PAPER 37

CORRELATION BETWEEN COSMIC RAY INTENSITY AND GEOMAGNETIC ACTIVITY

D. VENKATESAN

Royal Institute of Technology, Stockholm, Sweden

ABSTRACT

The Chree method of analysis has been adopted for the analysis of the Ionization Chamber data for Huancayo, Cheltenham and Godhavn for 1946 and for the former two stations for 1945. The same procedure is adopted for the planetary index K_p also.

The cosmic ray minimum (or maximum) precedes the minimum (or maximum) of K_p by about 4–5 days. It is also observed that the relative decrease in cosmic ray intensity per day, $-\Delta I/(I.\Delta t)$, follows the changes in K_p in a general way, and hence the electric field as would be expected from the consideration of the theory of emission of beams of particles from the sun with the associated frozen magnetic field and the electric field arising due to polarization.

The concept of a storm-producing beam consisting of ionized rarified gas ejected from the sun and reaching the earth in about a day, was first introduced by Schuster (see Fig. 1). The beam originates from the sun where magnetic fields exist. If this is the case, as pointed out by Alfvén [1] the field would be frozen in the beam, since the conductivity of the beam is large. The beam carries the field as far out as the earth. Due to the motion with the velocity V_B ($=2\times 10^8$ cm/sec) the beam becomes electrically polarized, the electric field being given by the equation

$$\mathbf{E}=-\frac{1}{c}.\mathbf{V}_B\times\mathbf{H}.$$

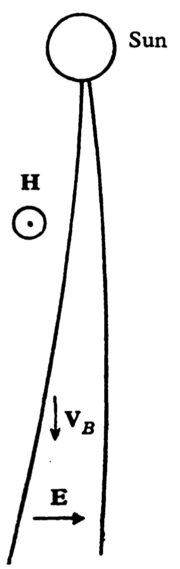

Fig. 1. Storm producing beam, emitted from the sun (equatorial plane).

The voltage V across the beam is given by $V=E.B$, where B is the breadth of the beam. Cosmic ray particles with energy V_0 on passing the beam change their energy

https://doi.org/10.1017/S0074180900237935 Published online by Cambridge University Press

by V. If ΔI is the change in intensity, the relative decrease in intensity per day is given by the equation:

$$-\frac{\Delta I}{I}=k\frac{V}{V_0}=kEB/V_0=\frac{k.E}{V_0}.\frac{2\pi R}{27}.\Delta t,$$

where k is a constant which depends on the measuring device, R is the earth–sun distance. Hence, the relative decrease in intensity per day $-\Delta I/I.\Delta t$ should follow the changes in the electric field. In connexion with magnetic storms and aurorae Alfvén has pointed out that the electric field in the beam is its most important property. This seems to gain support from cosmic ray results as well. If K_p, the planetary index, could be considered as a measure of the electric field, then the relative decrease in intensity per day $-\Delta I/(I.\Delta t)$ should follow the changes in the electric field or the K_p index.

The data that have been chosen for analysis are the Carnegie Institution Ionization Chamber Records [2] for 1945 and 1946. Fig. 2 shows the day-to-day variations in intensity at Huancayo. The former is a fairly undisturbed period while the latter shows heavy decreases. The data for 1946 has been restricted to the period February–October, so that even if we consider 1 month on either side, it is well within the disturbed period.

The superposed epoch method of analysis originally devised by Chree [3] for analysis of geomagnetic activity is used. The procedure is as follows. Five days in each month when the cosmic ray intensity is highest (or lowest) are selected and the intensity on these selected zero days are written down in a column designated '0' day. The data preceding these selected zero days are written down in columns to the left and are called -1, -2, -3, ... days respectively. Similarly the data corresponding to the days following the zero days are written to the right of the '0' day and are called $+1$, $+2$, $+3$, ... days respectively. The average value for each column is determined and a smoothening is carried out by taking the average intensity over 3 days. The values are plotted on a graph against the corresponding day numbers. The same procedure is adopted for the planetary index K_p, the zero days being the same as determined for the cosmic ray data.

Fig. 3 shows the results of the analysis for minimum intensity days for Huancayo for 1945. It is seen that the cosmic ray minimum precedes that of K_p by about 4–5 days. The result agrees with those of Simpson [4] and Kane [5], but differs from that of Van Heerden–Thambyahpillai [6]. The fair correspondence between the relative decrease in cosmic ray intensity per day, $-\Delta I/(I.\Delta t)$, and K_p is seen.

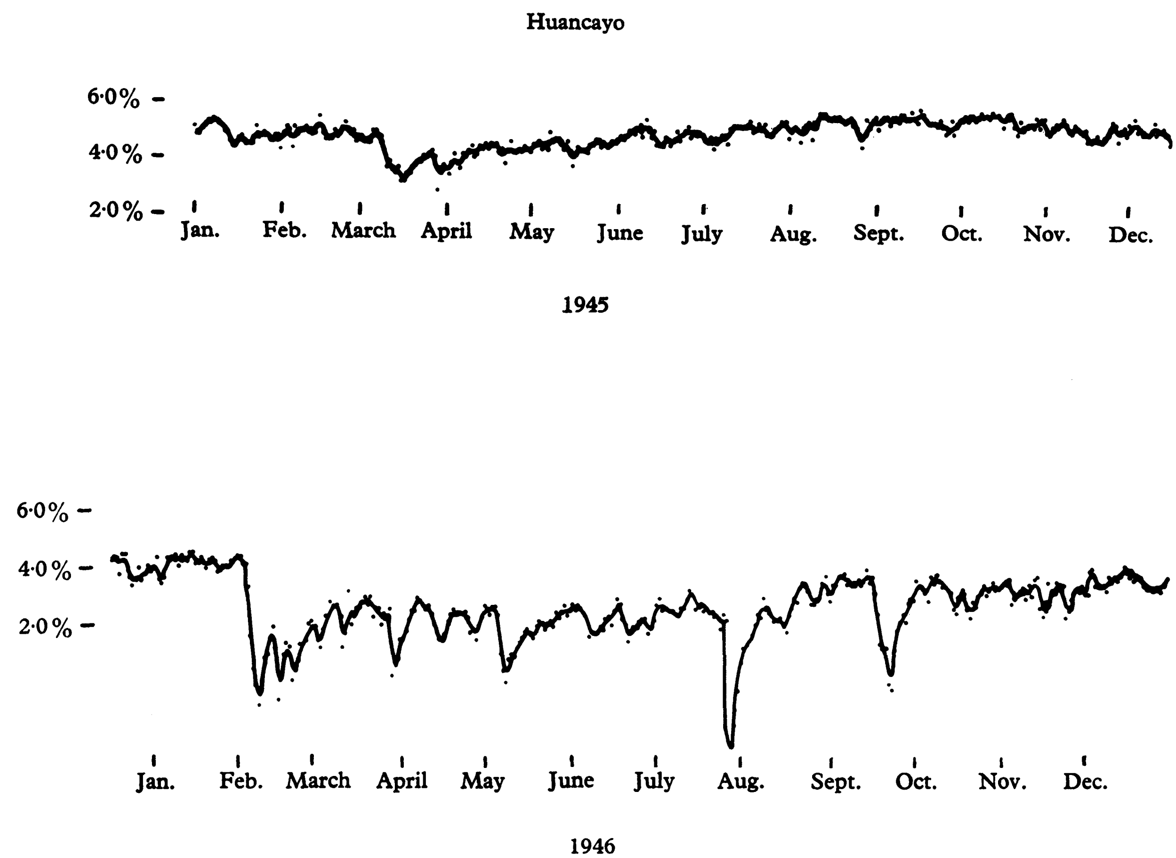

Fig. 2. Daily mean cosmic ray intensities at Huancayo for 1945 and 1946.

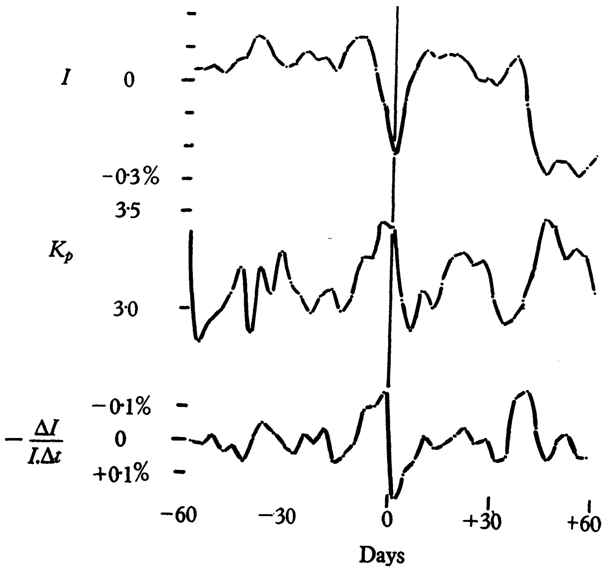

Fig. 3. Chree analysis for Huancayo for 1945 corresponding to five minimum intensity days per month. The top curve refers to cosmic ray intensity, middle one to K_p, and the bottom one to the relative decrease in intensity $-\Delta I/I.\Delta t$ per day, shown reversed.

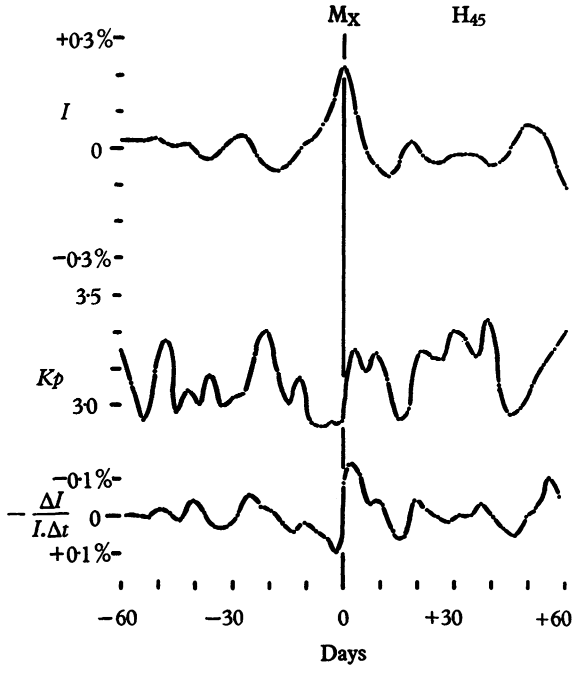

Fig. 4. Chree analysis for Huancayo for 1945 corresponding to five maximum intensity days per month. The top curve refers to cosmic ray intensity, middle one to K_p, and the bottom one to the relative decrease in intensity $-\Delta I/I.\Delta t$ per day, shown reversed.

https://doi.org/10.1017/S0074180900237935 Published online by Cambridge University Press

Fig. 4 shows the results of the analysis for Huancayo corresponding to maximum intensity days for the year 1945. The same feature, namely, the cosmic ray maximum preceding that of K_p is observed.

Fig. 5 shows the result for Cheltenham for the same year corresponding to maximum and minimum intensity days. The days of selection are the same as for Huancayo. Table 1 shows the correlation analysis for the various cases. The fair agreement between $-\Delta I/(I.\Delta t)$ and K_p can be seen from the figures and the table.

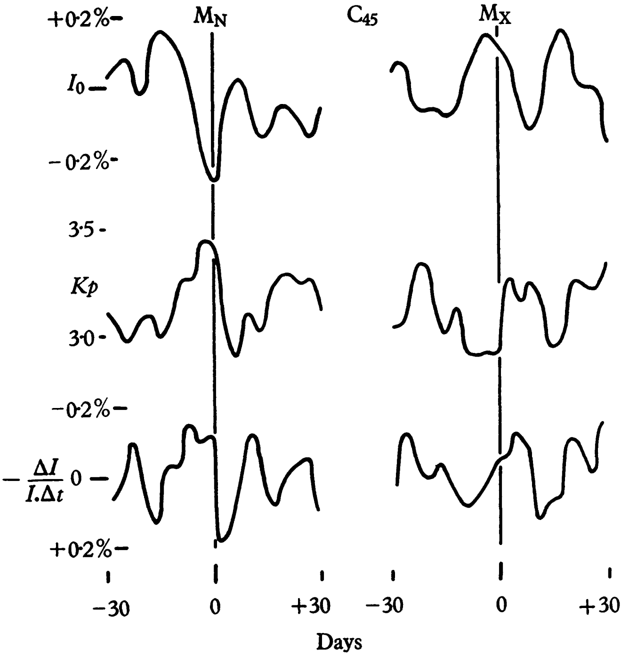

Fig. 5. Chree analysis for Cheltenham for 1945 corresponding to five days of minimum as well as five days of maximum intensity. The top curve refers to cosmic ray intensity, middle one to K_p, and the bottom one to the relative decrease in intensity $-\Delta I/I.\Delta t$ per day, shown reversed.

Table 1. *Correlation coefficient for—1945 between*

No.	Station	I and K_p	$-\frac{\Delta I}{I.\Delta t}$ and K_p	I and K_p	$-\frac{\Delta I}{I.\Delta t}$ and K_p
		Minimum intensity days		Maximum intensity days	
		For −30 to +30 days			
1.	Huancayo	$-0·34 \pm 0·03$	$+0·56 \pm 0·02$	$-0·49 \pm 0·02$	$+0·65 \pm 0·02$
2.	Cheltenham	$-0·59 \pm 0·02$	$+0·26 \pm 0·02$	$-0·68 \pm 0·02$	$+0·48 \pm 0·02$
		For −15 to +15 days			
1.	Huancayo	$-0·51 \pm 0·04$	$+0·59 \pm 0·08$	$-0·36 \pm 0·05$	$+0·52 \pm 0·04$
2.	Cheltenham	$-0·53 \pm 0·04$	$+0·33 \pm 0·05$	$-0·59 \pm 0·04$	$+0·40 \pm 0·04$

Fig. 6 shows the results for Huancayo, Cheltenham and Godhavn for the period February–October 1946. The same features seen in the data for 1945 are observed to an even more pronounced degree. If the analysis is restricted to 14 days on either side, the correspondence between the relative decrease per day, $-\Delta I/(I.\Delta t)$, and K_p is extremely high. This improvement when we restrict the analysis to 14 days instead of 30 days on either side is understandable, because the secondary series usually

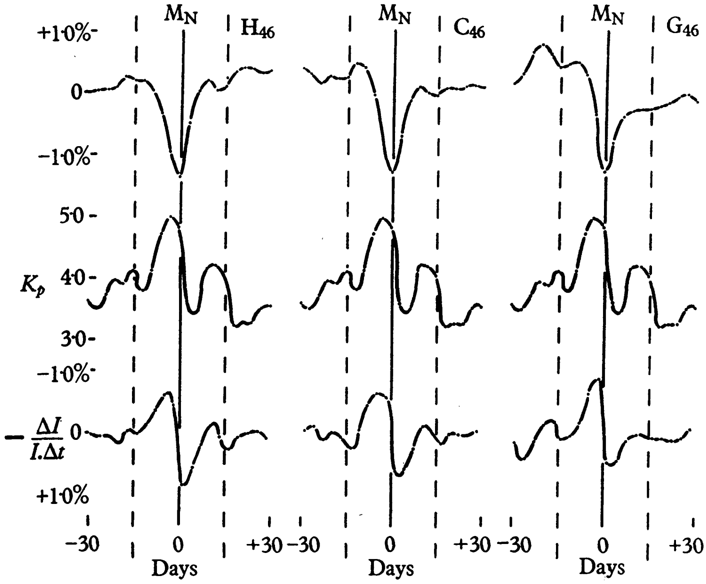

Fig. 6. Chree analysis for Huancayo, Cheltenham and Godhavn for 1946 corresponding to five days of minimum intensity per month. The top curve refers to cosmic ray intensity, the middle one to K_p, and the bottom one to the relative decrease $-\Delta I/I.\Delta t$ per day, shown reversed.

found in the 27-day variations, occurs after a separation of about 14 days, and this is not present to interfere, when we consider only 14 days on either side. Table 2 gives the correlation coefficients in the various cases.

The individual decreases during the period February–October, 1946 are considered for Huancayo, and the correlation between I and K_p, and $-\Delta I/(I.\Delta t)$ and K_p are presented in Table 3. The results are given for 3-day averages as well as for the day-to-day values. In general there is a negative correlation between I and K_p, and a positive correlation between $-\Delta I/(I.\Delta t)$ and K_p, as would be expected from the theory of the beam. This shows that $-\Delta I/(I.\Delta t)$ follows the changes in K_p in a general manner and hence the changes in the electric field.

Table 2. *Correlation coefficient for—1946 between*

No.	Station	I and K_p	$-\frac{\Delta I}{I.\Delta t}$ and K_p	I and K_p	$-\frac{\Delta I}{I.\Delta t}$ and K_p
		Minimum intensity days			
		From -30 to $+30$ days		From -15 to $+15$ days	
1.	Huancayo	-0.72 ± 0.01	$+0.58 \pm 0.02$	-0.63 ± 0.03	$+0.79 \pm 0.02$
2.	Cheltenham	-0.48 ± 0.02	$+0.65 \pm 0.02$	-0.42 ± 0.05	$+0.87 \pm 0.01$
3.	Godhavn	-0.16 ± 0.02	$+0.76 \pm 0.01$	-0.14 ± 0.05	$+0.90 \pm 0.01$

Table 3. *Huancayo—1946. Correlation coefficient between*

	Minimum intensity on	3-day averages		Day-to-day values	
		I and K_p	$-\frac{\Delta I}{I.\Delta t}$ and K_p	I and K_p	$-\frac{\Delta I}{I.\Delta t}$ and K_p
1.	8 February	-0.81 ± 0.02	-0.12 ± 0.06	-0.56 ± 0.04	0 ± 0.05
2.	16 February	-0.30 ± 0.05	$+0.67 \pm 0.03$	-0.35 ± 0.05	$+0.76 \pm 0.02$
3.	21 February	-0.60 ± 0.04	$+0.37 \pm 0.05$	-0.45 ± 0.05	$+0.56 \pm 0.04$
4.	2 March	-0.11 ± 0.06	-0.41 ± 0.05	-0.18 ± 0.38	-0.02 ± 0.06
5.	10 March	-0.70 ± 0.03	$+0.03 \pm 0.06$	-0.69 ± 0.03	-0.22 ± 0.03
6.	29 March	$+0.31 \pm 0.05$	$+0.72 \pm 0.03$	0 ± 0.05	$+0.45 \pm 0.05$
7.	15 April	-0.83 ± 0.02	$+0.16 \pm 0.06$	-0.76 ± 0.02	$+0.04 \pm 0.06$
8.	27 April	-0.23 ± 0.06	$+0.65 \pm 0.03$	0 ± 0.05	$+0.40 \pm 0.05$
9.	8 May	-0.68 ± 0.03	$+0.31 \pm 0.05$	-0.68 ± 0.03	$+0.28 \pm 0.01$
10.	9 June	-0.68 ± 0.03	$+0.31 \pm 0.05$	-0.66 ± 0.03	$+0.24 \pm 0.02$
11.	21 June	$+0.76 \pm 0.03$	$+0.25 \pm 0.06$	$+0.65 \pm 0.03$	-0.07 ± 0.06
12.	29 June	-0.76 ± 0.03	$+0.16 \pm 0.06$	-0.04 ± 0.05	$+0.35 \pm 0.05$
13.	9 July	-0.39 ± 0.05	$+0.15 \pm 0.06$	-0.26 ± 0.02	$+0.40 \pm 0.05$
14.	28 July	-0.69 ± 0.03	$+0.50 \pm 0.05$	-0.42 ± 0.05	$+0.60 \pm 0.04$
15.	15 August	-0.97 ± 0.00	$+0.53 \pm 0.04$	-0.60 ± 0.04	$+0.42 \pm 0.05$
16.	25 August	$+0.19 \pm 0.06$	$+0.25 \pm 0.06$	$+0.09 \pm 0.06$	$+0.55 \pm 0.04$
17.	1 September	$+0.68 \pm 0.03$	$+0.43 \pm 0.05$	$+0.18 \pm 0.04$	$+0.83 \pm 0.02$
18.	23 September	-0.39 ± 0.05	$+0.35 \pm 0.05$	-0.40 ± 0.05	$+0.14 \pm 0.05$

REFERENCES

[1] Alfvén, H. *Cosmical Electrodynamics* (Oxford University Press, 1950), ch. 6; *Tellus*, **6**, 232, 1954; *Tellus*, **7**, 50, 1955.

[2] *Cosmic ray results from Huancayo observatory, Peru*, vol. 16, Carnegie Institution of Washington, 1948.

[3] Chree, C. *Phil. Trans. Roy. Soc.* A, **212**, 76, 1913; Chree and Stagg, *Phil. Trans. Roy. Soc.* A, **227**, 21, 1928.

[4] Simpson, J. A. *Phys. Rev.* **94**, 426, 1954.

[5] Kane, R. P. *Phys. Rev.* **98**, 130, 1955.

[6] Van Heerden and Thambyahpillai, *Phil. Mag.* **46**, 1238, 1955.

https://doi.org/10.1017/S0074180900237935 Published online by Cambridge University Press

Schlüter: Did you measure the time of onset of 23 February 1956 cosmic ray increase at your different stations?

Forbush: Yes. I think from the original records one start of the increase was 3 or 4 min later at Godhavn, Greenland.

Schlüter: We had looked into the question of the 27-day variation of cosmic rays and the geomagnetic data some years ago. A negative correlation was found not only between CR and corpuscular activity (as measured by K_p) but also between CR and the ultra-violet emission of the sun (as measured by the W-numbers) which exceeds that due to the inter-correlation between both kinds of solar activity. I do not see any reasonable theoretical explanation for this effect and I therefore think it worth while to establish or to discard the existence of this effect.

Forbush: If you mean the correlation between cosmic ray intensity and the SW measure of Bartels we have not investigated this. One must take great care of mean correlations.

In connexion with Dr Venkatesan's high correlations referred to in the first part of his talk it should be pointed out that this correlation was between averages. One must remember that means of samples from a population with very low correlations between individuals in a pair, will exhibit a larger correlation which increases with the number of pairs in the mean. Furthermore, statistical tests of the significance of the correlation coefficients must take account of lack of statistical independence between successive samples.

Venkatesan: The necessity of looking into the individual storms has been realized and that is being looked into.

Forbush: An important point is also that successive days are independent.

Ehmert: If I have understood it correctly you find a change in phase between small magnetic perturbations influencing cosmic radiation and great storms on the other side. It seems that the first ones are connected with M-zones and the other ones are flares lying aside.

Biermann: Supplementing Dr Schlüter's remarks I would like to say that the original work on the effect of solar wave-radiation was chiefly done by Dr van Roka at our institute in Göttingen and that has been described in our treatise on *Kosmische Strahlung* (Springer Verlag 1953, ed. by Heisenberg). To this has only to be added that van Roka's theory of that effect advanced at that time now almost certainly appears to be disproved (see e.g. the more recent work by Simpson and his group).

Singer: How often does a cosmic ray decrease not correlate with magnetic storms?

Forbush: They are nearly always correlated.

Singer: Does the cosmic ray decrease arise about one day earlier than magnetic activity? Is that the general rule?

Forbush: No. We have only observed one large decrease starting before a magnetic storm.

Sarabhai: On 23 February 1956 we observed an increase of about 6% in intensity averaged over an hour at stations near the magnetic equator in India, Unfortunately, we do not know the profile of our increase and are unable to state whether the solar particles travelled in direct trajectories from the sun or were deflected or scattered. A comparison with Huancayo would be interesting.

In relation to Dr Venkatesan's paper I should like to draw attention to the work of the Japanese group where the characteristics of effective and non-effective magnetic storms have been studied. It would be important to understand why, according to the proposed model of Venkatesan, all magnetic storms do not produce a change of cosmic ray intensity.

Could Dr Forbush throw some light on the possible causes which are responsible for the standard deviation, after correcting for the barometric effect and world-wide changes, being more than what one would expect from errors of random sampling?

Forbush: Everything may cause the deviation, except the barometric effect. The data were corrected to constant barometric pressure.

Venkatesan: We have not overlooked possible occurrence of storms without cosmic ray activity. Professor Alfvén has mentioned about the possibility of a capture effect of cosmic ray in an electrically polarized beam. This could explain the presence of a storm which has no associated cosmic ray activity.

Singer: The world-wide character of the Forbush decrease shows that a large region around the earth is affected. Decreases are also observed near the geomagnetic pole and there the cosmic rays would have come from very large distances in a direction perpendicular to the ecliptic plane.

Denisse: The fact that the amplitude of the 27-day variation goes through zero at the moment when the solar activity has minimum intensity suggests that this variation is uniquely correlated with violent magnetic disturbances. However, since the storms do not show up a recurrence of 27 days it is not surprising that the amplitude of the 27-day variation is small.

Ehmert: The famous and expressive picture that Professor Forbush showed of the magnetic storm influence contains the influence of several storms following each other. However, analysis of some great magnetic storms showed that there is an extremely strong correlation between the ring-current field, as measured by the midnight field depression at Huancayo, and the cosmic ray deflection at the same time throughout the individual storm. The coefficient of influence varies from storm to storm but is constant for individual storms. I think that is a criterion on which the theories should be based.

Ferraro: Did you find this correlation with every great storm?

Ehmert: No, I must say there were only 4 or 5 that I was able to analyse.

Lovell: Although ionospheric absorption of the galactic radio emissions has been observed during the main auroral phases following a flare (see, for example, C. G. Little and A. Maxwell: *J. Atmos. Terr. Phys.* **2**, 356, 1952), the observation of a decrease in intensity at the time of the flare reported by Dr Forbush is probably unique. The Jodrell Bank observations of galactic radio emissions during this period are being published in the *Jodrell Bank Annals*. There were marked effects on the scintillation phenomena in the period 30–40 hr following the flare, but no effect whatsoever at the time of the flare. Two equipments were in operation as follows:

1. The 218 ft transit telescope on 90 Mc/s. Beam-width 3° to half power, centred on $13^{h}\ 28^{m}$. R.A.; $+42°\ 20'$ decln., at the time of the flare.

https://doi.org/10.1017/S0074180900237935 Published online by Cambridge University Press

2. An equipment on 80 Mc/s continuously following the Cassiopeia radio source. No significant change in the scintillations or signal strength occurred at the time of the flare.

It is considered that any intensity change exceeding 0·25 dB would have been prominent on these records, and this lack of absorption may be compared with the significant decrease reported by Dr Forbush on the lower frequency. It is hoped that this information will be of interest to Dr Forbush and his colleagues in their consideration of the nature of this effect. In the case mentioned above Little and Maxwell placed the region responsible at a height of well over 100 km and concluded that the effect was due to the reflexion of the incoming radiation near the upper boundary and not absorption during transmission through the region. It is to be hoped that a consideration of all the relevant data will enable the height of the region and the nature of the effect to be assessed in the present instance.

Ehmert: Ionospheric influence by the flare of 23 February 1956 was world-wide and observed also on the night hemisphere as a damping of long waves. From Professor Simpson's ascending values I evaluated the number of free electrons in the height between 40 and 90 km assuming with Budden a recombination coefficient of 10^{-14}. I found 1 to 5 electrons/cm^3. This is the lower limit given by this high coefficient. That is good enough for explaining the anomalies in long-wave propagation. Only in the auroral zones in Canada there seems to have been a further impact of particles.