares. As it is apparent this procedure resembles the correction outlined under *b*), and it was applied simply to confirm the result obtained in Fig. 3 *b*).

Now, one considers only those results obtained after correction for mean daily cycle effect (Figs. 2 *a*), 3 *a*) and 4 *a*)), one comes to the conclusion that no significative effect is revealed in each of the three analysed cases. However, results are changed if one exclusively takes into account the mean

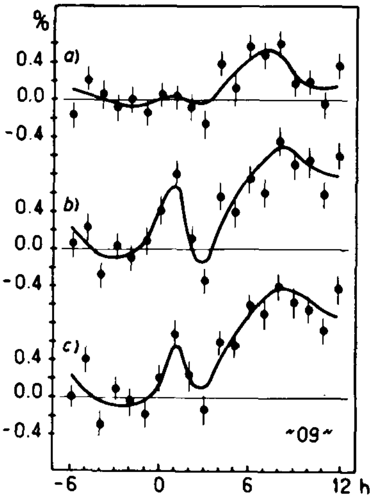

Fig. 3. – Cosmic ray intensity at Mt. Wellington (in the « 09 » impact zone) six hours before and twelve hours after the onset of 16 solar flares. *a*) Corrected for mean daily cycle; *b*) corrected for the « preceding » day effect; *c*) corrected with the pair of days around each solar flare (see text).

behaviour of the intensity for the day preceding that of the flare production. For Mt. Wellington in the « 09 » impact zone (Fig. 3 *b*)), there appears a significative peak around « zero hour » of 0.6 %, similar to that found by Firor for Climax (48° N). For Mawson and Mt. Wellington in the « 04 » impact zone (Figs. 2 *b*) and 4 *b*)) it is more difficult to come to the same conclusions.

Fig. 5 shows the behaviour of the nucleonic intensity for events of type B, for Mawson (curve *a*)) and Mt. Wellington (curves *b*) and *c*)) within the complementary regions of both « 09 » and « 04 » impact zones. As it should be expected, no increase following the onset of solar flares is observed.

Figs. 6, 7 and 8 show the distribution of « zero hours » for Mawson and Mt. Wellington. Hours in the dial are given in geomagnetic time. Weighted means of the position of « zero hours » are: 9.4 h for Mawson in the « 09 » impact zone, and 7.5 h and 1.4 h for Mt. Wellington in the « 09 » and « 04 » zones, respectively. This figures also show the distributions of « zero hours » for the stations in the complementary regions.

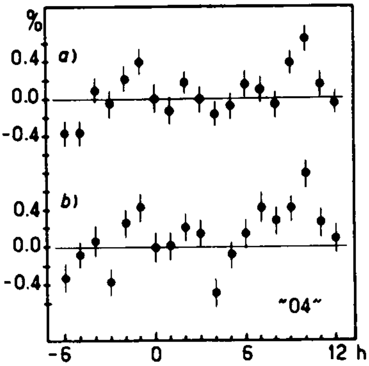

Fig. 4. – Cosmic ray intensity at Mt. Wellington (in the « 04 » impact zone) six hours before and twelve hours after the onset of 20 solar flares. *a*) Corrected for mean daily cycle; *b*) corrected for the « preceding day » effect.

Further examination of Mt. Wellington curves (Figs. 3 and 4) indicates that, whatever the correction applied, the intensity increases nearly 1 % several hours after the beginning of the flare. Considering the distribution in time of « zero hours » when the station is in the « 09 » impact zone (Fig. 7), one can deduce that this « second peak » appears near the time of the daily

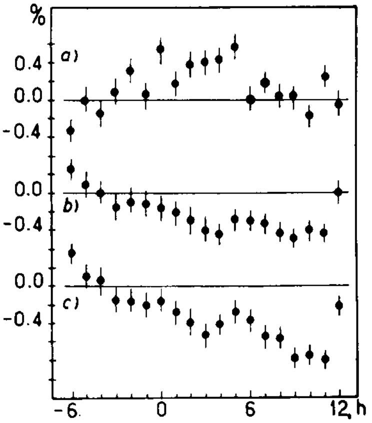

Fig. 5. – *a*): Cosmic ray intensity at Mawson, six hours before and twelve hours after the onset of 20 solar flares, occurring when the station was in the complementary region of the « 09 » impact zone (corrected for mean daily cycle). *b*) and *c*): Cosmic ray intensity at Mt. Wellington six hours before and twelve hours after the onset of 100 and 69 solar flares occurring when the station was in the complementary regions of the « 09 » and « 04 » impact zones, respectively. (Uncorrected for mean daily cycle).

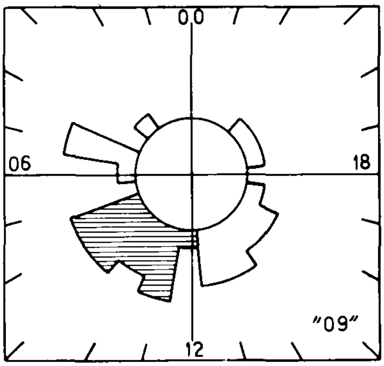

Fig. 6. – Distribution of « zero hours » at Mawson for solar flares occurring when the station was in the « 09 » impact zone (dashed area) and in the complementary region. It corresponds to Figs. 2 and 5*a*.

variation maximum. For the « 04 » impact zone, the distribution of « zero hours » is broader, nevertheless the peak falls again roughly after noon. This complementary result seems to be interesting enough for a further analysis. If this increase in amplitude of daily variation follows every solar flare, it would be revealed only when events are grouped in time over a more or less narrow distribution, as it is the case when impact zones are taken into account. This increase in amplitude after the production of a flare, if confirmed, could be explained by the same mechanism responsible for the normal daily variation, if one accepts that the additional radiation accelerated during the flare remains trapped for some time within the vicinity of the solar system.

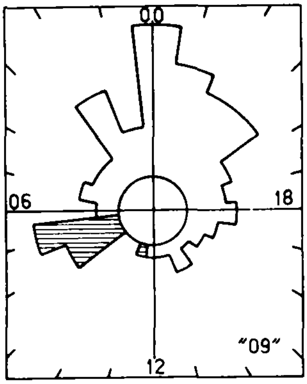

Fig. 7. – Distribution of « zero hours » at Mt. Wellington, for solar flares occurring when the station was in the « 09 » impact zone (dashed area) and in the complementary region. It corresponds to Figs. 3 and 5*b*.

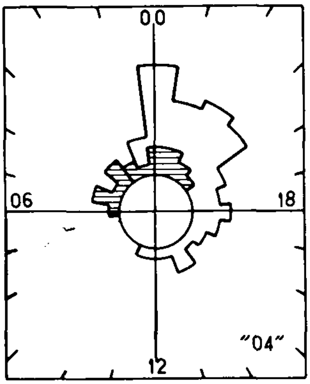

Fig. 8. – Distribution of « zero hours » at Mt. Wellington, for solar flares occurring when the station was in the « 04 » impact zone (dashed area) and in the complementary region. It corresponds to Figs. 4 and 5*c*.

## 6. – Conclusions.

From the results obtained above, it appears that if one considers the first point of view for data correction, namely, the use of an over all mean daily cycle properly weighted for « zero hours » distribution, our result agrees with a similar analysis made by TOWLE and LOCKWOOD for Mt. Washington, and both differ from that given by FIROR. The first two were obtained near the 1957 solar maximum, while Firor's analysis was made near the 1954 solar minimum. If in both periods different mean electromagnetic conditions in interplanetary space existed, it would be easy to understand the observed difference in solar flare effects.

However, we believe that a better correction for daily variation is that of the « preceding day » method used in the present work. In this case, the fact that only Mt. Wellington in the « 09 » impact zone shows a significative increase at « zero hour » might be explained taking into account the difference in magnetic rigidities of the particles able to arrive at the detector for each of the three cases considered. It must be noted that during the 1954 solar minimum neither the correction for mean daily cycle applied by FIROR to his data, nor the correction with our « preceding day » method would reveal any significative difference, because of the low solar activity of the epoch and the lower magnitude of the flares analysed, which prevent large changes between the solar flare preceding days' behaviour and the mean behaviour of cosmic ray intensity.

In summary, one can arrive to the following conclusions from the results obtained in the present work:

1) In analysing small flare effects it is important to choose an appropriate method of correction to take into account the masking effect of daily variation. The results appear to be strongly dependent on the method employed, and we suggest to consider the behaviour of cosmic ray daily variation around each analysed interval as a more suitable index of the correction to be applied.

2) It seems reasonable to continue investigating small flare effects along the solar cycle in order to obtain further evidence. Besides, it would be interesting to confirm the existence of the post-flare increase, for detectors suitably located, after the onset of the solar flares.

3) The use of the method of superposed epochs in an analysis of small flare effects presents several disadvantages, mainly due to the mixing of events occuring under different conditions. Certainly, it would be most convenient to use devices of such high counting rates that conclusions might be driven from every individual solar flare. In this case, it would be unnecessary to correct for other superposed variations; hence no uncertainties related to their day to day changes would arise. Balloons and rockets carrying cosmic rays counters, recording very low energy particles, are suitable instruments to reveal these small increases, but the chance of a flare occuring during a

flight is low. Earth satellites equipped with cosmic rays detectors appear to be a better tool for the continuous recording of these small solar flare effects.

* * *

The authors wish to express their sincere appreciation to Prof. A. G. FENTON and Prof. N. R. PARSONS and to the staff of the Cosmic Ray Group of the University of Tasmania for sending them data of their cosmic ray stations on which this work is based. They also wish to thank Miss M. C. BAVA for her assistance in numerical calculations.

## RIASSUNTO (*)

Per ricercare piccoli aumenti della radiazione cosmica associati allo sviluppo di brillamenti solari, abbiamo analizzato i dati registrati da due contatori di neutroni situati nell'emisfero meridionale. Si scelsero brillamenti di grandezza 2 o superiore, e l'analisi fu fatta solo quando i contatori si trovavano nelle zone d'impatto mattutine. Il comportamento dell'intensità dei nucleoni, al netto di correzione per la variazione giornaliera sovrapposta, non mostrò alcun aumento sensibile all'« ora zero ». Questo risultato è in contrasto con quello di FIROR, ma è in accordo con il più recente scritto di TOWLE e LOCKWOOD. Però nel presente lavoro e per una delle stazioni compare un sensibile picco se si applica un altro tipo di correzione. Per di più un altro sensibile aumento si verifica parecchie ore dopo l'insorgere dei brillamenti, con un picco molto stretto attorno al periodo di massimo della variazione giornaliera media. I dati esaminati vennero ricavati dalle registrazioni fatte a cura dell'Università di Tasmania a Mount Wellington (Hobart, Tasmania) e a Mawson (Antartide). Il periodo esaminato va dal luglio 1957 all'agosto 1958.

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(*) *Traduzione a cura della Redazione.*

H. GHIELMETTI, etc.
1960, Gennaio
*Il Nuovo Cimento*
Serie X, Vol. 15, pag. 87-98