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Study of cosmic ray diurnal variation on a day-to-day basis

A G ANANTH, S P AGRAWAL+ and U R RAO*
Physical Research Laboratory, Ahmedabad 380009
+Now at the Physics Department, Government Science College, Rewa 486001
*Now at the Indian Scientific Satellite Project, Peenya, Bangalore 562140

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Abstract. From a careful examination of the diurnal variation of cosmic ray intensity at high energies and the interplanetary field characteristics, the average characteristics of diurnal variation were recently explained by us in terms of a balance between outward convection and field aligned diffusion, the latter arising out of a positive radial density gradient. In this paper, we extend this new concept to explain the large variability observed in the diurnal variation on a day-to-day basis and further demonstrate that the measurement of diurnal anisotropy characteristic of cosmic ray particles on a day-to-day basis can be used directly to infer the nature and scale sizes of interplanetary field parameters. Comparing with the magnetic field vector, we show that this simple concept holds good on more than 80% of days. On the rest 20% of days which have a predominant morning maxima, the diurnal anisotropy characteristics seem to indicate the presence of a significant component of transverse diffusion current in addition to the normal convection and diffusion flow. Such days are found to be present in the form of trains of consecutive days and are found to be associated with abrupt changes in the interplanetary field direction having scale sizes > 4 hr. The value of $K_\perp/K_\parallel$ which is normally about $\leqslant 0{\cdot}05$ is found to be $\approx 1{\cdot}0$ on non-field aligned days.

Keywords. Cosmic rays; diurnal variation; interplanetary magnetic field; solar wind.

1. Introduction

For almost a decade it has been quite apparent that the average cosmic ray diurnal variation is consistent with it being due to corotation of these particles with the solar system magnetic fields which are themselves stretched in the form of an Archimedes spiral by the radially blowing solar wind. The large amount of experimental evidence (Rao *et al* 1963, McCracken and Rao 1965, Rao 1972) obtained from superneutron monitor data have conclusively shown that the yearly average diurnal variation is energy-independent up to a maximum energy $E_{\max} \approx 100$ GeV and practically invariant with the solar cycle. Till recently, however, it was widely believed that the amplitude of the observed diurnal variation was considerably less than that predicted by the usual Compton-Getting effect which was attributed to the existence of a significant perpendicular diffusion due to the presence of magnetic field irregularities. Recent low energy solar particle observations made by McCracken *et al* (1968, 1971) simultaneously at different heliolongitudes with widely spaced Pioneer deep space probes have clearly indicated that the azimuthal anisotropy at energies $\lesssim 100$ MeV is quite negligible and that the particle population is largely determined by the balance between radial convection and field aligned diffusion. In other words, it has been shown that at these energies $K_{\perp}/K_{\parallel} \lesssim 0{\cdot}05$. Extending these arguments to relativistic energies, McCracken *et al* (1968), Gleeson (1969) and Forman and Gleeson (1970) suggested that the diurnal anisotropy observed in the galactic cosmic radiation can also be understood as a superposition of simple convection and diffusion. Since then the apparent discrepancy between the observed amplitude of the average diurnal variation and the theoretically predicted amplitude has been successfully accounted for (Subramanian 1971) by a number of hitherto unaccounted second order effects such as the finite value of $E_{\max}$, improper normalisation, etc.

From a careful analysis of worldwide neutron monitor network data and their comparison with measured interplanetary field parameters, Rao *et al* (1962) and Hashim *et al* (1972) have independently demonstrated that the average diurnal anisotropy can, in fact, be explained completely in terms of simple convection and diffusion. According to this concept, the radial convective flow will be balanced by the inward diffusion on an average basis causing the net radial current to be zero and resulting in a corotational anisotropy of the right magnitude. Comparing with the interplanetary magnetic field (IPMF) data, Rao *et al* (1972) showed that the diffusion vector is field aligned both on average basis and also during days exhibiting enhanced diurnal variation, the diffusion current, on an average basis, being driven by a radial density gradient of $\approx 5\%$/A.U. which is consistent with the direct measurements (O'Gallagher 1972, Rao 1972). Since this paper (Rao 1972) forms the basis of our present investigation, it will henceforward be referred to as paper I.

Even though the average picture of the diurnal variation has now been explained quite satisfactorily in terms of a good physical model, the detailed picture of the diurnal variation, on a day-to-day basis, remains to be clearly understood. The large variability present in both amplitude and the time of maximum of the diurnal variation has been established by a number of workers (Rao and Sarabhai 1964, Patel *et al* 1968). In paper I, we pointed out that the new concept of the diurnal variation was capable of explaining the day-to-day variability in terms of varying diffusion current, there being no balance between convection and diffusion on a short term basis. A few specific examples were individually treated to demonstrate the validity of the theory showing that, even on days when the interplanetary field vector showed clear departure from the Archimedes spiral pattern the cosmic ray diffusion vector derived from observations were clearly field aligned. In this paper we present detailed analysis of diurnal anisotropy on a day-to-day basis to test the validity of the new concept and demonstrate that on most of the days the concept is valid. Further we also attempt to determine the detailed characteristics of few days on which the observed diurnal anisotropy shows departure from the simple convection and diffusion picture indicating the presence of a significant perpendicular diffusion on such days.

2. Data analysis

In order to examine the cosmic ray diurnal variation on a day-to-day basis in a statistically meaningful way, we have combined the data from six high latitude

Table 1. List of stations used to derive day-to-day diurnal anisotropy vectors

Stations	Geographic coordinates		Mean asymptotic coordinates		Cut-off rigidity (G.V.)
	Latitude (deg.)	Longitude (deg.)	Latitude (deg.)	Longitude (deg.)	
Inuvik	68·4	226	47	233	0·18
Calgary	51·1	246	28	269	1·09
Churchill	58·8	266	40	286	0·21
Deep River	46·1	283	27	319	1·02
Goose Bay	53·3	300	35	339	0·52
Kiel	54·3	10	31	63	2·29

neutron monitoring stations and having a narrow asymptotic cone of acceptance. Table 1 gives the relevant physical parameters of these stations. After taking out long term variation by moving average method, the data on each day are harmonically analysed to obtain the diurnal and semi-diurnal variation vectors for each of the selected stations. The diurnal and semi-diurnal anisotropy amplitude and phase in space as observed at each station are then derived, after correcting for the width and declination of the asymptotic cone of acceptance of the detector and geomagnetic bending using the variational coefficient techniques developed by Rao *et al* (1963) and McCracken *et al* (1965). In the present analysis, all days on which Forbush decreases take place have been rejected since on such days the sharp intensity gradients are likely to cause a large error in the determination of the diurnal vector. The anisotropy information from individual stations are then combined to derive the average diurnal anisotropy in space for each day. We have selected only those days on which there is a good interstation agreement in the observed diurnal vectors ($\sigma_{\text{amp}} \leqslant 0 \cdot 1\%$, $\sigma_{\text{pha}} \leqslant 30^\circ$) for all our further analysis. The percentage of such days is more than 80. We wish to emphasise the necessity of following the above procedure particularly when dealing with diurnal anisotropy on a day-to-day basis to avoid erroneous conclusions.

Figure 1 shows the histograms of the frequency of occurrence of both the time of maximum and the amplitude of the diurnal anisotropy vector for each day, during 1967–68 derived using the data from six selected stations (solid lines). In the same figure, the corresponding histograms for the diurnal anisotropy vectors as derived from the data from only one station, namely Deep River, are also shown (in dashed lines) for purposes of comparison. The good correspondence between the two sets of histograms demonstrates that the method of obtaining average diurnal anisotropy vectors using data from a number of similar stations provides the true anisotropy vector in space with improved statistics.

Following paper I we represent the observed diurnal vector (δ) as a summation of convective (δ_c) and diffusive anisotropy (δ_d) vectors.

$$\delta = \delta_c + \delta_d \tag{1}$$

$\delta_c = 3CV_p/V$ can be derived from a knowledge of solar wind velocity V_p, V being particle velocity and C the Compton-Getting factor. The diffusive anisotropy

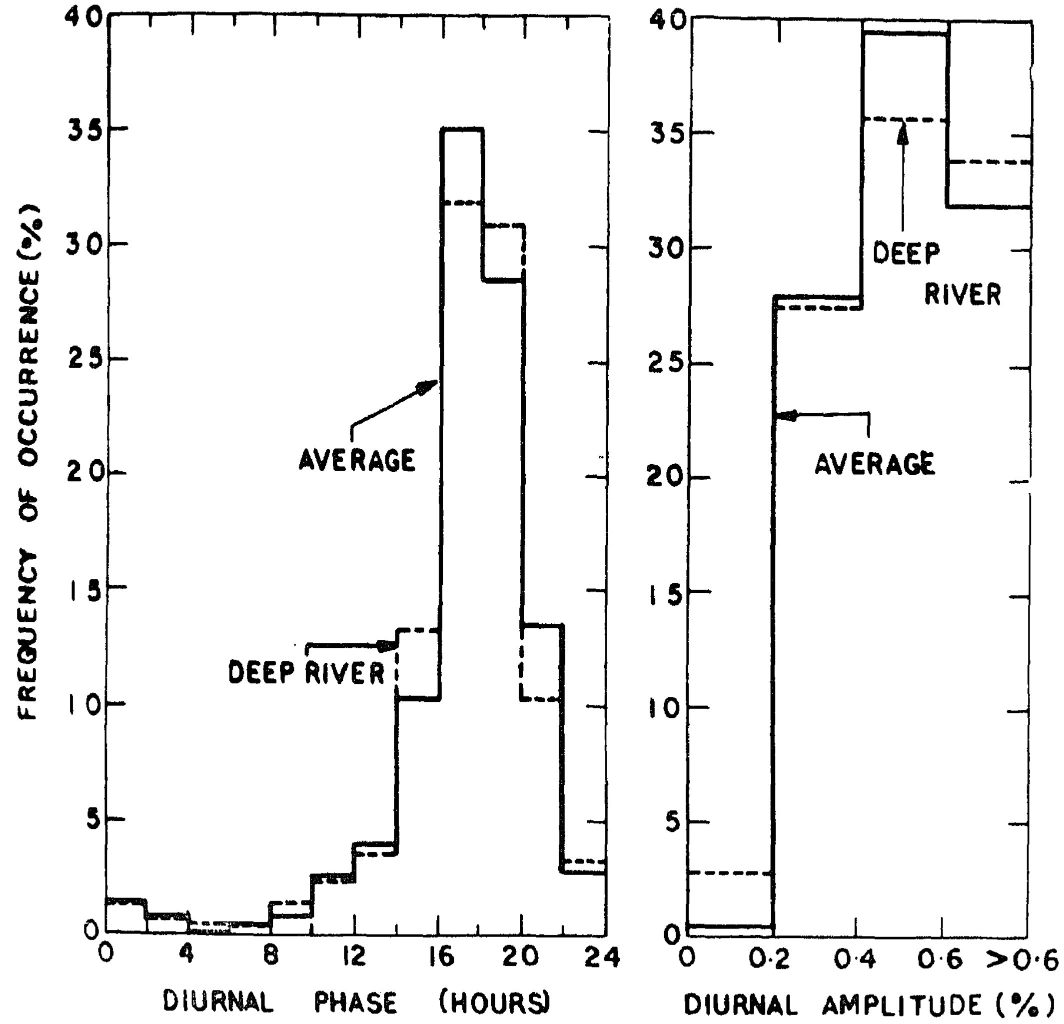

Figure 1. Histogram showing the frequency of occurrence of diurnal phase and amplitude in space obtained using average of six selected stations (solid lines) and also using only data from Deep River neutron monitor (dashed lines).

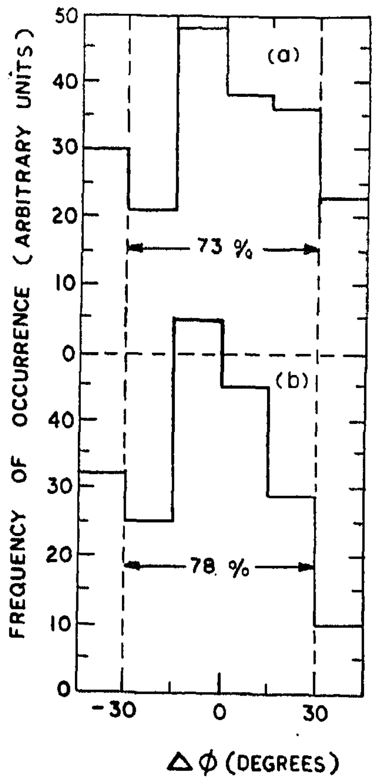

Figure 2. $\Delta\phi$ distribution is shown for a selected number of days (200 days) during 1967–68 for which both solar wind velocity and IPMF data are available. (*a*) shows the distribution for all the 200 days, and (*b*) shows the distribution for days on which there is a good interstation agreement in the determination of the diurnal phase.

vector (δ_d) for each day can be determined by subtracting the convection term δ_c from the observed diurnal anisotropy vector δ. In order to prove the field aligned nature of the diffusive vector, it is necessary to show the difference $\Delta\phi = \phi_d - \phi_B$, should be minimum ($\Delta\phi \approx 0$), *i.e.*, the phase of the diffusive vector ϕ_d is identical with the phase ϕ_B of the interplanetary magnetic field. However, due to large. statistical errors, we assume that the diffusive vector is field aligned if $\Delta\phi < 30°$ which is the practical limit of statistical significance one can impose on a daily basis. Days on which diffusion vector is not field aligned, *i.e.*, $\Delta\phi \geqslant 30°$, are designated as non-field aligned days.

3. Characteristics of diurnal variation on a day-to-day basis

Figure 2 shows the histogram of the frequency of occurrence of $\Delta\phi$ for 200 days in 1967–68 for which the data on solar wind velocity are available. It is seen from figure 2 (*a*) that on nearly 73% of days $\Delta\phi < 30°$. If we restrict our analysis to only those days on which there is reasonable interstation agreement in the determination of the diurnal phase (*i.e.*, $\sigma_{\text{pha}} < 30°$), the percentage of days on which the convection diffusion concept holds good increases to about 78% (figure 2 *b*) We may conclude that on nearly 80% of the days, the diurnal anisotropy is describable in terms of simple convection and field aligned diffusion.

Figure 3 shows some typical examples of field aligned nature of diffusion vector on a few selected days, on which either we have observed enhanced solar wind velocity (figure 3 *a*) or observed IPMF direction shows a large deviation from the mean field direction (figures 3 *b* and 3 *c*). In spite of the extreme conditions, it is evident from figure 3 that the diffusion vector is very well field aligned.

In order to extend the analysis for a larger sample of days, even when direct observations on solar wind velocity V_p are not available, we have utilised the empirical relationship between the index of geomagnetic disturbance ΣK_p and V_p for estimating V_p on such days. Existence of such a close empirical relationship between ΣK_p and V_p has been demonstrated by a number of workers (Snyder *et al* 1963, Pai *et al* 1967, Bame *et al* 1967). We have attempted to obtain such an empirical relationship between ΣK_p and V_p for 1967 using the available observations of V_p from Vela 3 satellite. Figure 4 shows the average solar wind velocity for each day for the above period plotted against ΣK_p, the correlation between V_p and ΣK_p is found to be ($0{\cdot}63 \pm 0{\cdot}03$) consistent with the relationship

$$V_p = (4{\cdot}98 \pm 0{\cdot}5) \cdot \Sigma K_p + (302 \pm 9) \tag{2}$$

Before using the empirical relationship, it is instructive to compare the results of $\Delta\phi$ distribution derived earlier (figure 2 *b*) with results obtained, using V_p values computed from the empirical relationship, given in eq. (2). Figure 5 shows the frequency distribution of $\Delta\phi$ for 170 days during 1967–68, $\Delta\phi$ being computed using V_p values obtained from the empirical relationship using eq. (2). $\Delta\phi$ distribution obtained using observed values of V_p for the same days is also plotted for comparison. The excellent correspondence between the two distributions confirms that the method of calculating the convective vector δ_c using wind velocity values computed using eq. (2) does not affect any of our conclusions. From a close examination of the data we also confirm that the maximum error introduced by this method is less than 10°, which is well within the statistical error on a day-to-day basis.

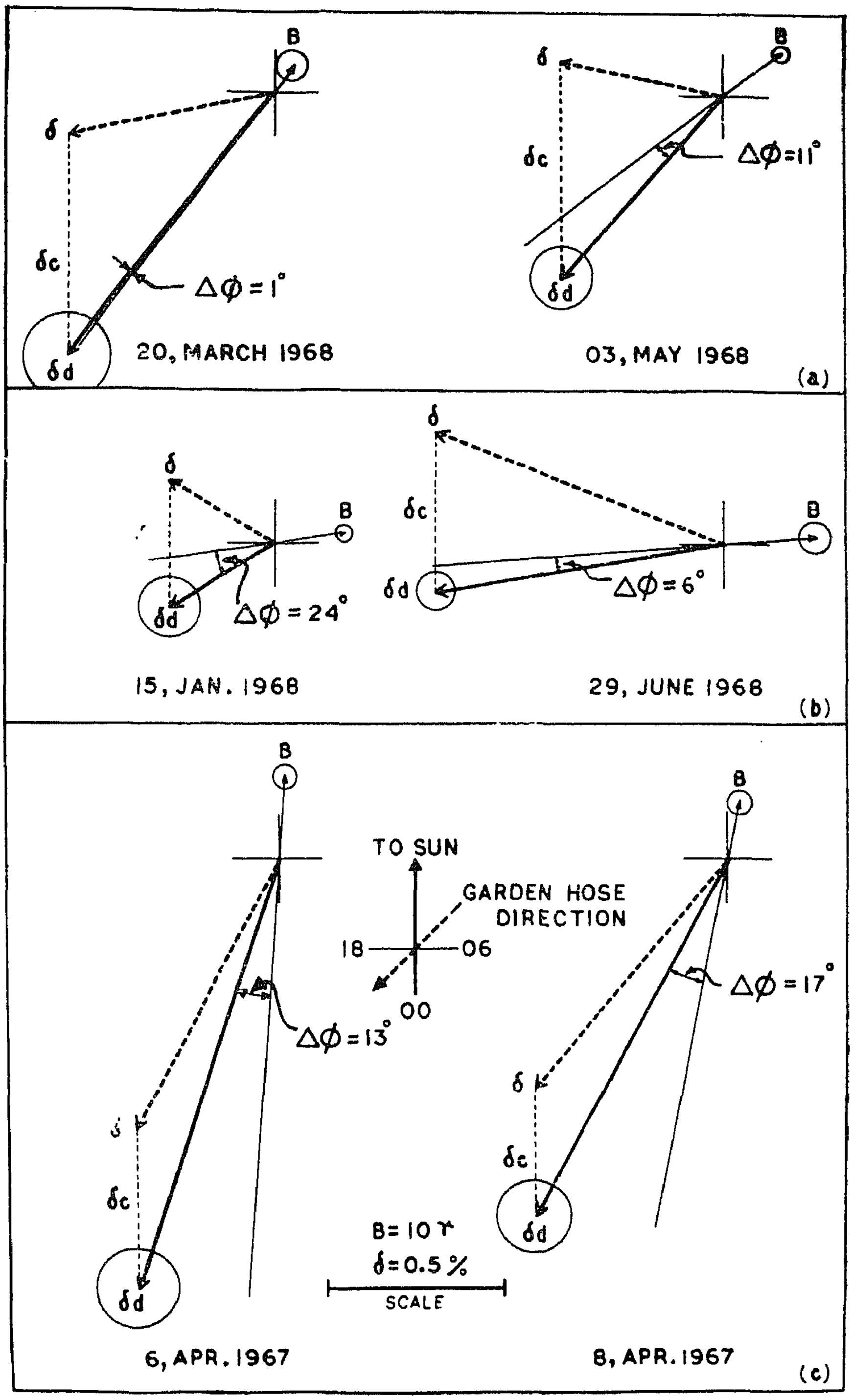

Figure 3. Typical examples showing the field aligned nature of the diffusion vector δ_d when (*a*) the convection δ_c is very much enhanced; and (*b*) and (*c*) the observed IPMF direction ϕ_B shows large departures from the mean Archimedian spiral angle.

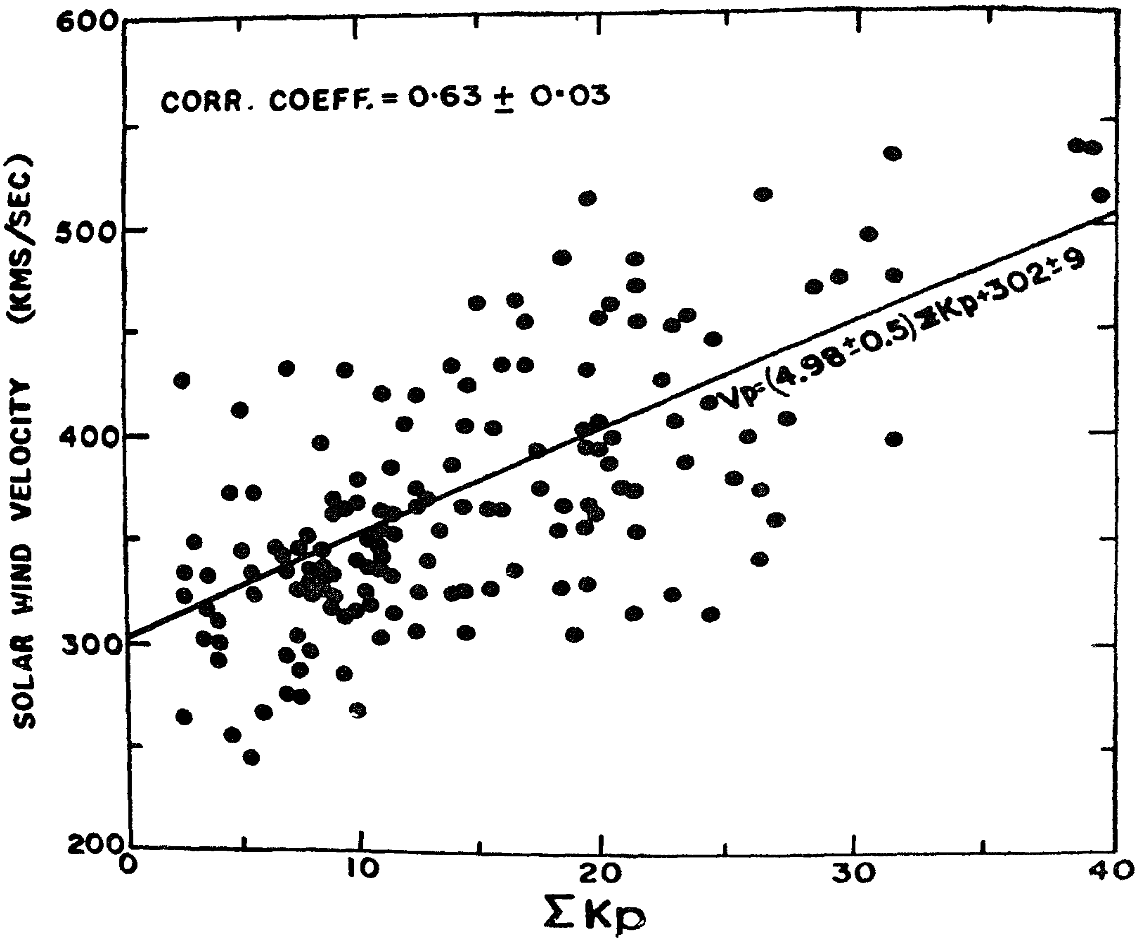

Figure 4. The correlation between observed solar wind velocity V_p and ΣK_p, the index of geomagnetic disturbance during 1967.

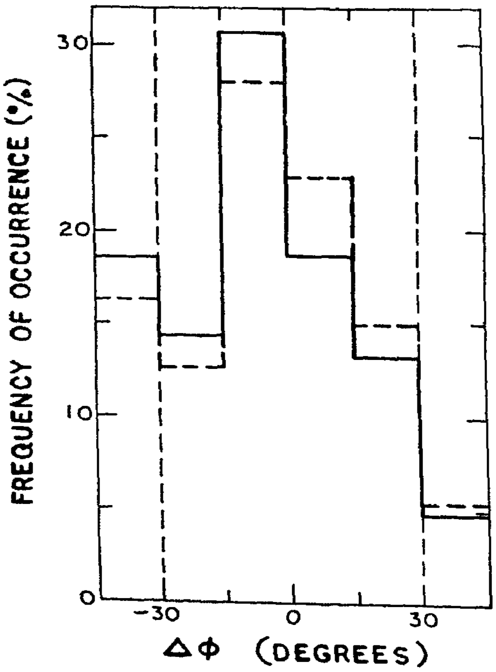

Figure 5. $\Delta\phi$ distribution for a selected number of days (solid line) during 1967–68, computed using V_p obtained from the empirical relationship shown in equation (2). The $\Delta\phi$ values obtained using actual observation of V_p for the same days is shown (dashed lines).

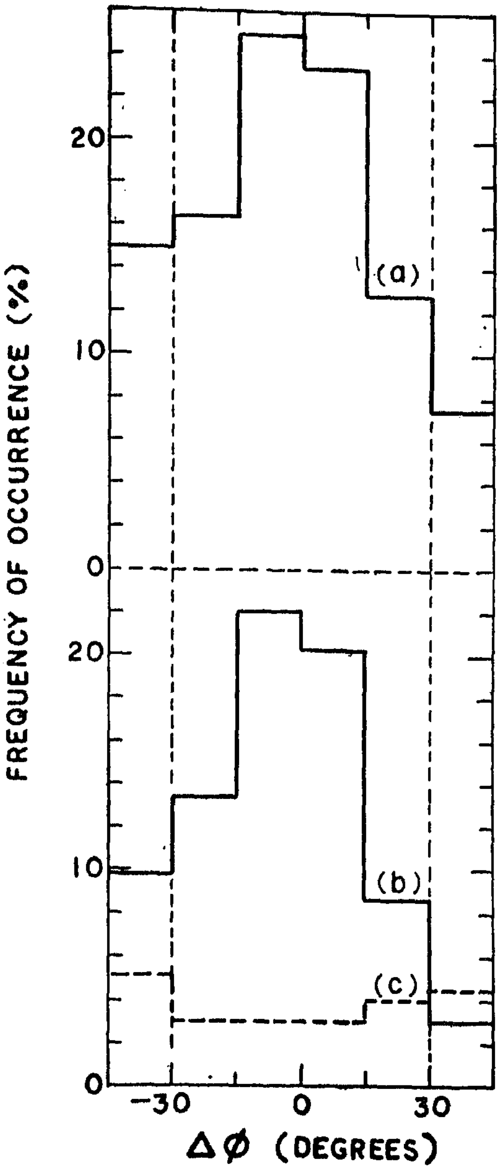

Figure 6. Histogram showing $\triangle\phi$ distribution on (*a*) nearly 400 days during 1967–68, (*b*) for days on which the observed diurnal time of maximum (α) is in between 15–21 hours, and (*c*) days on which α is in between 0–15 hours and 21–24 hours (dashed lines).

We have extended the analysis for the entire period 1967–68 by deriving convection vector on each day using the above relationship between V_p and ΣK_p. Figure 6 (*a*) shows the histograms of $\triangle\phi$ distribution for all the days (400 days) during 1967–68. We have also shown in the same figure the $\triangle\phi$ distribution separately for days on which the observed diurnal time of maximum is between (1) 15–21 hours (figure 6 *b*) and (2) 0–15, 21–24 hours (figure 6 *c*). It is evident from figures 6 (*a*) and 6 (*b*) that on more than 80% of the days the convection diffusion concept holds good. Also note that on days on which the diurnal time of maximum is between 0–15 and 21–24 hours (figure 6 *c*), the histogram of $\triangle\phi$ distribution is almost flat indicating that on those days on which the diurnal vector is far removed from the direction of corotation, the transverse diffusion currents are quite significant.

4. Characteristics of non-field aligned days

In this section, we examine the detailed characteristics and the solar terrestrial relationships of the days on which the diffusion vector is not field aligned ($\triangle\phi \geqslant 30°$), in order to understand the mechanism which causes the transverse diffusion to be significant on such days. We observe that majority of the non-field aligned days occur in trains of two or more consecutive days indicating that the mechanism

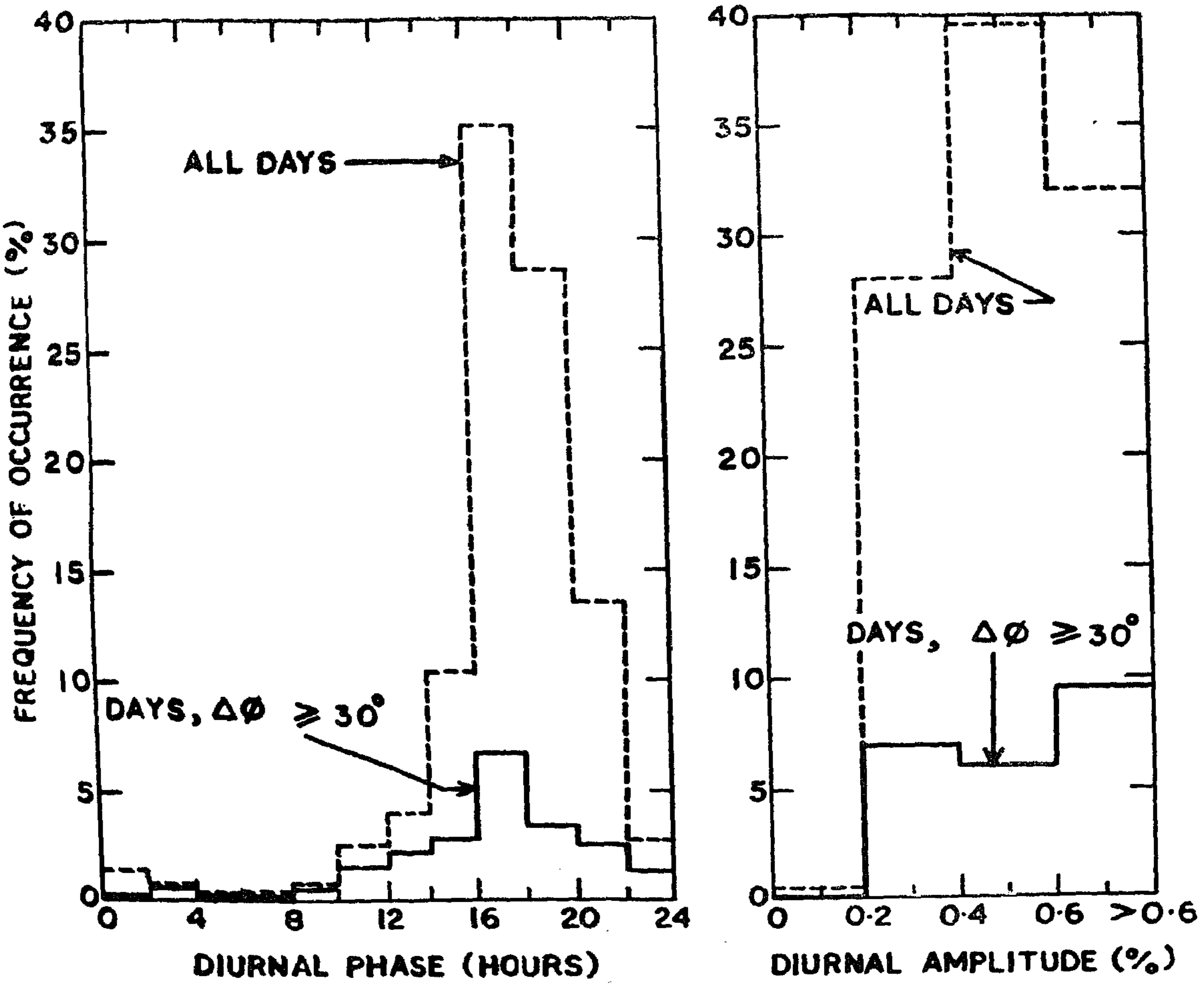

Figure 7. Histograms showing the distribution of diurnal phase and amplitude for the non-field aligned days (solid lines) during 1967–68. The corresponding histograms for all the 400 days on this period are also shown in dashed lines.

causing transverse diffusion is not a transient phenomenon, but persists over a period of time. In spite of the tendency for such days to occur on consecutive days, they do not show any characteristic features such as enhancement in the diurnal or semidiurnal components, ΣK_p index or large variability in interplanetary field parameters. Likewise no large deviation in the mean intensity or 27–day recurrence are observed during these days.

In figure 7 are plotted the frequency distribution of diurnal phase and diurnal amplitude for all the non-field aligned days (solid lines) during 1967–68. For comparison the histogram of diurnal phase and amplitude for all 400 days during 1967–68 is also shown (dashed lines). Whereas the familiar predominant peak around 18 hr direction is clearly evident from the histogram of the diurnal phase for all the days, the histogram for only non-field aligned shows a much flatter distribution. Further it is seen that practically all the days on which diurnal time of maximum is in the morning hours (0–12 hr) the diffusion vector is not field aligned.

Since the presence of trains of non-field aligned days indicate essentially quasi-permanent anomalous condition in the interplanetary space causing transverse diffusion currents we have concentrated on detailed examination of the interplanetary condition during such periods. In figure 8, we show the average IPMF vector for each day plotted end to end for a number of non-field aligned trains of days,

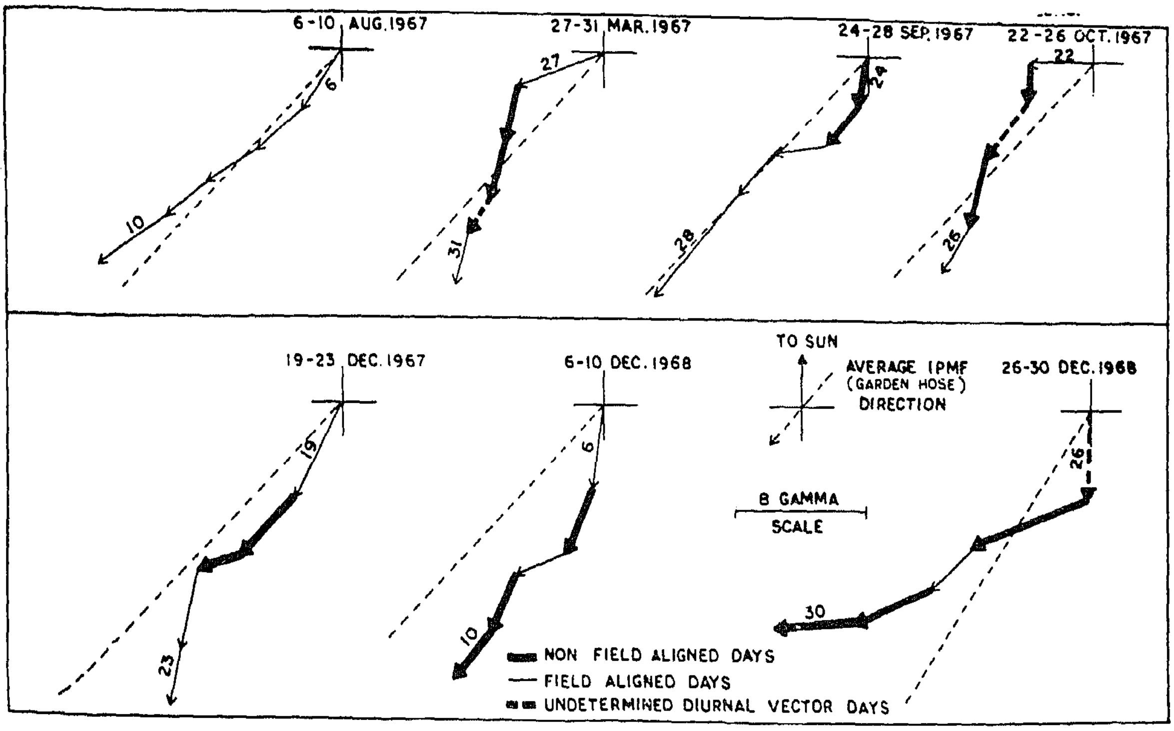

Figure 8. The interplanetary magnetic field vector for each day is plotted end to end for a few trains of consecutive non-field aligned days. For comparison the field vectors for one typical field aligned train of consecutive days (6–10 August 1967) is also shown.

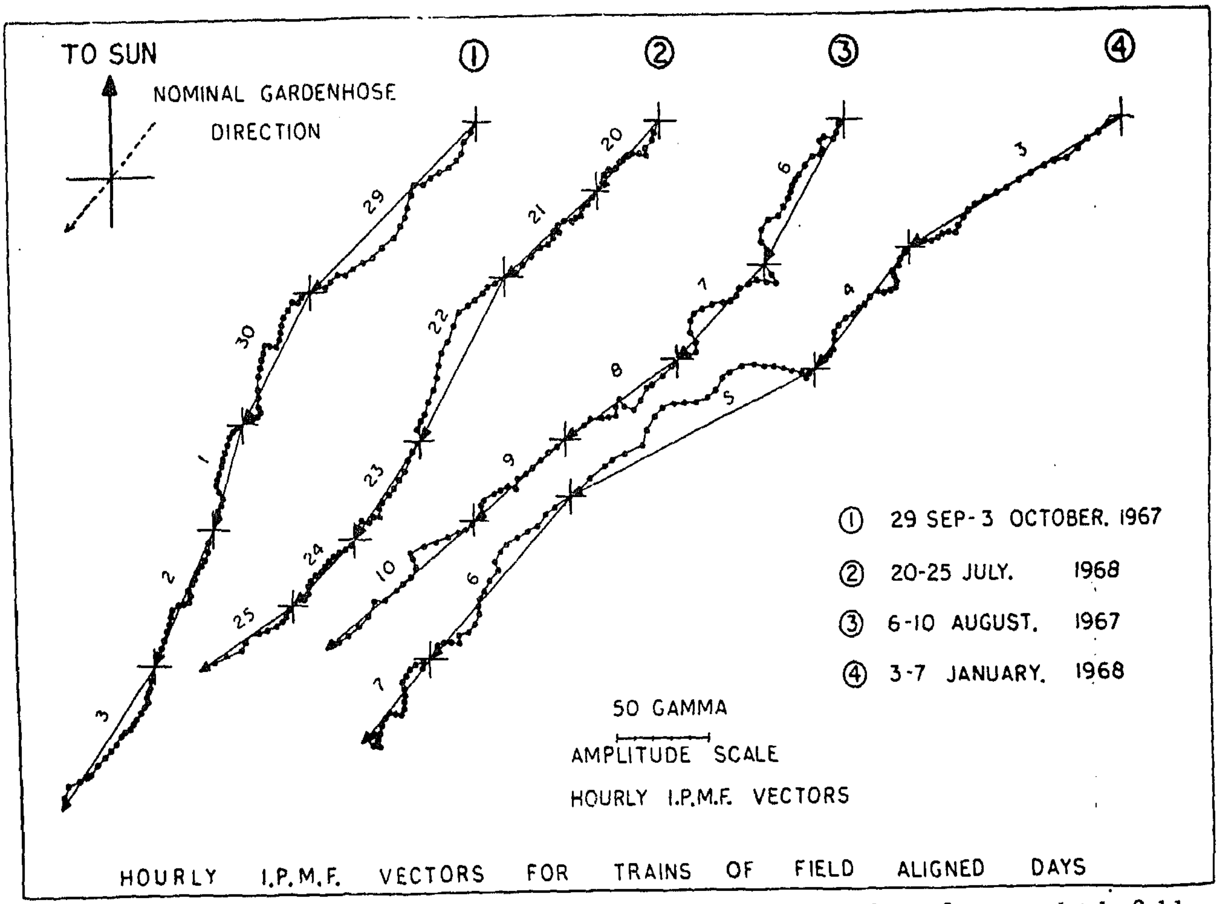

Figure 9. Hourly changes in the IPMF vector is shown for a few completely field aligned trains of days.

For comparison, the field vectors for a typical field aligned train of days is also shown. It is evident from the figure that on days on which the diffusion is field aligned the field vectors are well behaved and do not show significant departure from Archimedian spiral. On the other hand, on trains of days on which the diffusion is not field aligned, the field vectors show a large variability both in direction and in magnitude from day-to-day and often show large departures (> 45°) from the mean Archimedian spiral.

Before proceeding to examine in detail, the IPMF characteristics on non-field aligned days, it is instructive to examine the characteristics on field aligned days. Figure 9 shows the hourly changes in IPMF vector along with the daily mean for each day for a few typical trains of field aligned days. Examination of each of the trains shown in the figure clearly brings out the two most important characteristic features of the IPMF for these days:

(*a*) the change in the field vector from one hour to the next on the same day is relatively small, and

(*b*) the change in the field characteristics from one day to the next during each train of events is also negligible.

On the other hand, examination of trains of non-field aligned days shows that on such days large irregularities in the interplanetary field exist. In figure 10

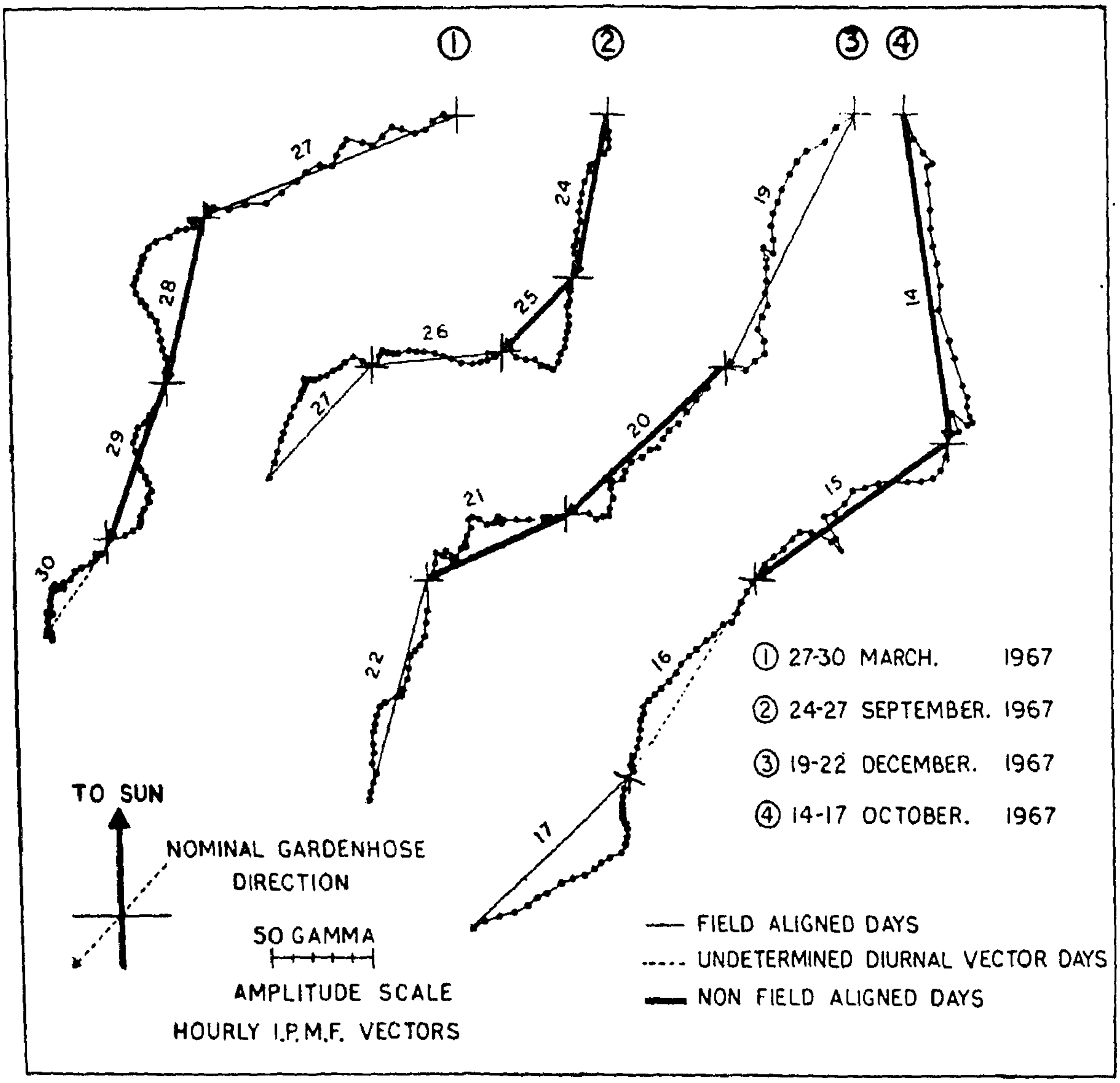

Figure 10. Hourly changes in the IPMF vector is plotted for few non-field aligned trains of days on which there is a large change in the daily mean IPMF vector from one day to the next.

are shown examples of trains of non-field aligned days when the IPMF vector exhibits large change from one day to another. The average daily field vector seems to change its direction by as much as 60–90° from one day to the next. Figure 11 shows examples of trains of non-field aligned days when the IPMF vector, even though does not show large changes from one day to the next, shows the continual presence of large irregularities having scale sizes of > 4 hr during each day.

In order to estimate the scale sizes of the irregularities present during the non-field aligned days, a power spectrum analysis of the IPMF data has been carried out and figure 12 shows the power density distribution of the radial component at various frequencies for a selected train of non-field aligned days (circles) and also for a train of completely field aligned days (dots). The figure clearly demontrates that in spite of the large errors associated with the limited data we have used, during non-field aligned trains of days there is a tendency for irregularities having scale sizes $\approx 4\cdot3$ hr and $6\cdot6$ hr to dominate when compared with field aligned trains of days. These irregularities can effectively scatter particles > 1 GeV and thus introduce a significant transverse gradient in addition to normal convection and diffusion during non-field aligned days.

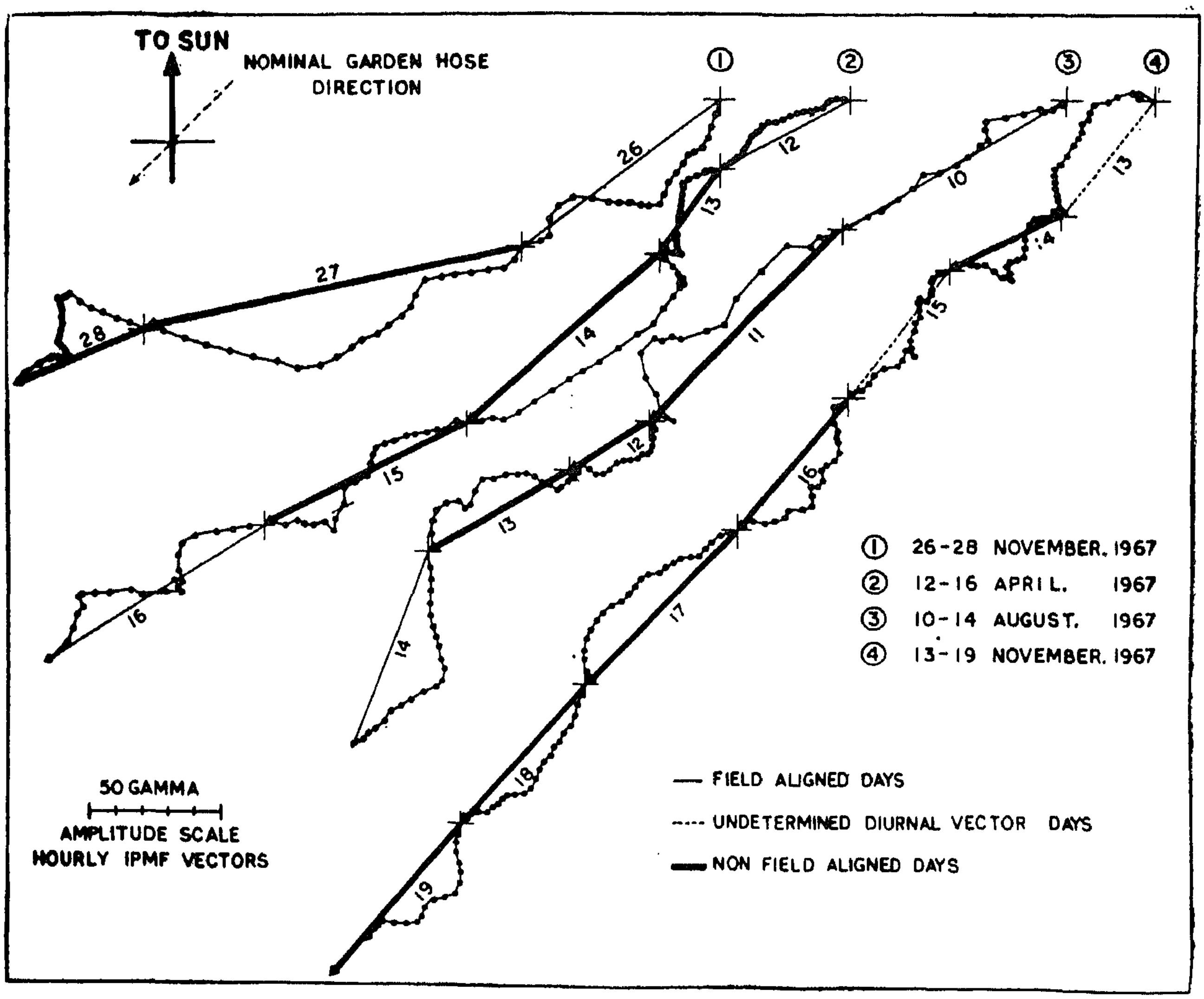

Figure 11. Hourly changes in the IPMF vector is shown for a few non-field aligned trains of days on which there is no day-to-day changes in the daily mean IPMF. Note the continual presence of irregularities of scales > 4 hr. on these days.

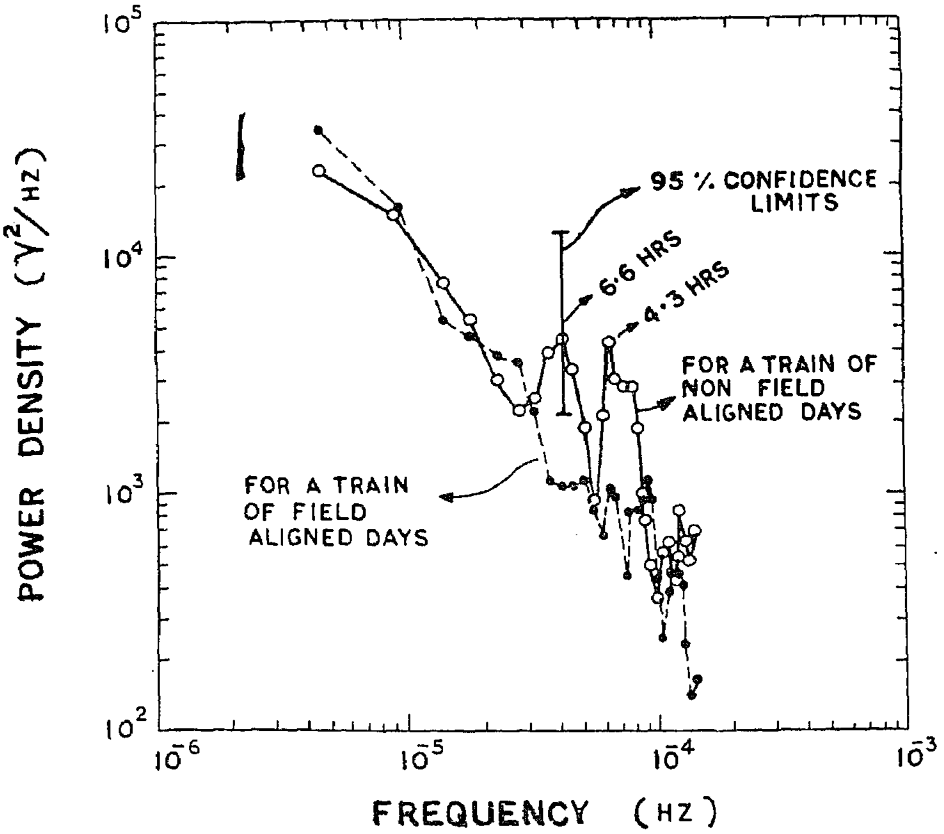

Figure 12. The power density of the radial component of IPMF is plotted against frequency for one typical train of field aligned days during 29 September to 3 October 1967 (shown by dots) and for a typical train of non-field aligned days during 14–18 November 1967 (by circles). Note the predominant peak at 4·3 hr and 6·6 hr during the train of non-field aligned days.

5. Discussion and conclusion

Following Forman and Gleeson (1970), we can write the expression for the net streaming of cosmic ray particles in the interplanetary medium as

$$S = S_c - K_\parallel \left(\frac{\partial U}{\partial r}\right)_\parallel - K_\perp \left(\frac{\partial U}{\partial r}\right)_\perp - F\left(\frac{\partial U}{\partial r}\,\frac{B}{B}\right) \tag{3}$$

where

$$F = \frac{V^2}{3\omega}\left[\frac{(\omega\tau)^2}{1+(\omega\tau)^2}\right],$$

$\partial U/\partial r$ is the radial density gradient and S_c is the convection current density. In paper I we showed that the diurnal variation, on an average basis, as well as enhanced diurnal variation are explainable in terms of simple convection and diffusion, *i.e.*, $K_\perp/K_\parallel$ is negligible. The diffusion current on such days was shown to be consistent with the expected radial density gradient. In this paper, we have conclusively demonstrated that this is indeed the case on more than 80% of the days even on the basis of individual days. .In other words, on a majority of days $K_\perp/K_\parallel$ is negligible ($\lesssim 0\cdot05$) or the third and fourth terms in the right hand side of eq. (3) may be neglected. Nonetheless on a small percentage of days ($\approx 20\%$), the interplanetary conditions are such that $K_\perp/K_\parallel$ can no longer be completely neglected, *i.e.*, the daily variation on such days cannot be completely accounted only by radial convection and field aligned diffusion and the transverse currents due to perpendicular diffusion do significantly contribute to the daily variation on such days. The association of large scale interplanetary magnetic field irregularities on these days of scale sizes ranging from a few hours ($\gtrsim$ 4 hr) to days clearly substantiates the above hypothesis. It may be noted that using power spectrum analysis Owens and Jokipii (1972) have recently demonstrated for the cosmic ray scintillations at Alert observed at low frequencies $< 5 \times 10^{-5}$ Hz (6 hr) are caused mainly by the fluctuating component of interplanetary magnetic field. They have suggested that the most likely mechanism for high energy cosmic ray scintillations at low frequencies is the strong interaction of these particles with magnetic field irregularities during their propagation in the interplanetary medium. It is interesting to note that the scale sizes which they derive for the field irregularities are consistent with our observations.

It is well known that the presence of irregularities cause random changes in the pitch angles of the particles as they move along the lines of force, the integrated effect of a large number of such irregularities being essentially to produce a three-dimensional random walk in the motion of particles. The resonant scattering due to irregularities is maximum for particles whose gyroradius (ρ) is of the same order as the scale size of the irregularities ($2\pi\rho$). In other words, to produce an appreciable scattering for particles of rigidity > 1 G.V., the scale sizes of the irregularities must be > 4 hr (assuming a mean solar wind velocity of 400 km/sec and average interplanetary field of 5 gammas) which are consistent with the observed scale sizes of the interplanetary field irregularities.

From the observed values of the diurnal variation during the trains of non-field aligned days, it is possible to estimate the value of $K_{\perp}/K_{\parallel}$. Assuming an average radial density gradient of 5%/AU, $K_{\parallel}$ at neutron monitor energies can be estimated to be $\approx 5 \times 10^{21}\,\rho\beta$ cm^2 sec^{-1}. On the other hand, examining a large number of trains of non-field aligned days when the average phase difference between the interplanetary field vector and diffusion vector ($\triangle\phi$) is about 42°, $K_{\perp}/K_{\parallel}$ ratio for non-field aligned days is found to be $\approx 1{\cdot}0$.

From the data and analysis presented in the foregoing sections, we draw the following conclusions:

(i) On an average basis the diurnal anisotropy of cosmic radiation is completely understood as a superposition of simple convection and field aligned diffusion. On a day-to-day basis, this concept holds good on more than 80% of the days.

(ii) On the rest of 20% of the days transverse diffusion also plays an important role. On these days, the diurnal time of maximum shows a preference to occur either during early morning (0–15) or during late evening (21–24) hours.

(iii) Days on which transverse diffusion is predominant seem to occur in trains of two or more consecutive days.

(iv) Such trains of days are usually associated with abrupt changes in the direction of interplanetary magnetic field. The non-field aligned days are associated with the presence of large irregularities in the interplanetary magnetic field of scale sizes > 4 hours.

(v) The value of perpendicular diffusion coefficient on non-field aligned days is quite significant. $K_{\perp}/K_{\parallel} \approx 1{\cdot}0$ for these days as compared to $\approx 0{\cdot}05$ observed on field aligned days.

(vi) From a careful examination of the cosmic ray anisotropy on a day-to-day basis, it is possible to infer the interplanetary field conditions and predict the nature and scale sizes of irregularities present in the magnetic field.

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