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DAY TO DAY CHANGES IN THE DAILY MEAN INTENSITY OF COSMIC RAYS

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ABSTRACT. Data obtained at Kodaikanal (geomag. lat. 1°N, altitude 2300 meter) for cosmic ray mesons and the nucleonic component are analysed for the first 12 months of the I.G.Y. (July 1957–June 1958). Day to day changes of the mean intensity and their relationship with geomagnetic phenomena are studied. Comparison is made with neutron monitor data at Huancayo, Ottawa and Resolute. A variation spectrum of the type $\delta D(E)/D(E) \propto E^{-1}$ is obtained.

I. INTRODUCTION

During the I.G.Y. period, several workers in the world have operated cosmic ray meson telescopes and neutron monitors on a continuous basis. The Physical Research Laboratory, Ahmedabad, India, also participated in this effort and contributed data for neutron monitors and cubical meson telescopes for the stations at Ahmedabad and Kodaikanal. Besides these instruments, a narrow angle telescope of semi-angles 10° in the E–W plane and 20° in the N–S plane was also operated at Kodaikanal during the I.G.Y. period. Since meson telescopes and neutron monitors at different latitudes and altitudes have different energy responses to the primary cosmic ray intensity, a comparison of data from these gives an idea about the energy dependence of cosmic ray variations.

In this communication we have described the results of an analysis of results obtained with five different cosmic ray measuring instruments. Details of these are given in Table I.

TABLE I

Details of the stations

Instrument	Situation	Alt. (met.)	Geomagnetic Lat.	Geomagnetic Long.	Cut off energies (BeV)
Meson telescope (10°×20°)	Kodaikanal	2343	1°	147°	15
Neutron pile	Kodaikanal	2343	1°	147°	15
,,	Huancayo	3400	−1°	354°	13
,,	Ottawa	101	57°	351°	2
,,	Resolute	17	83°	289°	0

II. ENERGY RESPONSE OF THE VARIOUS INSTRUMENTS

Before proceeding with an examination of the results of analysis of the data from the various instruments, it is advisable to get an idea of the differences in their energy responses. This was attempted by following Dorman's (1957) method, which is outlined below :

The number N (h) of secondary cosmic ray particles at a latitude λ and at an atmospheric depth (h) is given by

$$N_\lambda(h) = \int_{E_\lambda^c}^{\infty} D(E).M(E, h)dE \quad \dots \quad (1)$$

where $D(E)$ represents the primary energy spectrum at the top of the atmosphere and $M(E, h)$ is the "multiplity function" which gives the number of secondary particles produced by a primary particle of energy E. The lower limit of integration $E_\lambda{}^c$ is the minimum (critical) energy for arrival of primary cosmic rays in the vertical direction at latitude λ.

Dividing Eq. (1) by $N_\lambda(h)$ and multiplying by 100, we get

$$100\% = 100 \int_{E_\lambda^c}^{\infty} \frac{D(E)M(E, h)dE}{N_\lambda(h)} = \int_{E_\lambda^c}^{\infty} W(E, h)dE \quad \dots \quad (2)$$

where $W(E, h)$ represents the percentage contribution to the secondary component at depth h, due to primaries of energy E. $W(E, h)$ is known as the "coupling constant". A knowledge of its functional relationship with E is necessary to get an idea of the energy response of any particular instrument. W involves the product of the primary energy spectrum $D(E)$ and the multiplicity function $M(E, h)$. The primary energy spectrum of cosmic ray intensity is now fairly well established. But the multiplicity function $M(E, h)$ is difficult to calculate theoretically because of many complex processes involved in the interactions of primary cosmic ray particles with air nuclei. Dorman (1957) has pointed out that the coupling constants W can also be evaluated from a knowledge of the latitutde dependance of cosmic ray intensity, as follows :

Differentiating (1) partially with respect to $E_\lambda{}^c$, we get

$$\frac{\partial N_\lambda(h)}{N_\lambda(h)} = -\partial E_\lambda^c \frac{D(E) \, . \, M(E, h)}{N_\lambda(h)} = -\partial E_\lambda{}^c \, . \, W_\lambda(E, h) \quad \dots \quad (3)$$

It is clear, therefore, that $W(E, h)$ is directly related to the latitude effect of the secondary component observed at a depth h. Since the latitude effects of the various secondary components have been precisely obtained experimentally, the coupling constants $W(E, h)$ can be easily calculated for energies between 0 and 15 BeV which is the maximum vertical cut-off energy (at $\lambda = 0$). For higher energies, Dorman suggests extrapolation methods which are based partly on experimental results and partly on theoretical considerations.

The coupling constants $W(E, h)$ are different for different secondary components and for different altitudes and latitudes and have been calculated by Dorman from experimental latitude effect data. Fig. 1 gives the coupling constants as percentage per BeV for the various secondary components mentioned in Table I. Since the latitude dependence of the meson component at the altitude of Kodaikanal is not known, the coupling constants for the same are obtained by averaging the coupling constants for Ion-chamber measurements at 10 Km altitude and hard component measurements at sea-level.

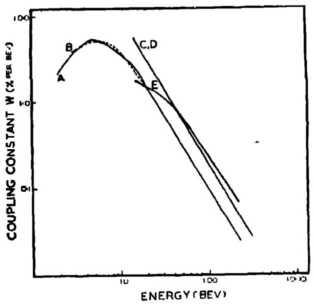

Fig. 1. Coupling constant W (percentage per BeV) for various secondary components. A-Resolute neutrons, B-Ottawa neutrons, C-Huancayo neutrons, D-Kodaikanal neutrons, E-Kodaikanal mesons. All plots are normalised to give $\int W.dE = 100$.

Knowing the value of W for all energies between E and ∞, it should be possible to calculate the mean energies to which the various instruments respond. A statistical method of obtaining the same would be to calculate mean energy $\bar{E}$ by the formula

$$\bar{E} = \frac{\int_{E_\lambda^c}^{\infty} W(E) \, . \, E \, . \, dE}{\int_{E_\lambda^c}^{\infty} W(E) \, . \, dE} \qquad \ldots \quad (4)$$

However, this method does not succeed for any of the curves given in Fig. 1 because of the following reason. For high emergies, the plots in Fig. 1 can be approximated to a relation of the type $W = k.E^{-\nu}$. However, the values of ν are all less than 2 whereas the integral in the numerator of Eq. (4) is convergent only if $\nu > 2$. Hence, Eq. (4) does not yield finite values for the mean energy $\bar{E}$.

Fonger *et al.* (1953) have avoided this difficulty by assuming an arbitrary definition of mean energy $\bar{E}$ as,

$$\frac{1}{1+\bar{E}} = \frac{\int_{E_\lambda^c}^{\infty} \frac{W(E) \, . \, dE}{1+E}}{\int_{E_\lambda^c}^{\infty} W(E) dE} \quad \ldots \quad (5)$$

Using this formula, the mean energies for the various secondary components referred to in Table I would be as follows:

Kodaikanal meson	54 BeV
Kodaikanal neutron	34 ,,
Huancayo ,,	34 ,,
Ottawa ,,	12 ,,
Resolute ,,	11.5 ,,

One may also view the energy response qualitatively by calculating the percentage of particles contributed by primaries confined to an energy range 0 to E for various values of E. Fig. 2 gives the percentages for the various secondary components.

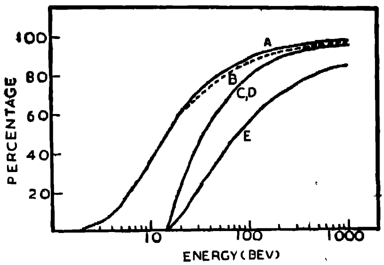

Fig. 2. Percentage of secondary particles contributed by primaries of energies below E. Symbols A, B, C, D & E have the same meaning as in Fig. 1.

It can be seen from Fig. 2 that for the neutron monitors at Ottawa and Resolute, almost 50% of the secondaries are due to primary energies between

0 to 15 BeV while for the nucleonic component at Huancayo and Kodaikanal the corresponding energy range is 15 to 35 BeV. For Kodaikanal meson intensity, the range is still higher viz. 15 to 75 BeV.

III. DAILY MEAN INTENSITY OF COSMIC RAYS

The daily mean intensities of the nucleonic component and meson component of cosmic ray intensity at the various places corrected for barometric effect only are plotted in Fig. 3 for the period July 1957 to June 1958. The daily means of *H*, the horizontal component of earths magnetic field at Kodaikanal, are also plotted.

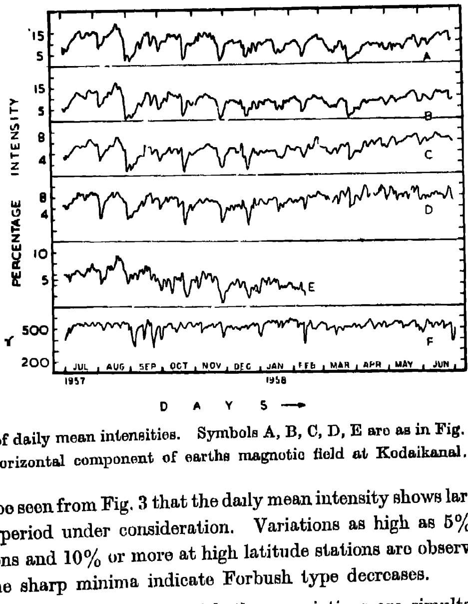

Fig. 3. Plot of daily mean intensities. Symbols A, B, C, D, E are as in Fig. 1. *H* represents the horizontal component of earths magnetic field at Kodaikanal..

It can be seen from Fig. 3 that the daily mean intensity shows large fluctuations during the period under consideration. Variations as high as 5% at the equatorial stations and 10% or more at high latitude stations are observed frequently. Many of the sharp minima indicate Forbush type decreases.

To find out the extent to which these variations are simultaneous at the various stations, correlation coefficients are calculated for the various pairs. They are given in Table II.

It can be seen from Table II that

(a) Kodaikanal neutrons and Huancayo neutrons are very highly correlated with each other but not so much with either Kodaikanal mesons or Ottawa and Resolute neutrons.

TABLE II

Correlation coefficients between the various components

	Kodaikanal meson	Kodaikanal neutron	Huancayo neutron	Ottawa neutron	Resolute neutron
Kodaikanal meson	1.00	0.68	0.70	0.70	0.59
Kodaikanal neutron	0.68	1.00	0 91	0.73	0.66
Huancayo neutron	0.70	0.91	1.00	0.86	0.71
Ottawa neutron	0.70	0.73	0 86	1.00	0.97
Resolute neutron	0.59	0.66	0.71	0.97	1.00

(b) Ottawa and Resolute neutrons are very highly correlated with each other.

It seems, therefore, that the mean intensity variations are broadly parallel at all the stations indicating a world wide nature of the variations, but there are differences also between stations at different latitudes as also between mesons and nucleonic component. It is also observed that the average ranges of the variations for Kodaikanal neutron and Huancayo neutron are about the same, while the ranges of neutron intensity at Ottawa and Resolute are more than twicet hose at Kodaikanal or Huancayo. Kodaikanal meson intensity has a range somewhat lesser than Kodaikanal neutron intensity. This indicates a strong energy dependence where lower energies have larger variations.

It must be noted, however, that the meson intensity is not corrected for upper air temperature effect and is not, therefore, directly comparable to the neutron intensities. The lower correlation between neutron and meson intensities could be due to this fact. Unfortunately, upper air radio-sonde data for Kodaikanal are not available and hence it is not possible to estimate and correct for the upper air temperature effect at Kodaikanal.

IV. RECURRENCE TENDENCIES IN THE DAILY MEAN INTENSITY VARIATIONS

To study the recurrence tendencies in the daily mean intensity, the days on which Ottawa neutron intensity showed maxima and minima were chosen as epoch days and Chree diagrams were drawn for the various intensities for $n = -60$ to $+60$ about the epoch day $n = 0$. These are shown in Fig. 4.

Fig. 4(a) and 4(b) refer to Ottawa neutron intensity maxima and minima respectively as epochs. It will be seen that there is a 27-day recurrence tendency for both the maxima and minima. Chree diagram for H, the horizontal component of earths magnetic field at Kodaikanal is also plotted in Fig. 4. It will be seen from Fig. 4(b) that H has a minimum at $n = 0$ which means that on cosmic ray minima days, value of H is also minimum. However, the magnitude of the minimum in H is rather small ($\sim$70 gamma). This is discussed further in Sectuoı V.

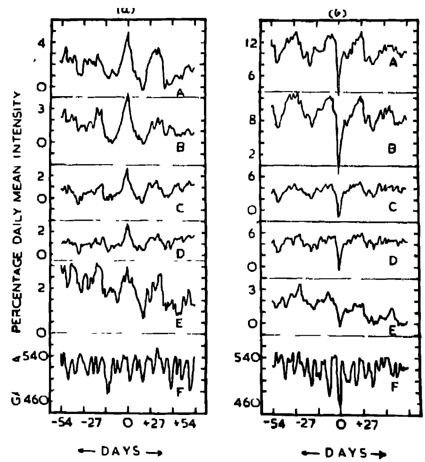

Fig. 4. Chree diagrams of daily mean intensities of cosmic rays and earth's magnetic field for Ottawa neutron intensity (a) Maxima and (b) Minima as epoch days.
A-Ottawa neutron, B-Resolute neutron, C-Huancayo neutron, D-Kodaikanal neutron, E = Kodaikanal meson, F = Horizontal component of earths magnetic field.

V. RELATIONSHIP WITH GEOMAGNETIC DISTURBANCES

As a measure of the geomagnetic disturbance of any particular day, a character figure C_p is evolved, which takes into account deviations from averages of the

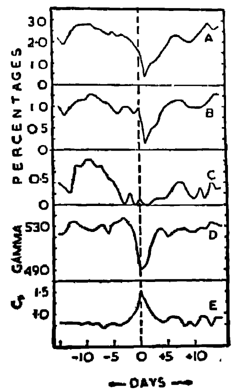

Fig. 5. Chree diagrams of daily mean intensities of cosmic rays and earths magnetic field for C_p maxima as epoch days. A-High latitude neutrons, B-Equator neutrons, C-Equator mesons, D-Horizontal component of earths magnetic field, E-C_p values.

variations in the various magnetic elements at several locations all round the world. Values of C_p range from 0 to about 2.0 To study the relationship between C_p and cosmic ray variations, days of maxima of C_p values were chosen as epoch days and Chree diagrams were drawn for the daily mean intensity of cosmic rays. These are shown in Fig. 5.

It seems that C_p maxima are followed within a day or two by cosmic ray minima. This is in agreement with earlier observations of similar nature by workers elsewhere (e.g. Simpson 1954).

However, it is found that the changes in the mean cosmic ray intensity associated with C_p maxima are not very large. Thus, the changes at equator are of the order of 1% only whereas it is seen from Fig. 1, that the mean intensity variations are sometimes as large as 5% for equatorial stations. It is obvious, therefore, that there is no one-to-one relationship between C_p maxima and cosmic ray minima. Apart from the possibility that some of the cosmic ray changes have apparently no connection with C_p maxima at all, it is also possible that all C_p maxima are not on the same footing so far as their effects on cosmic ray intensity are concerned. It is worthwhile, therefore, to see whether a criterian could be decided, upon which one could separate out those C_p maxima which are better related to cosmic ray changes than the others. In the past, attempts have been made (Sekido *et al.*, 1955) to study separately cosmic ray storms which are, and are not, associated with geomagnetic disturbances. However, the selection criterion there is the effect on cosmic ray intensity itself. We have adopted a criterion which was first introduced by Allen (1944). The C_p maxima are divided into 4 groups ac-according to whether they are preceded and/or succeeded by significant maxima at 27 day interval. Thus, the four groups are :—

Group A: C_p maxima preceded and succeeded by C_p maxima at ± 27 days.
$^+C_p{}^+$

Group B: C_p maxima succeeded by C_p maxima at $+27$ days but not preceded at -27 days.
$^\circ C_p{}^+$

Group C: C_p maxima preceded by C_p maxima at -27 days but not succeeded at $+27$ days.
$^+C_p{}^\circ$

Group D: C_p maxima having no preceding or succeeding maxima at ± 27 days.
$^\circ C_p{}^\circ$

Taking C_p maxima in each group separately as epoch days, Chree diagrams were drawn for the various cosmic ray intensities as also for the horizontal component of earths magnetic field. In Table III, we have summarised the main features of the Chree diagrams. For comparison, the main features as revealed by Fig. 5 for all C_p maxima as epochs are also included in Table III.

It is clearly seen from Table III that though all types of C_p maxima produce cosmic ray minima at about $n = 0$ to $+2$, the magnitude of the drop in cosmic

TABLE III

Repationship between *Cp* maxima and cosmic ray intensity

Epoch days ($n = 0$)	Range of Cp	Cosmic ray minima at	Magnitude of cosmic ray intensity drop			Ratio of range high lat : equator (neutrons)	Horizontal component of magnetic field at Kodaikanal		
			Equator		High lat.		Min. at	Intensity drop	Remarks
			Meson	Neutron	Neutron				
All C_p max.	About 0.5 to 1 5	$n = +1$ day	0.5%	1.0%	2.0%	2.0	$n = 0$	45 gamma	Maximum at $n = 0$ very prominent.
${}^{+}C_p^{+}$ max.	,,	About $n = +1$	0.5%	0 5%	1.5%	3.0	About $n = +1$	40 gamma	Large fluctuation of H values on days on either side of $n = 0$.
${}^{\circ}C_p^{+}$ max.	,,	,,	0.5%	0.5%	1.5%	3.0	$n = 0$	55 gamma	,,
${}^{+}C_p^{\circ}$ max.	,,	,,	1.2%	1.5%	3 0%	2.0	$n = +1$	60 gamma	,,
${}^{\circ}C_p^{\circ}$ max.	,,	,,	1.2%	1.5%	4 5%	3.0	$n = 0$	70 gamma	Effect at $n = 0$ very prominent.

ray intensity is not the same for all. Thus, $^{+}Cp^{0}$ and $^{0}Cp^{0}$ maxima which are characterised by either a fading or an absent recurring tendency have the largest effect on cosmic rays. The effect is about 1.5% at equator and 4% at high latitude for neutrons. The ratio of these two is, however, about the same for all types of C_p maxima.

It seems, therefore, that C_p maxima which do not have recurring tendencies produce the greatest reduction in cosmic ray intensity. From the last two columns of Table III, it is seen that the association of all C_p maxima with characteristics of H variation is not the same. Thus the C_p maxima of the $^{+}C_p{}^{0}$ or $^{0}C_p{}^{0}$ type show a larger range in the value of H as compared to the range due to other C_p maxima.

It is now well-known that geomagnetic disturbances of the recurring type are associated with coronal activity and C.M.P. of weak coronal emission. On the other hand, the non-recurring type disturbances are associated with S. C. type of magnetic storms and also with sunspot groups of complex magnetic field, and with C.M.P. of sunspot groups having high activity in solar radio noise. It seems, therefore, that cosmic ray events have a better association with phenomena of the latter type.

There are, however, two major apparent discrepancies in these observations. They are as follows :

(a) Through C_p maxima having little or no 27 day recurrence tendencies are better associated with cosmic ray minima, the Chree diagrams for cosmic ray intensity minima as epochs show prominent recurrence tendencies as shown in Fig. 4(b).

(b) Though the non-recurring type C_p maxima are also associated with S. C. type magnetic storms, there is no one-to-one relationship between cosmic ray storms (viz. sharp minima of cosmic ray intensity) and the S.C. type storm decreases of the horizontal component of earths magnetic field.

These discrepancies can, however, be understood if the following assumptions are made:

(i) The recurring type geomagnetic disturvances do have some effect on cosmic ray intensity though the effects are not so prominent as in the case of effects of non-recurrent type storms. This is borne out by results given in Table III.

(ii) The non-recurring type disturbance need not be assumed to be directly responsible for cosmic ray minima but both may have a common source of origin. The effects of the common source may persist longer in cosmic ray intensity than in geomagnetic disturbances.

(iii) As stated earlier, all cosmic ray intensity minima are not associated with minima of horizontal component of earth's magnetic field. However, when a Chree diagram is drawn for intensity minima of the horizontal component of magnetic field at Kodaikanal as epoch days, it is found that the cosmic ray intensity shows a prominent minimum on or about the epoch days and the magnitude of this minima is quite large, about half of the general range of variation in cosmic ray intensity (Fig. 6). Thus, all cosmic ray storms are not associated with magnetic storms of the S.C. type. But many of the S.C. type magnetic storms are associated with cosmic ray storms. This is not incompatible with (a) and (b) above.

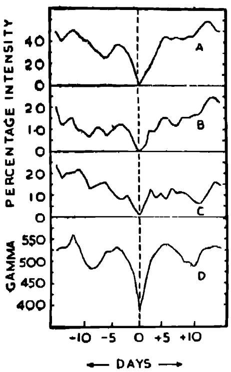

Fig. 6. Chree diagrams of daily mean intensities of cosmic rays for minima of horizontal component of earth's magnetic field as epoch days. A-High latitude neutrons, B-Equator neutrons, C-Equator mesons, D-Horizontal component of earth's magnetic field.

VI. ENERGY DEPENDENCE OF THE VARIATIONS IN PRIMARY INTENSITY

As has been shown so far, fluctuations as high as 5% at equator and 10-15% at high latitudes are observed in cosmic ray intensity. It is obvious, therefore, that the variations of cosmic ray intensity have energy spectra significantly different from the primary energy spectrum. Referring to Eq. (1), we obtain by differenciating partially with respect to $D(E)$,

$$100 . \frac{\partial N_\lambda(h)}{N_\lambda(h)} = \int_{E_\lambda^\circ}^{\infty} \frac{\partial D(E)}{D(E)} . \; W_\lambda(E, h) dE \quad \ldots \quad (6)$$

For the L.H.S., the experimental values are about 3—4% for Kodaikanal mesons, about 5% for Kodaikanal and Huancayo neutrons and about 10-15% for Ottawa and Resolute neutrons.

It is found that a variation spectrum of the type $\partial D(E)/D(E) \propto E^{-1}$ fits the experimental values reasonably well.

It should be noted, however, that such a spectrum fits only to the gross effects mentioned above. In individual events and for smaller time intervals, far too large effects (100% or more) have been observed at high latitudes. The energy spectrum involved there should be far more steep. Values as high as E^{-5} have been suggested (Sekido and Murakami, 1955).

VII. CONCLUSION

The broad conclusions of the above analysis may be summarised as follows

(1) The daily mean intensities of cosmic rays as observed by meson telescope and neutron monitors at the stations of Kodaikanal, Huancayo, Ottawa and Resolute show large fluctuations during the period July 1957 to June 1958. The range of fluctuations is about 3—5% and 5% for mesons and neutrons respectively at equatorial stations and 10—15% for neutrons at high latitudes.

(2) The maxima and minima of the daily mean intensity of cosmic rays exhibit strong 27-day recurrence tendencies.

(3) An analysis with *Cp* maxima as epochs indicates that *Cp* maxima are followed by cosmic ray minima with a probable lag of 1 or 2 days. Amongst the *Cp* maxima, the non-recurrent types seem to be better associated with cosmic ray minima.

(4) Cosmic ray storms are not invariably associated with magnetic storms but magnetic storms of the S.C. type are many times associated with cosmic ray minima.

(5) Large cosmic ray intensity decreases are world-wide in nature but their magnitude seems to be more than double at high latitudes as compared to that at equator.

(6) The day to day variations of cosmic ray intensity are energy dependent. The variation spectrum $\partial D(E)/D(E)$ is of the type E^{-1} where $D(E)$ is the primary energy spectrum.

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APPENDIX

Epoch dates for the various Chree diagrams

Month	Ottawa maxima	Ottawa minima	$^{+}C_p{}^{+}$ max.	$^{o}C_p{}^{+}$ max.	$^{+}C_p{}^{o}$ max.	$^{o}C_p{}^{+o}$ max.	H minima
Jul. 57	27					19	
Aug.	21	5,30		3,6	29	13	
Sep.	20	3,14 23,30	2	23	29	4,13	5,13, 23,30
Oct.	10	23		14	21		
Nov.	13	27	9,18	7		26	27
Dec.	6,16,28	22	6		11,31	1	31
Jan. 58	10	18	21			18	
Feb.	5,23	12		6,21	17	11	11
Mar.	20	15,26			5,19	12,25	
Apr.	25	30	3,29	17			
May	26	31	14,26			29,31	
Jun.				7			