VARIATIONS OF INTENSITY AND ANISOTROPY OF COSMIC RAYS MEASURED AT THE GEOMAGNETIC EQUATOR*

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ABSTRACT

A study of cosmic ray intensity variations has been conducted during 1956–57 at the equatorial mountain station of Kodaikanal, using a standard neutron monitor. The data have been examined to look for the relationship between the day-to-day changes of intensity, the variance of bi-hourly deviations, the occurrence of large bi-hourly deviations at different hours of the day and the associated parameters of the daily variation. The results are related to the electromagnetic state of interplanetary space as determined by streams of solar matter in the neighbourhood of the earth, carrying with them frozen magnetic fields. Comparison is made with the model elaborated by Dorman.

The principal conclusions are as follows:

(1) Day-to-day changes of intensity involve increases as well as decreases with respect to a base intensity for the period in question.

(2) The daily variation of intensity of local neutrons, at an equatorial mountain station during 1956–57, has often a large diurnal as well as a semi-diurnal component.

(3) On days of high geomagnetic disturbance, the daily variation exhibits abrupt changes indicative of the source being situated at a distance shorter than the range of the geomagnetic field. On geomagnetically quiet days, the daily variation has a form consistent with its being related to an anisotropy in interplanetary space. On days of moderate geomagnetic disturbance, the daily variation has changeable characteristics.

(4) Correlated day-to-day changes of mean intensity and daily variation have been confirmed. For geomagnetically disturbed days, the semi-diurnal component is greater than the diurnal component for increases of intensity, and conversely for decreases of intensity.

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(5) An examination of the time series of Cp for high intensity and for low intensity indicates the presence of a component of the frozen magnetic field in the direction of the solar dipole field. However, during the period of observation the solar dipole field and the sunspot field were in the same direction. Therefore, the results obtained cannot be considered either to confirm or refute the possibility of beams carrying sunspot fields with them.

1. INTRODUCTION

THE solar daily variation of cosmic ray intensity exhibits a number of features which are clearly of non-meteorological origin. Moreover, many of these relate to radiation outside the influence of the geomagnetic field and provide information concerning the anisotropy of the primary radiation. The anisotropy is of a variable character, undergoing change from day to day, and its 12-month average characteristics also change markedly from year to year with striking relationships with the 11 and 22-year cycles of solar activity. The main features of these changes have been summarized elsewhere.[1]

For a physical interpretation of the solar anisotropy of cosmic rays, in the context of its great variability, it is important to examine the distinctive forms of the daily variation that occur on individual days. It is also very useful to have knowledge of the relationship of the different forms with the level of daily mean intensity as well as with the perturbation of the geomagnetic field by particle radiation from the sun. Often, however, the standard error of an experimental determination of the daily variation on an individual day is too large to permit valid conclusions, and data are then averaged over a number of days grouped together on some criteria. Past studies[2–6] have been mainly concerned with the change of daily variation of intensity associated with geomagnetic disturbances, sometimes in combination with decreases of daily mean cosmic ray intensity. Yoshida[7] has examined several interesting features of a storm-time anisotropy which may be considered to be superimposed over a quiet period anisotropy during geomagnetic disturbances. The changes of the storm-time anisotropy up to several days following the onset of a magnetic storm, the changes related to the solar cycle of activity, and the energy dependence of the anisotropy have been studied. Sarabhai and Nerurkar[8] have made a phenomenological classification of three types of daily variations observed in the meson intensity at low latitudes, the first designated '*d*' type has a maximum near noon, the second designated '*n*' type has a maximum soon after midnight, and the third designated '*s*' type has two maxima. Sittkus[9] as well as Remy and Sittkus[10] have similarly observed the occurrence on groups of days of distinct types of daily variations. An interesting feature about the occurrence of daily variation with large amplitude is that it is associated with about the same degree of geomagnetic disturbance as the daily variation with average or small amplitude. Sarabhai and Bhavsar[11] have found that '*d*' and '*n*' type days are respectively associated with increases and decreases of daily mean intensity.

It is now fairly clear that many features of the variations of intensity and of anisotropy of primary cosmic radiation are related to emission of particle radiation from the sun which alters the electromagnetic state of interplanetary space. A number of physical processes have been suggested to explain the observed effects, but their respective roles, which may be expected to differ on different occasions, have not been evaluated. We are thus quite far removed from an understanding of the phenomena which would permit us to draw conclusions concerning the electromagnetic state of interplanetary space from cosmic ray and geomagnetic indices. As a first step it is important to distinguish between states on phenomenological considerations and then relate the states to theoretical models which have been proposed

We present here an account of some new results from a study of data collected with a standard neutron monitor at Kodaikanal (geomagnetic latitude = 1° N., longitude 77° E., altitude 7,688 feet above sea-level) from December 1956 to September 1957. We have looked at the relationship between the day-to-day changes of intensity, the variance of bi-hourly deviations, the occurrence of large bi-hourly deviations at different hours of the day and the associated parameters of the daily variation. We have also studied the relationship of these with Cp, the daily planetary character figure for geomagnetic disturbances, which has often been considered to be an index of solar corpuscular radiation reaching the earth. In the analysis we have attempted to make a distinction between changes in the level of the cosmic ray intensity, which we can study on a day-to-day basis, and a daily variation of intesity. The former could be ideally measured by placing an omnidirectional detector at a point in space unhindered by the shadow of the earth. The latter would be observed, even though all characteristics of the primary radiation are constant, by a detector scanning a region of space in which cosmic ray intensity is anisotropic. In practice we are far removed from the ideal situation since our measurements are made on the surface of the earth with a changeable atmosphere above it. The variations which we study can be due to anisotropy, meteorological factors, and those referred to as primary variations which could be due to all other causes. Nevertheless, it is possible, as we describe later, to devise procedures of analysis which permit us to gain information on the primary variations of intensity and anisotropy of cosmic rays, as well as the relationship between the two and of each of them with geomagnetic disturbances.

We show in this communication that very significant new information can be derived if the daily variation represented by 12 bi-hourly deviations is studied, instead of just the diurnal component of the variation. We present evidence which indicates that variations of primary intensity can occur independently of the creation of a strong anisotropy, and conversely, an anisotropy may exist with intensity at normal level. However, there are many instances when the changes of intensity and of anisotropy, as reflected in the form of the daily variation, are correlated in the manner observed by Sarabhai and Bhavsar. These are distinct from changes associated with geomagnetic disturbances reported earlier, and increases of intensity over a normal level of daily mean intensity, as well as decreases, are found to occur in these correlated changes. The relationship of cosmic ray changes with Cp is more complex than has hitherto been believed.

The results are discussed in relation to the electromangetic state of interplanetary space in the neighbourhood of the earth, particularly with reference to the model developed by Nagashima,[12] Nerurkar[13] and Dorman[14] on basic physical processes suggested by Alfven.

2. DATA

The influence of meteorological changes on cosmic ray intensity can be removed with little ambiguity from the data consisting of successive bi-hourly intensities by applying a barometric correction to the intensity measured by a neutron monitor. The bi-hourly intensities were first reduced to a standard barometric pressure, using a coefficient $\beta = -0 \cdot 94\%$ per mm. of Hg. The primary variations of intensity can be studied in terms of averages over a period of 24 hours, so as to get an integrated effect for all directions in space which are scanned by the instrument as the Earth goes through one complete rotation about its own axis. Thus moving averages over 12 bi-hourly intensities provide a time series for changes of daily mean intensity. The day-to-day changes of the daily mean intensity on 306 individual days, during the period of study, have been plotted in Fig. 1. The value of Cp, the daily planetary character figure of geomagnetic disturbances, is also plotted alongside.

The days involving large and rapid decreases, with a change of intensity exceeding $2 \cdot 5\%$ in 24 hours, and three days on either side have been marked in the above figure. During the period of study there were three such events, of which two were associated with large changes of Cp. As it is difficult to correct the daily variation on these days for the trend of day-to-day changes in intensity, they have been excluded from the main study of the daily variation. Days on which two or more bi-hourly values were missing are also excluded. Thus the number of days available for study of the daily variation reduces to 239. Before examining the data for daily variation, the bi-hourly deviations were corrected for the trend of day-to-day changes of intensity, derived from the time series obtained by taking moving averages over 12 successive bi-hourly values.

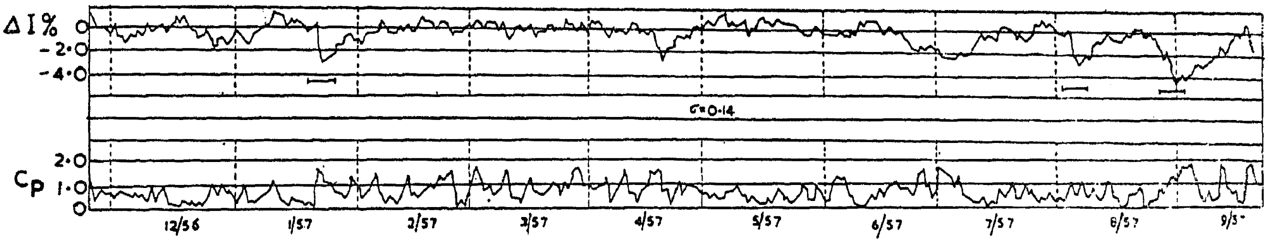

FIG. 1. The per cent. deviation ΔI of daily mean cosmic ray intensity at Kodaikanal and the daily planetary character figure Cp of geomagnetic disturbance, during the period December 1956 to September 1957.

3. DAY-TO-DAY CHANGES OF COSMIC RAY INTENSITY AND OF DAILY VARIATION

3.1 *Daily mean intensity*

The day-to-day changes of the daily mean intensity have been studied by considering the per cent deviation Δ I of the daily mean intensity from the mean intensity of the entire period. Figure 2 shows the histogram of days grouped according to the magnitude and sign of Δ I. The histogram drawn with solid line represents the distribution for all the 306 days while the one

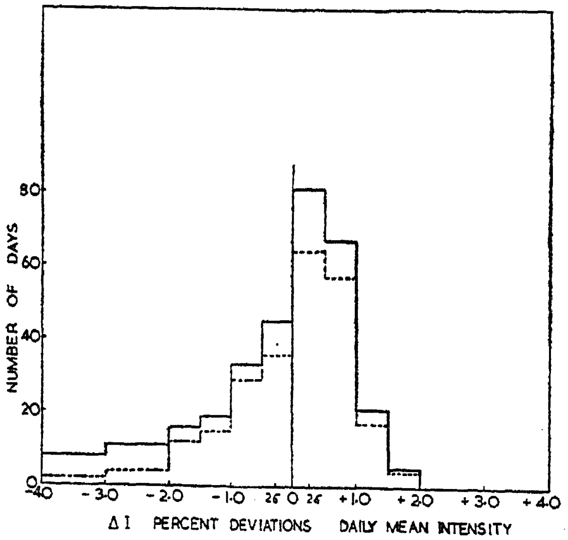

FIG. 2. Histogram of occurrence of positive and negative per cent. deviations ΔI of daily mean cosmic ray intensity. The histogram in full line corresponds to a sample of all days during the period of study, while the diagram in dotted line corresponds to the sample of days used for study of daily variation.

with dotted line represents the distribution for the 239 days used for the study of the daily variation. Neither distribution is symmetrical with respect to the mean. For an amplitude Δ I greater than 1·5%, negative deviations are more frequent than positive deviations.

For the purpose of separation of days on which we have either a positive or negative deviation or normal daily mean intensity, we consider a 3-sigma level of significance which corresponds to a deviation of 0·45%. Days having Δ I greater than + 0·45% are designated I^+ days, whereas days with Δ I less than − 0·45% are designated I^- days. The group of days with average intensity, for which Δ I lies between + 0·45% and − 0·45%, are designated I° days.

3.2 *The variance of bi-hourly deviations*

The variance Σ^2 is an index of the variability of the twelve successive bi-hourly intensities on each day. The variance of the twelve bi-hourly deviations from the daily mean intensity on each individual day was calculated after correcting for the trend of the day-to-day changes of daily mean intensity. For a Poisson's distribution, the variance is expected to have a value less than $2{\cdot}5\times5\times10^5$ in 99·9% cases. Hence we define days of low variance as those with $\Sigma^2 < 2{\cdot}5\times5\times10^5$ and designate them as $\Sigma_L{}^2$ days. The days with significant disturbance of the bi-hourly deviations have been classified into days of medium variance $\Sigma_M{}^2$ where $2{\cdot}5\times5\times10^5 \leqslant \Sigma_M{}^2 \leqslant 3{\cdot}5\times5\times10^5$, and days of high variance $\Sigma_H{}^2$, where $\Sigma_H{}^2 > 3{\cdot}5\times5\times10^5$.

On a day on which there is a large anisotropy, there would also be a large daily variation of intensity, and this would be reflected in the variance being greater than normal. The distribution of Σ^2 for 239 days is shown in Fig. 3. Anisotropy is small or absent on about half of all days. On about 28% of the days there is a moderate anisotropy and for the remaining 23% of the days there is $\Sigma_H{}^2$ indicating a strong anisotropy.

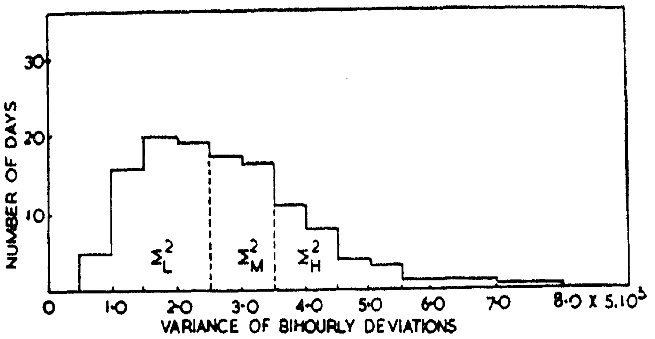

FIG. 3. Histogram of variance Σ^2 on individual day of deviations of bi-hourly cosmic ray intensity from daily mean intensity.

3.3 *Bi-hourly deviations and daily variation*

As indicated earlier, the bi-hourly values were first corrected for the trend of the day-to-day changes of daily mean intensity. A bi-hourly deviation Δi_x from daily mean intensity of bi-hourly intensity, centred at hour x, is considered positive or negative if its amplitude exceeds the 2-sigma level of significance which corresponds to $1{\cdot}0\%$. A positive deviation is designated as Δi_x^+ or x^+, and a negative deviation as Δi_x^- or x^-.

The number of days on which a significant positive deviation Δi_x^+ occurs corresponding to each bi-hour is plotted in Fig. 4. The distribution of negative deviations Δi_x^- is also plotted, but with the ordinate reversed. The average number of deviations greater than 1% of each sign at each bi-hour, that could occur in the period covered by our data, purely through chance is six. Primary variations of intensity with a time scale of change, which is short compared to 24 hours, could also produce significant bi-hourly deviations which would not be eliminated by the process of applying correction for day-to-day changes of intensity. These as well as deviations arising through chance should occur with equal probability at all bi-hours. On the other hand, bi-hourly diviations, which are connected with a daily variation of intensity, should occur preferentially at certain bi-hours. These deviations and the bi-hours at which they occur are of particular interest in our study of the anisotropy of cosmic ray primary radiation. Their identification depends on two considerations. Firstly, the number of significant deviations should greatly exceed the number expected through chance causes. We take note

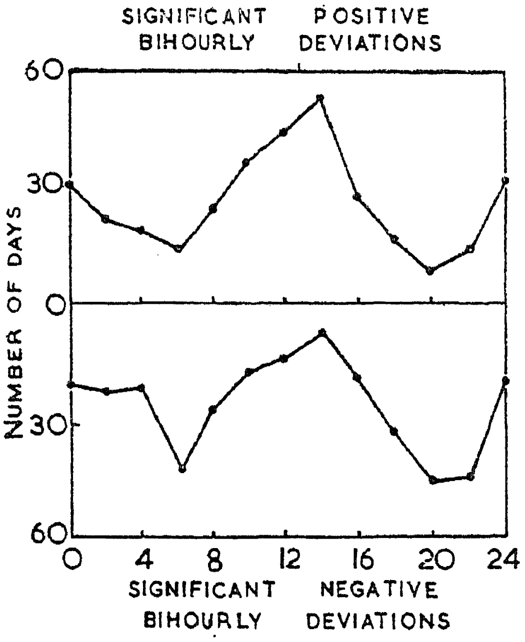

FIG. 4. Diagrams showing frequency of occurrence at different hours of positive and negative bi-hourly deviations Δx of significant amplitude.

of only those bi-hours for which the number of deviations significant at the 2-sigma level is five times the expected number of six significant deviations of each sign at each bi-hour. Secondly, the histograms of significant positive and negative deviations, which are shown in Fig. 4, should demonstrate a pattern of regular changes in contrast to random behaviour.

At many bi-hours, the number of deviations exceeding ± 2 sigma is far greater than six and hence the association of the particular significant deviations with a daily variation of intensity is suggested. It would be observed that positive deviations occur most frequently at 14, 12 and 10 hours, and again at 0 hours. Negative deviations occur most frequently at 20, 22 and 18 hours, and again at 6 hours. These hours are designated "important hours". At several bi-hours, the occurrence of significant positive as well as negative deviations is simultaneously more than can be expected from chance, and this is strongly suggestive of the existence of more than one type of daily variation which can occur on different days.

4. CORRELATED CHANGES OF DAILY VARIATION, DAILY MEAN INTENSITY AND GEOMAGNETIC DISTURBANCES

4.1 *Daily mean intensity and Cp associated with bi-hourly deviations*

Using the Chree method of superposed epochs, we have studied the relationship between significant bi-hourly deviations occurring at "important" hours, and the changes of daily mean intensity I and of Cp. It is found that on epoch days, 10^+ and 22^- are associated with a daily intensity significantly below mean, and 6^- with an intensity significantly above mean. The mean value of Cp for epoch days is almost the same as the mean value for the whole period under consideration.

The importance of individual bi-hourly deviations at 6 and 22 hours is borne out by Table I where the average daily mean intensity and average Cp on days associated with positive and negative bi-hourly deviations of varying magnitude at these hours are shown. Days with Σ_L^2 have not been considered as they represent a state when there is a non-significant anisotropy of primary radiation and hence it is then not meaningful to relate the form of the daily variation to the modulation of the daily mean intensity. It will be observed that increasing negative deviations at 6^- hours are associated with increasing daily mean intensity. On the other hand, increasing negative deviations at 22^- hours are associated with decreasing daily mean intensity. There is some evidence that the converse is true for positive deviations at both hours but the number of days on which such deviations are significant at the 2-sigma level is very small. In the connection seen here between negative deviations at one bi-hour with an increase of daily mean intensity, and a negative deviation at another bi-hour with a decrease of daily mean intensity, we have an indication that I^+ represents a true increase of intensity while I^- a decrease and the normal intensity for the period of the solar cycle is in or near the I^0 group. Thus, in contrast to the observations of Thambyapillai and Elliot[15] that 27-day recurrences of intensity represent exclusively decreases of intensity, the present study indicates that in general the modulation of cosmic rays on a day-to-day basis involves increases as well as decreases of the daily mean intensity.

TABLE I

Relationship of bi-hourly deviations at 0600 and 2200 hours with Cp and Averaged mean I for $\Sigma_M{}^2$ and $\Sigma_H{}^2$ days

0600 hours				2200 hours			
Groups of deviation	No. of days	Averaged mean I × 32	Mean Cp	Groups of deviation	No. of days	Averaged mean I × 32	Mean Cp
$\geq +2\sigma$	6	1269·2	0·40	$\geq +2\sigma$	5	1276·8	0·84
$+\sigma$ to $+2\sigma$	15	1268·1	0·71	$+\sigma$ to $+2\sigma$	11	1277·1	0·88
0 to $+\sigma$	25	1269·0	0·73	0 to $+\sigma$	22	1270·2	0·70
0 to $-\sigma$	18	1270·8	0·97	0 to $-\sigma$	20	1274·7	0·69
$-\sigma$ to -2σ	26	1271·2	0·73	$-\sigma$ to -2σ	27	1268·7	0·76
$\leq -2\sigma$	25	1276·1	0·87	$\leq -2\sigma$	30	1268·5	0·86

4.2 *Daily mean intensity and daily variation*

The 239 days which have been used for the study of the daily variation are divided into groups of days of intensity I^+, I^0 and I^- classified according to the criterion described earlier. The average daily variation for each of these groups is then calculated. The results are shown in Fig. 5. The parameters $\bar{r}_1, \bar{\phi}_1, \bar{r}_2, \bar{\phi}_2$ relating to the diurnal and the semi-diurnal components of the average daily variation are given in Table II. For both I^+ and I^-, significant positive deviations occur at 12 and 14 hours and negative deviations at 20 hours. As we have observed earlier, I^+ is related to a daily variation having a large negative deviation at 6 hours, and I^- is related to one with large negative deviation at 22 hours. It is interesting to note that the negative deviations at 20 hours are part of a sharp minimum for I^+ days but are part of a broad minimum for I^- days. The daily variation for I^+ days is thus characterised by two sharp minima, one on either side of a predominant broad maximum near noon. On the other hand, the daily variation on I^- days is characterized by a broad maximum near noon, a broad minimum in the evening, and a subsidiary maximum at midnight. The diurnal component for I^+ has a time of maximum at 13 hours and for I^- a maximum at 10 hours. This is consistent with the observation of Sarabhai and Bhavsar with a narrow angle meson telescope that a daily variation with a maximum near noon is related to increases of mean intensity, while a daily variation with an earlier time of maximum is related to a decrease of mean intensity.

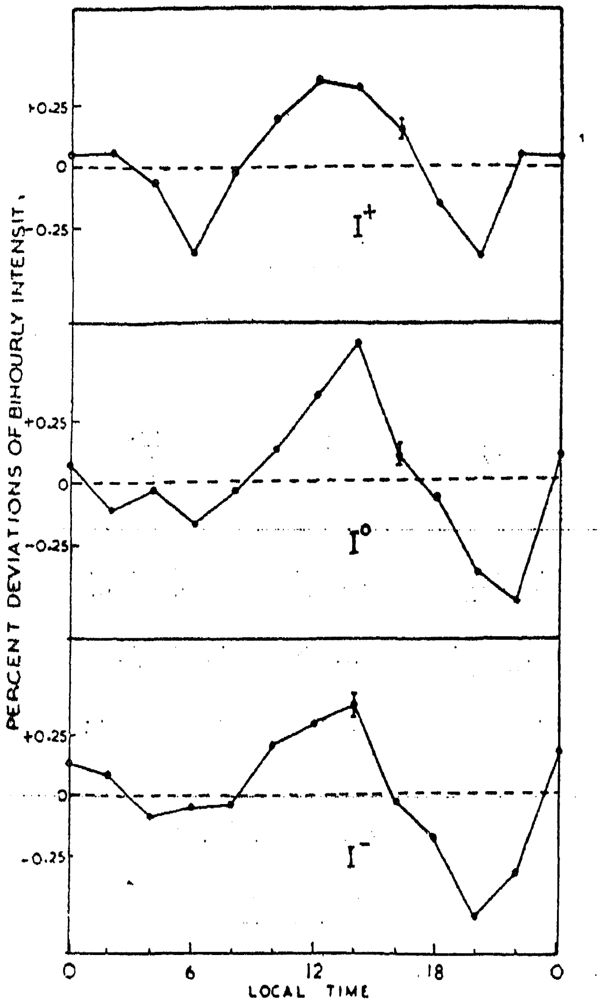

FIG. 5. Average daily variation of cosmic ray intensity for days of high (I^+), normal (I^0) and low (I^-) daily mean intensity.

4.3 *Geomagnetic disturbances and daily variation*

Many authors have examined the changes in the diurnal component of the daily variation associated with geomagnetic disturbances. A further criterion that has often been applied relates to the occurrence of sharp decreases of daily mean intensity associated with geomagnetic storms. In the present data, days involving large sudden decreases of cosmic ray intensity have been removed. The remaining 239 days were divided into three groups of Cp designated as Cp^L, Cp^M, Cp^H corresponding to $Cp^L \leqslant 0{\cdot}5$, $0{\cdot}6 \leqslant Cp^M \leqslant 0{\cdot}9$ and $Cp^H \geqslant 1{\cdot}0$ respectively. The mean daily variation for these three groups of days is plotted in Fig. 6. The characteristics of the harmonic components of the mean daily variation and the mean Σ^2 for each group are given in Table III. The daily variation for all three groups of days has a predominant maximum near noon with minima on either side of it. The subsidiary maximum near midnight is much smaller than the principal maximum near noon. The noticeable alteration in daily variation for Cp^L and Cp^H groups relates to the form of the principal maximum and the minima on either side of it. These are sharp for the Cp^H group but are quite broad for the Cp^L group. The time of maximum of the diurnal component for the two groups

TABLE II

The characteristics of the mean daily variation for groups of I

Group	No. of days	$r_1 \pm \sigma$* %	ϕ_1	$r_2 \pm \sigma$ %	ϕ_2	Mean Σ^2 $\times 5{\cdot}10^5$
I^+	82	$0{\cdot}17 \pm 0{\cdot}02$	$\pi + 15°$	$0{\cdot}24 \pm 0{\cdot}02$	25°	2·75
I^0	84	$0{\cdot}26 \pm 0{\cdot}02$	$\pi + 6°$	$0{\cdot}26 \pm 0{\cdot}02$	49°	2·61
I^-	63	$0{\cdot}22 \pm 0{\cdot}03$	153°	$0{\cdot}24 \pm 0{\cdot}03$	51°	2·67

* σ = Standard Error.

TABLE III

The characteristics of the mean daily variation for groups of Cp

Group	No. of days	$r_1 \pm \sigma$* %	ϕ_1	$r_2 \pm \sigma$ %	ϕ_2	Mean Σ^2 $\times 5{\cdot}10^5$
Cp^H	67	$0{\cdot}19 \pm 0{\cdot}03$	$\pi + 7°$	$0{\cdot}31 \pm 0{\cdot}03$	45°	2·77
Cp^M	66	$0{\cdot}15 \pm 0{\cdot}03$	144°	$0{\cdot}16 \pm 0{\cdot}03$	38°	2·57
Cp^L	96	$0{\cdot}27 \pm 0{\cdot}02$	$\pi + 7°$	$0{\cdot}26 \pm 0{\cdot}02$	33°	2·69

* σ = Standard Error.

remains almost unchanged while the amplitude of the diurnal component is smaller for Cp^H than for Cp^L group. This is contrary to the observations of Sandstrom[2] from a study of the meson component at a high latitude station during 1947–50. Sandstrom found an increase of r_1, and a shift of ϕ_1 to earlier hours with increasing Cp. On the other hand, Sarabhai and Sastry,[19] at Kodaikanal with a meson telescope have observed during 1956, a behaviour similar to that reported here for the daily variation of local neutrons at the same station. The difference between the results relating to 1947–50 and 1956–57 is understandable on the observations of Yoshida[7] that the disturbance vector, which displaces the vector representing the quiet period diurnal variation, has itself an eleven-year period of change in amplitude as well as time of maximum. Thus the net change that is observed with Cp^H should be dependent on the period of observation relative to the phase of the solar cycle of activity. Our observations are qualitatively in agreement with Sandstrom's if account is taken of this fact.

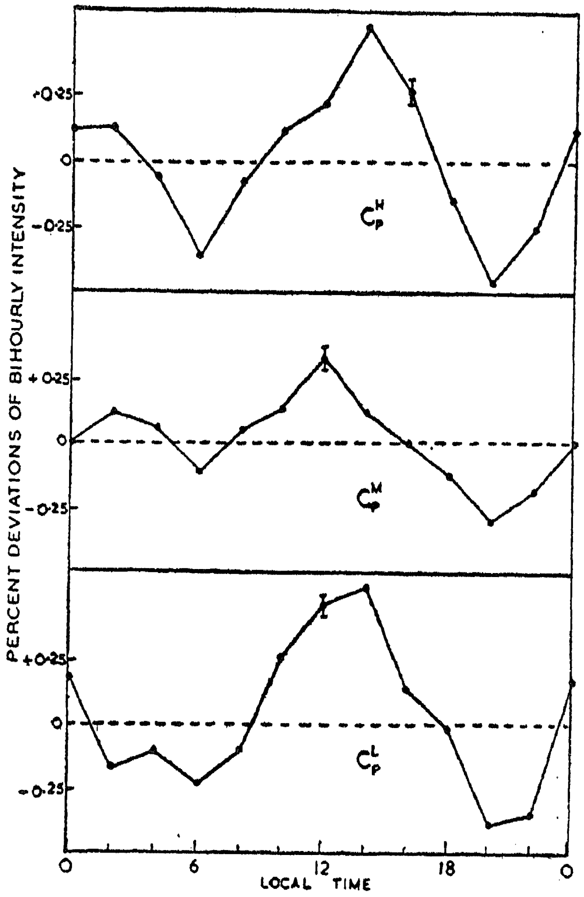

Fig. 6. Average daily variation of cosmic ray intensity for days of high (Cp^H), medium (Cp^M) and low (Cp^L) index of daily planetary character figure for geomagnetic disturbance.

If the criterion for storm days relates to the occurrence of geomagnetic disturbances associated with decrease of daily mean intensity I, as has been considered by some authors,[2–3] we should compare the form of the daily variation for the subgroup $Cp^H\ I^-$ with the rest of the days for which we have

Cp^{M} or Cp^{L}. In a later section the daily variations of all the subgroups corresponding to the three classes of Cp and I are given. For the group corresponding to storm days (Cp^{H} I^{-}), the diurnal component of the daily variation has $r_1 = 0{\cdot}30 \pm 0{\cdot}02\%$, $\phi_1 = 159°$ as compared to $r_1 = 0{\cdot}22 \pm 0{\cdot}04\%$, $\phi_1 = \pi + 7°$ for the diurnal variation on non-storm days. The increase of the diurnal amplitude and its shift to earlier hours during storm days is in conformity with the observations of other workers. The Cp^{M} group with intermediate value of Cp corresponds to a much smaller average daily variation than the average daily variation for Cp^{H} group (disturbed days) and Cp^{L} group (quiet days). On the other hand, the mean Σ^2 for Cp^{M} is approximately the same as for Cp^{H} and Cp^{L} groups. This indicates that the small amplitude of the average diurnal variation on Cp^{M} days is due to the great variability of the form of the daily variation rather than to an intrinsically small anisotropy on individual days.

4.4 *Characteristics of the daily variation on individual days*

The conclusions derived from an examination of the characteristics of the average daily variation for groups of days, sorted according to I and Cp, may be confirmed by studying separately for each group the histogram of the time of maximum ϕ_1 of the diurnal component of the daily variation on days on which its amplitude r_1 is significant at the 2-sigma level. The histograms of ϕ_1 and ϕ_2 for the groups I^{+}, I^{0} and I^{-} as well as for the groups Cp^{H}, Cp^{M} and Cp^{L} are shown in Fig. 7. It will be observed that the ϕ_1 histograms

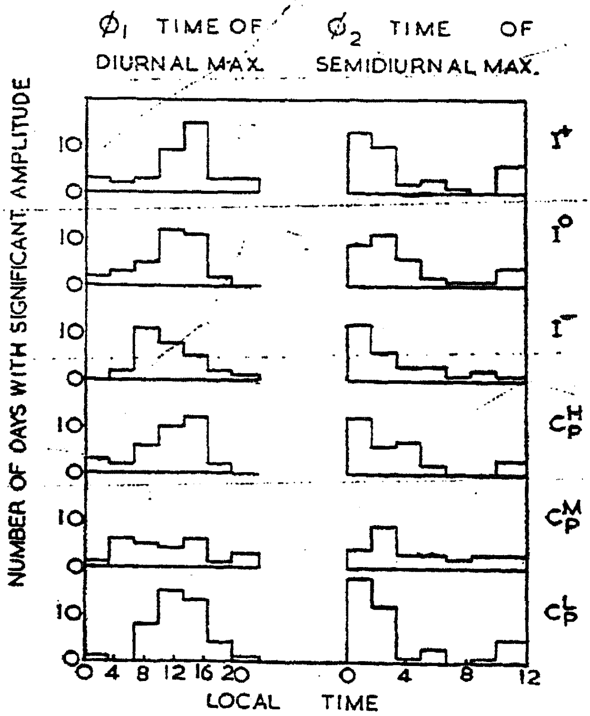

FIG. 7. Histograms of occurrence of time of maximum ϕ_1 of diurnal component and ϕ_2 of semi-diurnal component on days on which the amplitudes of the respective components have significant amplitude during groups of days in the I^{+}, I^{0}, I^{-} and Cp^{H}, Cp^{M} and Cp^{L} characteristics·

for I^+ and I^- groups are significantly different and reveal a shift of time of maximum as observed previously in the average daily variation curves for the I^+ and I^- days. The histogram for the I^0 group is intermediate between the histograms for I^+ and I^- groups. The shift to earlier hours in the time of maximum of the diurnal component of the average daily variation for the I^- group compared to the I^+ group is therefore also a feature of the daily variation on individual days in the respective groups. The histograms of time of maximum ϕ_2 of the semi-diurnal component remain unaltered for all three groups of I.

The histograms of ϕ_1 for the Cp^M group corresponding to days with intermediate values of Cp, when compared with the histograms for Cp^H and Cp^L groups, reveal that the daily variation on individual days of the Cp^M groups is of a more variable character than the variation on days of the Cp^H and Cp^L groups. As we have remarked earlier, the small amplitude of the average daily variation of the Cp^M group is due to a large scatter of the time of maximum for both the diurnal and semidiurnal components of the daily variation rather than to a small amplitude of the daily variation on individual days of the group.

5. THE ELECTROMAGNETIC STATE OF INTERPLANETARY SPACE

5.1 *Specification of state from modulation of cosmic ray intensity and geomagnetic disturbances*

Experimental evidence indicates that the modulation of cosmic ray intensity, the anisotropy of the primary radiation and geomagnetic disturbances are phenomena which are related in some ways, but the relationship of any two of them is not constant at all times. All three have marked solar relationships and an interesting possibility exists of being able to interpret them in terms of streams of ionized solar matter emitted from the sun. On this basis, the cosmic ray effects may be related to the influence of the streams on the electromagnetic state of interplanetary space in the environment of the earth, and the geomagnetic effects to the interaction of the streams with the geomagnetic field. Dorman has considered in detail the type of effects which may be observed. In attempting to verify this approach, we can start with a phenomenological identification of the state of the environment of the earth in terms of observable effects produced in cosmic rays and in geomagnetic changes.

We can, to begin with, examine the anisotropy or daily variation associated with the nine states characterised simultaneously by values of I and of Cp. For this purpose, the 239 days were first divided into three groups, I^+, I^0, I^- and these three were each further subdivided into groups Cp^H, Cp^M, Cp^L.

The mean daily variation for each of the nine states is plotted in Fig. 8. The characteristics of the diurnal and the semi-diurnal components corresponding to the mean daily variations are given in Table IV. The following are the noteworthy features:

TABLE IV

The characteristics of mean daily variation and mean Σ^2 for states of Cp and I

I Cp		I^+	I^0	I^-
Cp^H	No. of days	22	23	22
	$r_1 \pm \sigma^* \%$	$0\cdot10 \pm 0\cdot04$	$0\cdot27 \pm 0\cdot04$	$0\cdot30 \pm 0\cdot04$
	ϕ_1 degrees	$\pi + 28$	$\pi + 20$	159
	$r_2 \pm \sigma \%$	$0\cdot32 \pm 0\cdot04$	$0\cdot35 \pm 0\cdot04$	$0\cdot24 \pm 0\cdot04$
	ϕ_2 degrees	38	55	58
	Mean $\Sigma^2 \times 5\cdot10^5$	2·7	2·9	2·7
Cp^M	No. of days	25	21	20
	$r_1 \pm \sigma \%$	$0\cdot07 \pm 0\cdot04$	$0\cdot22 \pm 0\cdot04$	$0\cdot21 \pm 0\cdot04$
	ϕ_1 degrees	170	150	120
	$r_2 \pm \sigma \%$	$0\cdot15 \pm 0\cdot04$	$0\cdot26 \pm 0\cdot04$	$0\cdot11 \pm 0\cdot04$
	ϕ_2 degrees	30	46	30
	Mean $\Sigma^2 \times 5\cdot10^5$	2·6	2·5	2·6
Cp^L	No. of days	35	40	21
	$r_1 \pm \sigma \%$	$0\cdot26 \pm 0\cdot03$	$0\cdot32 \pm 0\cdot03$	$0\cdot20 \pm 0\cdot04$
	ϕ_1 degrees	$\pi + 19$	$\pi + 5$	162
	$r_2 \pm \sigma \%$	$0\cdot27 \pm 0\cdot03$	$0\cdot25 \pm 0\cdot03$	$0\cdot33 \pm 0\cdot04$
	ϕ_2 degrees	20	44	25
	Mean $\Sigma^2 \times 5\cdot10^5$	2·9	2·5	2·7

* σ = Standard Error.

(*a*) The variance Σ^2 for all the nine states is comparable. However, the amplitude of the average daily variation for all Cp^M states has a magnitude much smaller than for Cp^H and Cp^L states. Thus the large variability of the daily variation on individual days of the Cp^M state is present for each of the states corresponding to I^+, I^0, I^- respectively.

(*b*) Leaving aside states involving Cp^M, we see more clearly than before the characteristic features associated with I^+, I^0 and I^- for Cp^H and Cp^L. The largest positive bi-hourly deviation occurs at 14 hours for I^0, with Cp^H as well as with Cp^L. The sharp negative deviation at 6 hours associated with I^+ is also seen for I^0 Cp^H, but not for I^0 Cp^L. A sharp positive deviation at midnight is observed for I^0 Cp^H and for I^- Cp^L states.

(*c*) $\bar{r}_1$ and $\bar{r}_2$ are significant in all states except those involving Cp^M.

r_1 and $\bar{\phi}_1$ are dependent on I as well as Cp states: but $\bar{\phi}_2$, the time of maximum of the semi-diurnal component, is the same for all states.

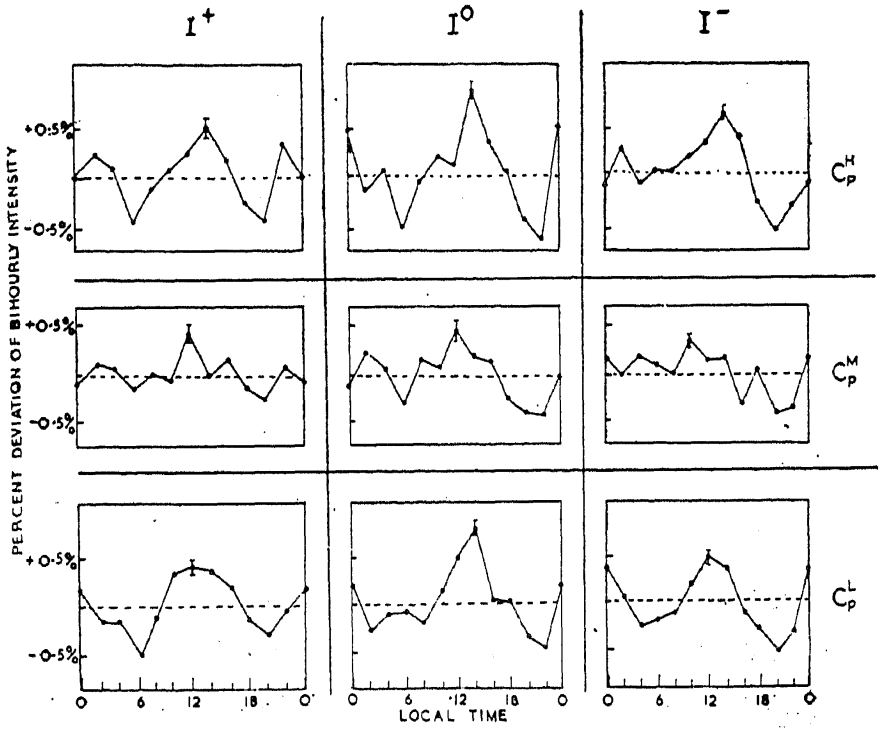

FIG. 8. Average daily variation of cosmic ray intensity for the 9 states formed by paired characteristics of I (columns) and of Cp (rows).

(*d*) At Kodaikanal, during the period of experimentation, differentiation of days, in respect of I^+ and I^- states, using the characteristics of the harmonic components of the daily variation on individual days, is possible only for Cp^H days. We then have

$r_1/r_2 \geqslant 1$ for I^- days and $r_1/r_2 < 1$ for I^+ days. This is because while in the latter state the semi-diurnal component predominates over the diurnal component, the reverse is the case in the former state. Differentiation in this manner is not possible in general because for $Cp^L\ I^-$ state, $r_1/r_2 < 1$ as is the case for the $Cp^H\ I^+$ state.

5.2 *Specification of state in terms of modulation of daily mean intensity and anisotropy of cosmic rays*

In the preceding section it has been pointed out that there is no significant difference in the mean variance Σ^2 for the nine states characterised by values of I and Cp. In order to study the nature of the daily variation associated with low, medium and high variance the I^+, I^0, I^- states were subdivided into groups with $\Sigma_H{}^2$, $\Sigma_M{}^2$ and $\Sigma_L{}^2$. The mean daily variation for each of these nine groups is shown in Fig. 9. The characteristics of the harmonic components are indicated in Table V.

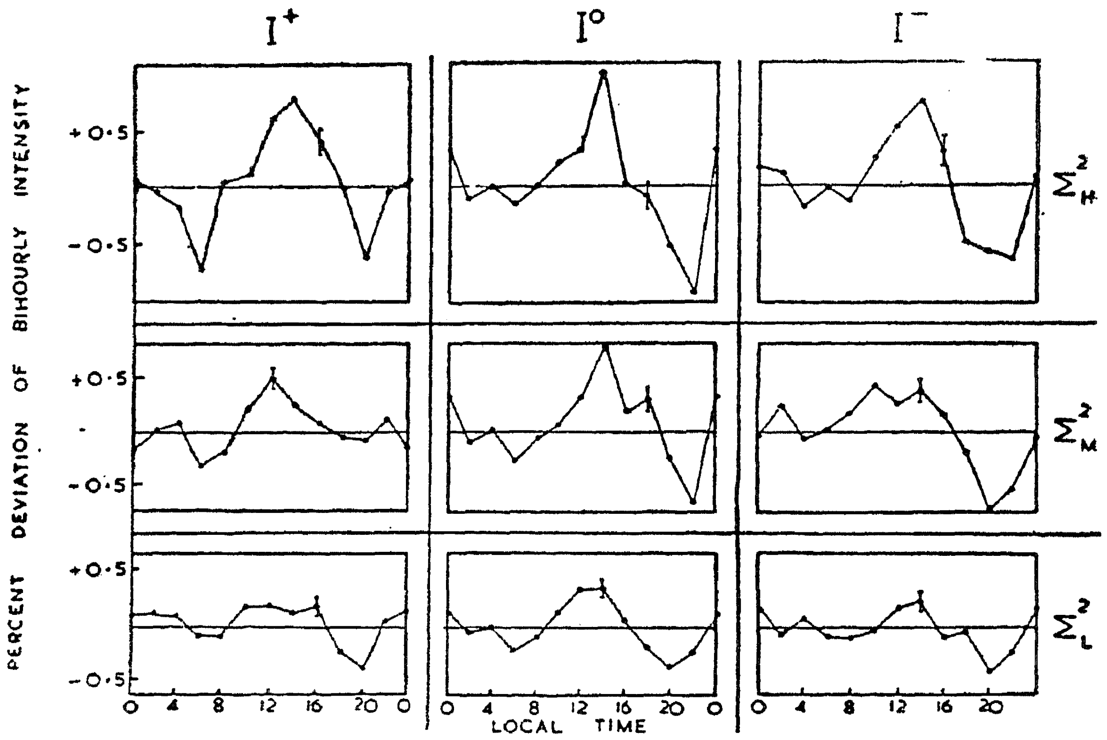

FIG. 9. Average daily variation of cosmic ray intensity for the 9 states formed by paired characteristics of I (columns) and of Σ^2 (rows).

As is to be expected, the daily variation is largest for $\Sigma_H{}^2$ and is least for $\Sigma_L{}^2$. The characteristic differences in the nature of the daily variation for I^+, I^0 and I^- states are shown well for $\Sigma_H{}^2$ and $\Sigma_M{}^2$ states; but for $\Sigma_L{}^2$ state the differentiation is not clear as the state includes all days on which the amplitude of the daily variation is comparable with the magnitude of bi-hourly deviations which can occur through chance causes. Other interesting points are as follows:

TABLE V

The characteristics of the mean daily variation, mean I and mean Cp for states of I and Σ^2

I Σ^2		I^+	I^0	I^-
Σ_H^2	No. of days	20	20	13
	$r_1 \pm \sigma^*$ %	0·37±0·04	0·39±0·04	0·38±0·06
	ϕ_1 degrees	$\pi+27$	173	163
	$r_2 \pm \sigma$ %	0·41±0·04	0·36±0·04	0·42±0·06
	ϕ_2 degrees	34	58	37
	Mean Cp	0·84	0·71	0·94
	Mean I	1282×32	1272×32	1259×32
Σ_M^2	No. of days	25	21	19
	$r_1 \pm \sigma$ %	0·19±0·04	0·30±0·04	0·36±0·05
	ϕ_1 degrees	$\pi+32$	$\pi+20$	143
	$r_2 \pm \sigma$ %	0·19±0·04	0·26±0·04	0·39±0·05
	ϕ_2 degrees	15	60	46
	Mean Cp	0·66	0·68	0·95
	Mean I	1282×32	1273×32	1258×32
Σ_L^2	No. of days	36	43	30
	$r_1 \pm \sigma$ %	0·19±0·03	0·20±0·03	0·07±0·04
	ϕ_1 degrees	139	180	163
	$r_2 \pm \sigma$ %	0·19±0·03	0·23±0·03	0·17±0·04
	ϕ_2 degrees	15	35	45
	Mean Cp	0·68	0·63	0·78
	Mean I	1281×32	1275×32	1259×32

* σ = Standard Error.

(*a*) On about half of all days belonging to each of the states I^+, I^0 and I^-, there is no anisotropy large enough to be significant under the conditions obtaining in our experiment.

(*b*) The states $\Sigma_H{}^2 I^-$ and $\Sigma_M{}^2 I^-$ have the greatest mean Cp, indicating that geomagnetic disturbances are associated with decreases of the daily mean intensity occurring simultaneously with the creation of a strong anisotropy. The decreases are of greater amplitude than the increases.

(*c*) The $\Sigma_L{}^2$ states are in general associated with moderate to low mean Cp.

5.3 *Sequential changes of intensity I and of Cp connected with states*

Using the Chree method of superposed epochs, we have examined the time series of the daily mean cosmic ray intensity and of Cp on days preceding and following epoch days, defined by the occurrence of a particular state. If the modulation of cosmic ray intensity is produced by an electric field associated with a frozen magentic field in a beam of ionized solar matter in the neighbourhood of the earth, it has been suggested by Alfven[16] that the magnitude of the quantity $-1/I\ dI/dt$, representing the rate of change of intensity from day-to-day, would be proportional to the magnitude of the electric field in the beam. A modulation of intensity by the electric field is then inferred by Venkatesan[17] when there is high correlation between the time series of $-1/I\ dI/dt$ and of Cp derived through Chree analysis.

Figure 10 shows the time series for Cp^L and for Cp^H epochs. The Cp^L state at epoch is related to a gradual increase of daily mean cosmic ray intensity commencing about six days before epoch. The maximum is reached one day after epoch and is followed by a decrease which extends for several days beyond the day ($+ 4$) when average intensity is reached. The time series for Cp has a very interesting form. Cp is low only for $- 2$ to $+ 1$ days and rapidly regains average value after epoch. It is not suggestive of Cp^L epochs representing a state when solar beams are absent in the neighbourhood of the earth. There is apparently no relationship between the time series of Cp and of $- 1/I\ dI/dt$. If we are to infer from this that the electric field in the beam plays an insignificant role, we would be required to explain what we consider to be the increase of cosmic ray intensity through an alternative acceleration process of a type which involves preferentially the low energy primaries, the radius of curvature of whose orbits are less than the width of the stream. However, we might question the correctness of a basic assumption which is made in looking upon the time series for Cp as indicating the relative position of the solar beam with respect to the earth. It does not appear likely that we can follow this reasoning for geomagnetic quiet days for which we have the Cp^L state. It would then be not appropriate to conclude that we have here an increase of intensity not related to the electric field in the beam. Without knowledge of the energy dependence of the radiation involved in the increase, it is difficult to resolve this major ambiguity in interpretation.

For the time series in Fig. 10 relating to the Cp^H state at epoch, there is an abrupt decrease of intensity starting one day before epoch. The intensity reaches a minimum one day after epoch and then gradually recovers to normal value in about five days. There is close association between the time series of $- 1/I\ dI/dt$ and of Cp, with the former having a maximum value on epoch days. On the interpretation outlined earlier, this indicates the influence of the electric field in the beam in producing decreases of intensity. Moreover, there is a marked anti-correlation between the time series of I and of Cp which suggests that the decreases are also produced through processes not connected with the electric field. The additive effects of the processes for the Cp^H state result in the decreases of intensity being much larger than the increases of intensity for the Cp^L state.

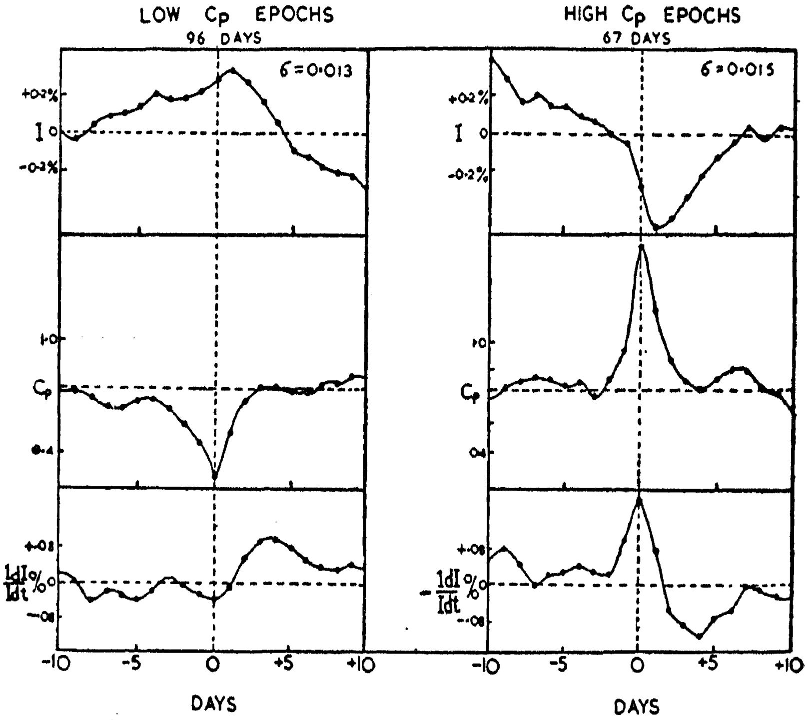

FIG. 10. Chree analysis of I and of Cp for Cp^L and Cp^H epochs corresponding to low and high degree of geomagnetic disturbance respectively. The time series for $- 1/I\ dI/dt$, derived from the time series of I, is also shown.

We have seen earlier that both I^+ and I^- states can occur in conjunction with either Cp^H or Cp^L states. In Fig. 11 we show the time series from $- 10$ to $+ 30$ days of I and Cp for the occurrence at epoch of the states $I^+\ Cp^H$,

$I^+ Cp^L$, $I^- Cp^H$ and $I^- Cp^L$. It will be observed that for $I^+ Cp^L$ state, the intensity remains high for several days after epoch and then decreases sharply to a negative level.

The time series of I and of Cp for $I^- Cp^H$ and for $I^- Cp^L$ states are similar except for a relative shift corresponding to a change from the Cp^H state to Cp^L state. The detailed features of both time series appear to be preserved for at least ten days on either side of epoch during the shift that is associated with change from Cp^H to Cp^L. If $I^- Cp^H$ state is associated with a condition in which a solar beam envelopes the earth, the $I^- Cp^L$ state appears to correspond to conditions a few days later as the beam moves away from the earth.

The time series in Fig. 11 are suggestive of a 27-day recurrence tendency in I, only for $I^- Cp^L$ state at epoch. The time series of Cp are devoid of any notable features such as a 27-day recurrence tendency, and bring out rather well that during the period of investigation, solar activity had already risen to a level where there were at almost all times a large number of active regions on the sun.

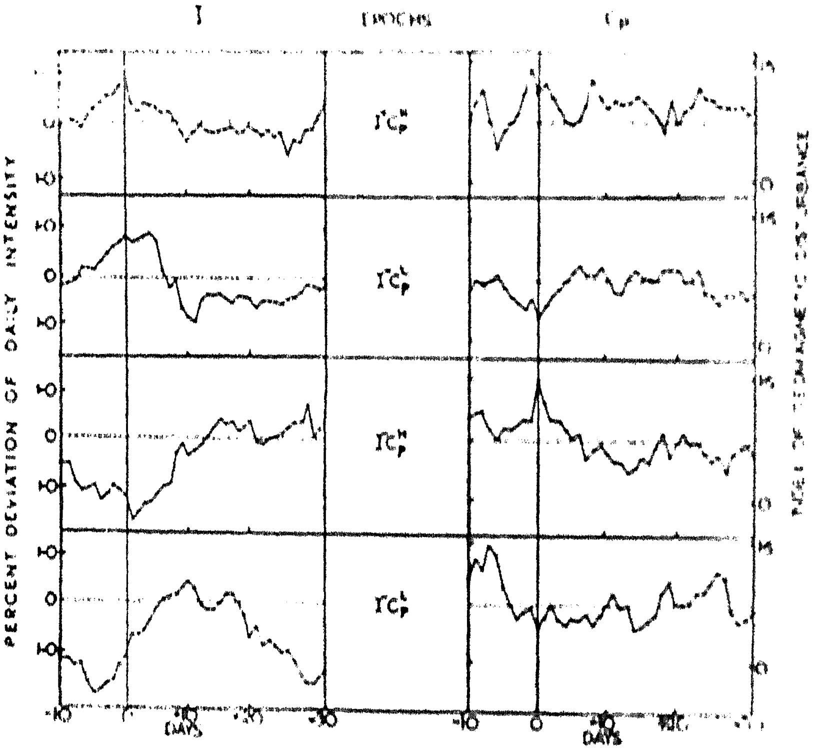

FIG. 11. Chree analysis of I and of Cp for epochs corresponding to the 4 states $I^+ Cp^H$, $I^+ Cp^L$, $I^- Cp^H$ and $I^- Cp^L$.

We can study the time series for epochs corresponding to states specified by I^+ or I^- which are associated with the presence of large anisotropy signified by Σ_H^2 or the relative absence of a significant anisotropy indicated by Σ_L^2. The time series of I, of Cp and of $-1/I\, dI/dt$ for the states $I^+ \Sigma_H^2$, $I^+ \Sigma_L^2$, $I^- \Sigma_H^2$ and $I^- \Sigma_L^2$ at epoch are indicated in Figs. 12 A, B, C and D respectively.

For I^+ state, the correlations of the time series of I^+ and of $-1/I\, dI/dt$ are both rather low. For I^- state there is good correlation of Cp with $-1/I\, dI/dt$ only for the Σ_H^2 state. There is anti-correlation between Cp and I for both I^- states, though this is higher for Σ_H^2 than for Σ_L^2. On the basis of the model

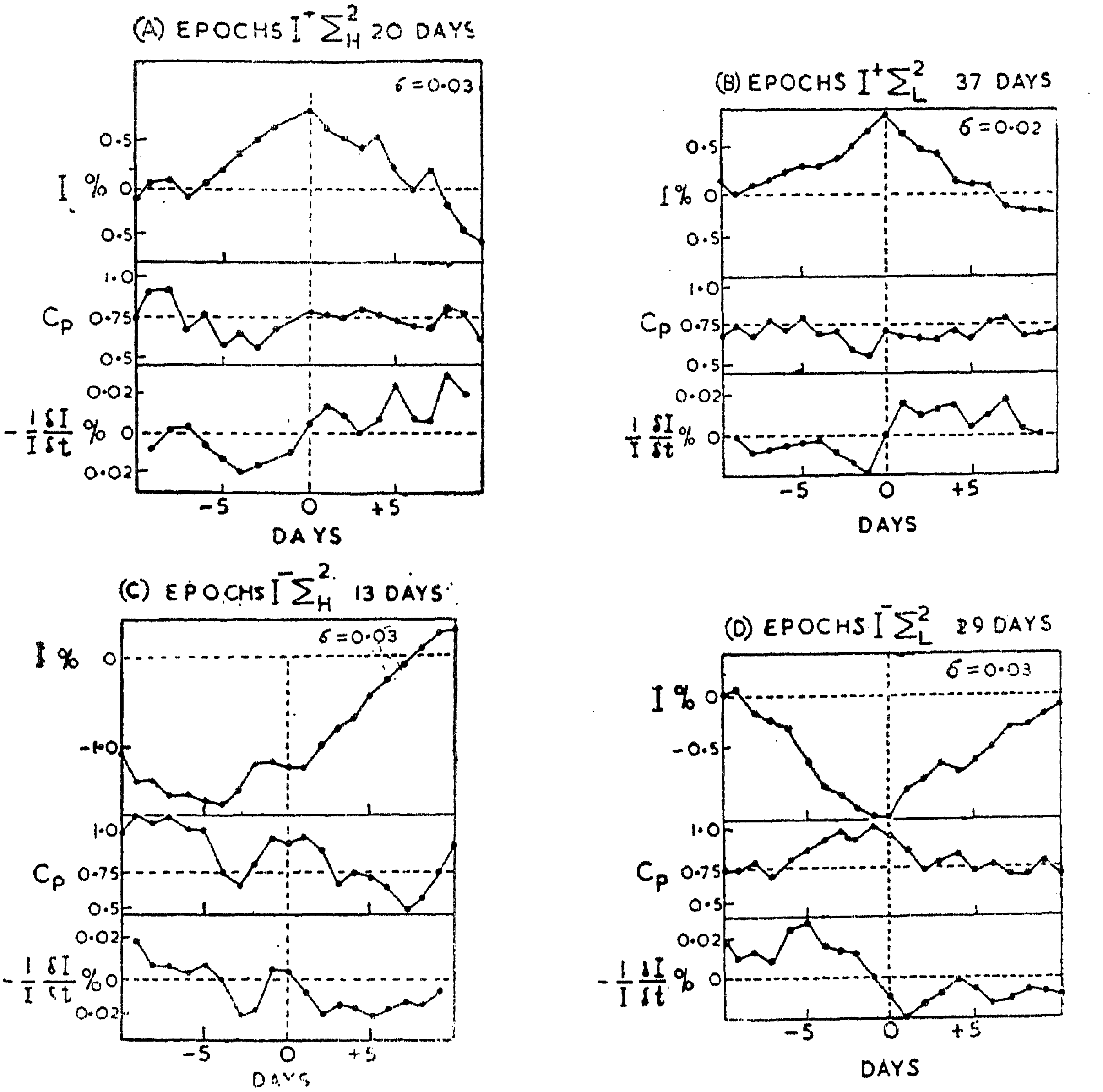

Fig. 12. Chree analysis of I and of Cp for epochs corresponding to the states $I^+ \Sigma_H^2$ (Fig. 12 A), $I^+ \Sigma_L^2$ (Fig. 12 B), $I^- \Sigma_H^2$ (Fig. 12 C) and $I^- \Sigma_H^2$ (Fig. 12 D). The time series for $-1/I$, dI/dt derived from the time series of I is also shown in each figure.

which we have discussed earlier, this would imply that when decreases of intensity are related to Cp as well as to an electric field in the beam, there is also present a strong anisotropy. Decreases can also occur without a strong anisotropy but then they are not associated with an electric field in the beam.

6. Interpretation of Experimental Results

6.1 *The solar daily variation and the anisotropy of primary cosmic radiation*

The daily variation of cosmic ray intensity is generally described in terms of its diurnal and semi-diurnal components or, sometimes, by the difference between the mean intensities during daylight and night hours. With either method, the analysis is capable of revealing only those changes in intensity within 24 hours which are gradual and represent deviations of intensity, positive or negative, which persist for several hours. While sudden changes of intensity lasting for one to two hours, which recur at the same solar time on different days, should properly be considered features of a solar daily variation of intensity, it has been widely believed that the occurrence of such changes is improbable. Therefore, the adoption of techniques of analysis which would be incapable of revealing them has not been considered a handicap. Moreover, unless the apparatus which measures cosmic ray intensity has a high counting rate and an adequate angular resolution for directions of incidence, it would be impossible to establish with appropriate statistical significance single bi-hourly deviations which are associated with a daily variation. A neutron monitor at a mountain elevation, with its high counting rate and a directional sensitivity towards the vertical due to the rapid attenuation of the nucleonic component in inclined directions, provides a convenient instrument to test the existence or otherwise of such changes. The unambiguity in applying to the local neutron intensity, a correction for atmospheric changes, is an added advantage when studying the primary variations of cosmic rays.

We have earlier examined the mean daily variation associated with states specified by deviations of daily mean intensity I and magnitude of Cp, the index of geomagnetic disturbance. Amongst the hours at which significant bi-hourly deviations occur on a large number of days, designated ' important hours ', positive deviations at 0 hour and negative deviations at 6 hours represent sharp changes of intensity. Positive deviations near noon and negative deviations in the late evening correspond to a broad maximum and a broad minimum respectively. Moreover, the maxima and minima of the daily variation for Cp^H state are sharp while for the Cp^L state they are broad Thus in studies which have been made by considering the diurnal and the semi-diurnal components rather than the individual bi-hourly deviations, the influence of the sharp maximum at midnight and the sharp minimum at 6 hours is underestimated in relation to the broad features near noon and in the late evening.

The study made at Kodaikanal during 1956–57 reveals that sharp changes of bi-hourly intensity are not only present as features of a daily variation on some days, but they are of considerable significance. It is, therefore, meaningful to refine existing techniques of experimentation to be able to deal with single bi-hourly deviations in addition to the diurnal and the semi-diurnal components of the daily variation. The abrupt increases and decreases of bi-hourly intensity at certain periods of the day, which occur particularly in association with geomagnetically disturbed days, would be indicative of the source of the changes being nearer the earth than the anisotropy produced in streams of solar matter outside of the main influence of the geomagnetic field. This conclusion is reached from the zenith angle response of a neutron monitor and the large scatter in asymptotic longitude of primaries, with orbits parallel to the plane of the ecliptic, which influence the intensity measured at the geomagnetic equator.

On a number of days during the period of observation, the daily variation of local neutrons at Kodaikanal has significant diurnal and semi-diurnal components. Taking this result in relation to observations made by Sarabhai *et al.*,[18] concerning the form of the daily variation of meson intensity at Kodaikanal and at Huancayo at different periods of the solar cycle, it is clear that the form of the daily variation is dependent on latitude and elevation of station, of the geometry of instrument, the secondary component which is measured and the period of observation in relation to the cycle of solar activity. Certain conclusions which have been drawn in the past are related to particular conditions obtaining in the experiment. For instance, the distinction observed, by Sarabhai and Bhavsar with narrow angle telescopes in 1955 at Ahmedabad, between two types of daily variations differing in the time of maximum of the diurnal component, is seen only during Cp^H state at mountain stations at the equator in 1956–57 where the semidiurnal component is present on a large number of days along with a diurnal component. ϕ_2 at Kodaikanal during 1956–57 remains remarkably constant on a day-to-day basis in contrast to ϕ_1. When we relate this with the observation of Sarabhai and Sastry[19] that ϕ_2 for the annual mean daily variation at Huancayo goes through a 22-year cycle, it is clear that we have a situation where there are two types of changes, one with a long period related to gross changes in the condition of interplanetary space in the plane of the ecliptic. There is superposed on it a day-to-day effect related to localised conditions associated with individual beams in the neighbourhood of the earth.

Because of the foregoing, there are many features of the daily variation and changes in it which are not similar on a global basis. Nevertheless they respond to physical conditions in interplanetary space; the differences in the daily variations being due to the region of the anisotropy which is scanned by the instrument and the primary energy response of the instrument.

6.2 *Cosmic ray effects produced by solar streams with trapped magnetic fields*

Dorman has considered the detailed implications of the cosmic ray effects that can be produced by streams of ionised solar matter in the neighbourhood of the earth. Day-to-day changes in the electromagnetic state of interplanetary space are expected to be produced by streams in which ionised matter travels outwards from the sun with a velocity of about 10^8 cm./sec. A stream carries with it a frozen magnetic field which may be derived from the local field at the place of ejection of the stream, or from the dipole field of the sun. With increasing radial distance from the sun, the radial and transverse components of the trapped field get progressively weaker, the radial component more so than the transverse components. Moreover turbulence can set in at a certain stage and this would further weaken the trapped field. Thus the magnitude and orientation of the trapped field within a beam in the neighbourhood of the earth, and in consequence the electromagnetic state can have a great degree of variability from beam to beam and at different periods of the cycle of solar activity.

Amongst the most important effects of beams which can be observed on the earth are the changes of intensity and of isotropy of the primary cosmic radiation and the disturbances of the geomagnetic field. The effects are as follows:

(*a*) Changes of cosmic ray intensity can be produced firstly, by the electric polarization of the beam through what is often referred to as the electric effect which is proportional to $(\vec{u} \times \vec{\mathrm{H}})\, b$. Here $\vec{u}$ is the radial velocity of the particles of the beam while $\vec{\mathrm{H}}$ and b are the frozen magnetic field in the beam and the width of the beam, both at $\mathrm{R}_{\oplus}$ respectively. The electric field can produce a modulation of intensity not only while the earth is within a beam but also when it is outside of it during the few days when the beam is approaching or receding from the earth. The second process which is often referred to as the magnetic effect produces a modulation of cosmic ray intensity through the reflection by the beam of low energy primaries. This effect can be expected mainly when the earth is within the beam.

When the earth is not within the beam, the electric effect is operative only on particles above a certain minimum energy determined by $\vec{\mathrm{H}}$ and b of the beam. The modulation is not present in cosmic ray primaries below a critical energy Ec (from 5 to 20 BeV, and sometimes according to Dorman as high as 100 BeV), but for primaries above Ec, the per cent modulation decreases with increasing primary energy. When the earth is within a beam both the electric and the magnetic effects should be operative. An effect, which can be observed only in low energy primaries when the earth is outside the beam, is related to the drift imposed by the outward gradient of the trapped field in the beam. The modulation of intensity by the magnetic effect would be observed preferentially in low energy primaries, in the region 2 to 20 BeV (sometimes up to 100 BeV) as compared to primaries of higher energy.

(*b*) All the processes discussed above in connection with the modulation of cosmic ray intensity would also disturb the isotropy of the primary radiation which could be observed through study of the daily variation. In addition, the form of the daily variation is related to the orientation of the trapped magnetic field of the beam and to the distance from the sun at which the magnetic field gets weakened through turbulence. The energy dependence of the anisotropy is closely related to the energy dependence of the process of modulation of the mean intensity discussed above.

(*c*) At the present moment there is no clear understanding of the physical processes through which the characteristics of the beam can be related in a quantitative way to the magnitude of Cp, the daily planetary character figure of geomagnetic disturbance. According to current thinking, geomagnetic disturbances are related to the interaction of the solar beams with the geomagnetic field and it is expected that the important properties of the beam would be the energy in the beam, its density ρ and its velocity u. Thus a beam which has its trapped magnetic field largely randomised through turbulence would have negligible effect on cosmic rays but could still produce geomagnetic disturbances. While over a long period it may perhaps be legitimate to associate high Cp with the presence of a beam, we have little basis, at the present moment, to make specific inferences concerning ρ or u from the magnitude of Cp. The occurrence of high Cp in a time series of Cp, nevertheless appears to be of value in indicating the relative position of the beam with respect to the earth.

From the foregoing considerations we can relate the electromagnetic state of the environment of the earth to the modulation of daily mean intensity I (I^+, I^0, I^-), to the absence ($\Sigma_L{}^2$) or the presence of anisotropy ($\Sigma_M{}^2$ or $\Sigma_H{}^2$), and to Cp. The orientation of the trapped magnetic field in a beam is of critical significance to the nature of modulation and anisotropy (daily variation) produced. The particular effects of the component perpendicular to the ecliptic ($\uparrow$ or $\downarrow$), the radial component ($\odot$) and the transverse component in the plane of the ecliptic ($\rightleftarrows$) of the frozen field are summarised in Table VI. The latitude and longitude of the anisotropy are indicated by the angles ϕ and χ respectively at the earth produced by a virtual source. χ is measured with respect to the sun-earth line. $\chi = 0$ indicates a time of maximum of the diurnal component at noon. At an equatorial station, the measured time of maximum would then be at about 6 hours due to the geomagnetic deflection of particles.

TABLE VI

Characteristics of the source of diurnal variation related to orientation of magnetic field in the beam

Direction of magnetic field	Effect observed	Beam to the left of earth		Beam to the right of earth		Beam surrounding the earth	
		Position positive source	Position negative source	Position positive source	Position negative source	Position positive source	Position negative source
↑	Anisotropy	$0 < X < (\pi/2)$ $\delta = 0$	..	..	$X \leqslant (3\pi/2)$	$0^* < X < (\pi/2)$	$\pi^* < X < (3\pi/2)$
↓	Anisotropy	..	$X \leqslant (\pi/2)$	$X \leqslant (3\pi/2)$	..	$\pi^* < X < (3\pi/2)$	$0^* < X < (\pi/2)$
→	Anisotropy	$\delta \leqslant (\pi/2)$	..	$\delta \leqslant (\pi/2)$	..	$0^* < \delta < (\pi/2)$ $\chi = 0$	$-(\pi/2) < \delta < 0^*$
←	Anisotropy	..	$\delta > (\pi/2)$	..	$\delta \leqslant (\pi/2)$	$-(\pi/2) < \delta < 0^*$	$0^* < \delta < (\pi/2)$
⊙	No effect on isotropy	..	..	..	..	..	..

ote: For low energy particles the position of the source will be nearer the limit marked with a star and would shift towards the other limit with increased primary particle energy.

Dorman has attempted to test the validity of the model by comparing characteristics of the average diurnal variation measured under a variety of experimental conditions and relating them to predictions from theory. As regards the stream characteristics he makes distinction principally between streams of the first kind with H $\approx 10^{-5}$ gauss which he relates to the quiet period diurnal variation and those of the second kind with H $\approx 10^{-4}$ which he relates to storm-time daily variation.

Dorman's comparison with experimental results is inadequate to test rigorously the validity of the model mainly because he relies on time averages over long periods and he considers only the diurnal component to describe the daily variation. Thus he neglects important aspects of the form of the daily variation and significant changes that take place in the form. The inadequacy is worst at an equatorial station such as Huancayo during 1948 to 1953 where the form deviates significantly from a simple diurnal variation. Moreover, it is evident from our results that phenomenological distinction requires to be made between states defined not only in terms of a quiet period and a storm-time daily variation but also by other factors. While we are unable at present to study detailed characteristics on individual days, the average daily variation requires to be examined separately at least for states distinguished phenomenologically on considerations of modulation of intensity and geomagnetic disturbances.

The effect of streams on cosmic ray intensity and anisotropy is summarised in Table VII. The important states which can be identified in terms of the observable features indicated here are as follows:

(1) Condition $I^0\ \Sigma_L^2$ may be associated with two unique states. The first is related to the absence of a beam, when we should expect low Cp, and the second is related to earth in a beam with no H at R_0^+. There would then be high Cp but no effect would be observable in cosmic rays.

(2) If we have I^0 and simultaneously Σ_M^2 or Σ_H^2, then the earth should be within a beam or situated symmetrically between two beams. This could be checked by looking at the time series of Cp for $I^0\ \Sigma_H^2\ Cp^L$ and $I^0\ \Sigma_M^2\ Cp^L$ epochs and verifying whether we have one beam or two beams symmetrically situated to the right and to the left of the earth. The daily variation should show a maximum, outside the geomagnetic field, between 12 and 18 hours for $\uparrow$ H and between 12 and 6 hours for $\downarrow$ H which would approximately correspond to a diurnal maximum at an equatorial station between 8 to 14 (nearer to 8 hours for the low energy particles) and 2 to 8 hours (nearer to 2 for low energy particles) respectively.

TABLE VII

Geomagnetic disturbances, cosmic ray intensity variation and anisotropy produced by solar beams

		Earth in beam	Earth outside beam but near it
		(*a*) No trapped magnetic field in beam at $R_\odot$	
1.	Effect on Cp	Relative increase of Cp on earth entering beam and relative decrease when it crosses the earth	No change in Cp
2.	Effect on daily mean intensity I	No effect, occurrence of I^0	No effect, occurrence of I^0
3.	Effect on isotropy	No effect, occurrence of Σ_L^2	No effect, occurrence of Σ_L^2
		(*b*) Beams having frozen magnetic field 10^{-4} to 10^{-5} gauss at $R_\odot$	
1.	Effect on Cp	Relative increase of Cp on earth entering beam and relative decrease after it crosses the beam	No effect
2.	Effect on daily mean intensity I	Electric and magnetic effect on I, occurrence of I^+, I^0, I^-	Only electric effect is present, occurrence of I^+ and I^-
3.	Effect on isotropy	Both the electric and magnetic effects are present and the observed effect depends on the orientation and magnitude of H, occurrence of Σ_M^2 and Σ_H^2	Electric effect is more important but the effect of the magnetic field is also present to a small extent. Occurrence of Σ_M^2 and Σ_H^2

(3) If we have I^+ and I^- with Σ_M^2 or Σ_H^2 we could have one of the three following conditions:

(*a*) The beam is in the plane of the ecliptic but outside the earth to the left or to the right of it.

(*b*) The beam is in the plane of the ecliptic and the earth is in the beam.

(*c*) The beam is above or below the plane of the ecliptic and the beam does not strike the earth at any stage.

The first two conditions can be identified by an increase of Cp and the third by the absence of change of Cp. Whether, in the first case, the earth is to the right or to the left of a beam can be determined by looking at the time series of Cp. There is then a precise relationship between I and the nature of the daily variation as indicated in Tables IV and V.

It will be observed from this discussion that a correlated study of the daily variation of cosmic rays on individual days, the modulation of the daily mean intensity and the time series of Cp can enable a verification of the proposed model for the interpretation of the variations. Moreover, if the model is substantially correct, we have a tool to determine the electromagnetic state of beams in the neighbourhood of the earth. From the limited data collected so far and the analysis already undertaken, the authors have been able to make a beginning along these lines. The preliminary results can be summarised as follows:

(1) Out of the total number of days of observation during the period 1956–57, on 21% of the days we had the condition $I^0 \Sigma_L^2$, which is indicative of the absence of beams or the absence of a frozen magnetic field at R♁. Of these, 5% are high Cp days indicating the earth in beams without H. Medium Cp days have been neglected as they represent a transitional state and cannot indentify the presence or absence of beams.

(2) On 18% of all days, we have $I^0 \Sigma_H^2$ or $I^0 \Sigma_M^2$ and this represents the earth within the beam or symmetrically situated between two beams. The first state (earth in the beam) is identified by high Cp and occurs on 6% of the days. While the second state (earth symmetrically situated between two beams) is identified by low Cp and occurs on 8% of days.

(3) The relationship of the time series of Cp with those of I and $-1/I\ dI/dt$ for I^+ and I^- epochs for conditions which relate to the presence or the relative absence of a strong anisotropy of the primary radiation have been studied in Section 5.3 (Fig. 12). It has been observed that for decreases of intensity, there is high correlation between the time series of I and Cp on days with high anisotropy as well as on days with low anisotropy. On the

other hand, the correlation of the time series for Cp and $-1/I\, dI/dt$ is good only for Σ_H^2 days when there is a strong anisotropy. Decreases of intensity can, therefore, be produced by the electric effect as well as the magnetic effect. When there is strong anisotropy present the electric effect is also observed. This implies that there are processes whereby a decrease of intensity can occur without the creation of a significant anisotropy.

(4) An examination in Fig. 12 of the time series for I and Cp for both increases as well as decreases of I indicates that for I^+ epoch days, Cp is high on and after the epoch while, for I^- days, it is high on or before the epoch. Also when I^+ epochs are divided into groups characterised by high and low anisotropy it is seen that only epochs with high anisotropy are preceded by distrubance. This shows that for the I^+ days the beams approach from the left and produce a strong anisotropy while for the I^- days, they recede to the right. This implies that the component of electric field in the ecliptic plane as seen from the earth is in the direction left to right. This indicates the presence of a component of the frozen magnetic field in the same direction as the earth's magnetic field. The direction of the magnetic field is in confirmity both with the expected direction of the sunspot field during this period and the direction of the magnetic field of the sun.

(5) While decreases can be due to both electric and magnetic effects of the beam, the increases can be due mainly to the electric effect and hence the decreases due to the two processes are additive while increases would represent the net result of their opposing effects on I. As has been shown in Section 3·1 this corresponds to the observations at Kodaikanal where the decreases of cosmic ray intensity are larger in amplitude than increases.

7. CONCLUSIONS

We summarise here some of the principle conclusions that emerge from the present study.

(1) Day-to-day changes of intensity involve increases as well as decreases with respect to a base intensity for the period in question. Decreases are much larger in amplitude than increases. Decreases are generally related to the so-called " magnetic effect " of beams, but if the " electric effect " is also present, there is high anisotropy.

(2) The daily variation of intensity of local neutrons at an equatorial mountain station, during 1956–57, has often a large diurnal as well as a semi-diurnal component. The prominent features of the variation are a maximum near noon and a minimum at 2,000 hours. There is often a second maximum near midnight and a minimum at 0600 hours.

(3) On days of high geomagnetic disturbance, the daily variation exhibits abrupt changes indicative of the source being situated at a distance shorter than the range of the geomagnetic field. On geomagnetically quiet days, the daily variation has a form consistent with its being related to an anisotropy in interplanetary space. On days of moderate geomagnetic disturbance, the daily variation has changeable characteristics.

(4) Correlated day-to-day changes of mean intensity and daily variation have been confirmed. For geomagnetically disturbed days, the semi-diurnal component is greater than the diurnal component for increases of intensity, and conversely for decreases of intensity. Low anisotropy is on the average associated with days of moderate and low Cp.

(5) An examination of the time series of Cp for high intensity and for low intensity indicates the presence of a component of the frozen magnetic field in the direction of the solar dipole field. However during the period of observation the solar dipole field and the component of the sunspot field perpendicualr to the ecliptic were in the same direction. Therefore the results obtained cannot be considered either to confirm or refute the possibility of beams carrying sunspot fields with them.

(6) For a rigorous test of various interpretations that are proposed there is need to refine measuring techniques to enable study of the daily variation on individual days. It is also necessary to examine single bi-hourly deviations in addition to the diurnal and semi-diurnal components of the daily variation.

(7) Cosmic ray evidence concerning anisotropy and modulation of intensity appears to be very promising in supplementing geomagnetic data for the specification of the electromagnetic state of interplanetary space, in the neighbourhood of the earth. The orientation of the trapped magnetic field in a beam is of crucial significance to the nature of modulation and anisotropy or daily variation that is produced. At the present moment no detailed verification of the modulation theories involving beams could be considered to have been achieved. It appears that beams certainly play an important role, but it is more than likely that we have other processes as well.

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