THE LARGE AMPLITUDE EVENT OBSERVED OVER THE PERIOD 22 MAY TO 4 JUNE, 1973

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(Received 3 July, 1979)

Abstract. The enhanced diurnal variation of cosmic-ray intensity observed over the period 22 May to 4 June, 1973 was analysed. The main characteristic of this large amplitude wave train is that the enhanced diurnal variation shows a maximum around 1600 h. For this analysis data from high-latitude neutron monitors and from the satellite HEOS-2 were used. This diurnal variation is caused by the superposition of convection and field-aligned diffusion due to an enhanced density gradient of $\sim 8\%\ \mathrm{AU}^{-1}$. It is shown that the diffusive vector is field-aligned on the days which are separated from magnetic sector boundaries.

1. Introduction

It is well known that the average characteristics of cosmic-ray diurnal anisotropy are adequately explained by the co-rotational concept (Parker, 1964; Axford, 1965). This concept supports a mean diurnal amplitude in space of 0.4% along the 1800 h direction using the world-wide neutron monitor data. However, the observed day-to-day variation both in amplitude and time of maximum, and the abnormally large amplitudes or abnormally low amplitudes of consecutive days, cannot be explained in corotational terms.

In recent years many scientists (Rao *et al.*, 1972; Kane, 1974; Owens and Kash, 1976) used a new concept for the interpretation of the diurnal variation. McCracken *et al.* (1968) first suggested the extension of this new concept from the solar cosmic events to the observed diurnal variation, and theoretical formulation was provided by Forman and Gleeson (1975). According to this mechanism the diurnal variation can be explained in terms of radial convection together with diffusion, which is mainly along the magnetic field line. The corotational concept is a special case of the convective–diffusive model with which we can explain the characteristics of the diurnal variation even on a day-to-day basis.

Several workers have attempted to find the possible origin of the 'large amplitude wave trains' of enhanced diurnal variation of cosmic rays and to develop a suitable realistic theoretical model which can explain the diurnal anisotropy in individual days. These interesting variations last many days and give an enhanced diurnal variation of crest to trough amplitude of 3–4%. Hashim and Thambyahpillai (1969) and Rao *et al.* (1972) have shown that the enhanced diurnal variation in interplanetary space during such events shows a maximum around 2000 h. Kane (1970) and Bussoletti (1973) have noticed that quite often an enhanced intensity is presented along the corotation

Astrophysics and Space Science **68** (1980) 137–149. 0004–640X/80/0681–0137$01.95

direction and it is not correlated with the garden-hose direction. In the present work is shown that an enhanced intensity may appear in the direction of 60° E of the Sun–Earth line and a depressed intensity in the direction of 120° W of the Sun–Earth line. This phase shift of the diurnal anisotropy to earlier hours is well understood in terms of the convective–diffusive mechanism (Kane, 1974). It is also shown that the diffusion is field-aligned on all days of the event except those which are characterized by magnetic sector boundaries. This result supports the model of cosmic-ray diffusion in the enhanced diurnal variation. Recently Owens and Kash (1976) have noted the non-field-aligned diffusion on days of nominal diurnal amplitude which are influenced by magnetic sector passages.

The large amplitude event observed over the period 22 May to 4 June, 1973 was selected for the present analysis. This event occurred in the last part of the recovery phase of a Forbush decrease. During this period the interplanetary magnetic field at the orbit of the Earth measured with space probes and satellites was quiet and the geomagnetic activity, as indicated by the k_p index, was low. Only between 28 and 30 May, due to sector passages, was the magnetic field disturbed. This event might be considered independent of 'flare-generated' phenomena (Bussoletti, 1973) and the evolution of the anisotropy shows the usual trend of all quiet events of enhanced amplitude.

2. Data Analysis

In order to examine the spatial characteristics of the enhanced diurnal variation of cosmic rays during this wave train, data were used from a few high and middle latitude neutron monitor stations which are listed in Table I. These stations are appropriately selected so that they have cut-off rigidities $\leqslant$ 2.20 GV (except for the Climax station which has a cut-off rigidity 3.03 GV), and are well distributed in longitude. Their asymptotic cones of acceptance are narrow in longitude ($\pm 30°$) and make small angles with the plane of the ecliptic, etc (Hashim and Thambyahpillai, 1969; Rao *et al.*, 1972). As the Earth spins on its axis, each of these stations scan a narrow region of the celestial sky.

The mean intensity for the period of the first five days of May 1973, which is prior to the onset of the Forbush decrease and is not accompanied by large changes in flux, was used as the control for each station. The time dependence of the percentage departures of intensity, intensity-time diagrams, is shown in Figure 1.

From the intensity of each station the mean intensity of Alert and McMurdo neutron monitor stations was subtracted, and these intensities (with respect to azimuthal direction relative to the Sun–Earth line) were plotted (Hashim and Thambyahpillai, 1969). A typical example of these intensity-direction diagrams is shown in Figure 2. The asymptotic cone of each station moves through 15° in azimuth during an hourly interval, and since the width of the asymptotic cone is 30° for most of the stations considered here, each hourly value represents the average effect over 45° in

TABLE I

Stations whose data have been utilized in the present analysis

Station (NM-64)	Symbol	Geographic coord.		Threshold	Mean asymptotic coord.	
		Latitude (deg)	Longitude (deg)	rigidity (GV)	Latitude (deg)	Longitude (deg)
Sanae	SA	−70.30	357.7	1.06	−21	19
Leeds	LE	53.8	358.5	2.20	4	52
Utrecht	UT }	52.1	5.1	2.76	− 2	62
Kiel	KI }	54.3	10.1	2.29	3	64
Oulu	OU }	65.0	25.4	0.81	30	63
Kerguelen	KE	−49.4	70.2	1.19	−26	87
Novosibirsk	NO	54.8	83.0	2.91	10	130
Magadan	MA	60.1	151.0	2.10	12	191
Inuvik	IN	68.4	226.3	0.18	47	233
Calgary	CA	51.1	245.9	1.09	28	269
Climax	CL	39.4	253.8	3.03	26	296
Deep River	DR	46.1	282.5	1.02	27	319
Swarthmore	SW }	39.9	284.6	1.92	−10	331
Durham	DU }	43.1	289.2	1.41	25	332
Goose Bay	GB }	53.3	299.6	0.52	35	339
Alert	AL	82.5	297.7	<0.05	77	331
McMurdo	MC	−77.9	166.6	<0.05	−74	261

azimuth. An integrated view of the evolution of the anisotropy is provided by these three-dimensional diagrams, but space limitations do not allow us to present all of them here.

For this the average of all stations of these intensities at each direction in space was estimated and the direction of anisotropy in the equatorial plane was determined. A polar diagram for each day (Mathews *et al.*, 1969) is shown in Figure 3. In this analysis the method proposed by Bussoletti *et al.* (1972) was used and the data were corrected for geomagnetic bending so that the real daily mean situation of the anisotropy into space was estimated with a high precision. These 'average diurnal waves', which give the amplitude of the daily mean anisotropy component in the corresponding longitude for the period of 22 May to 4 June 1973, are shown in Figure 4. The estimated diurnal anisotropy vectors in space were compared with interplanetary magnetic field data and solar wind data from the HEOS-2 satellite.

3. Experimental Results

An examination of the entire series of the intensity–direction diagrams and the polar diagrams reveals the following features:

On 22 May the intensity from a broad cone of directions centred around 60° E of the Sun–Earth line is seen to be 1–2% below that from the opposite direction. On

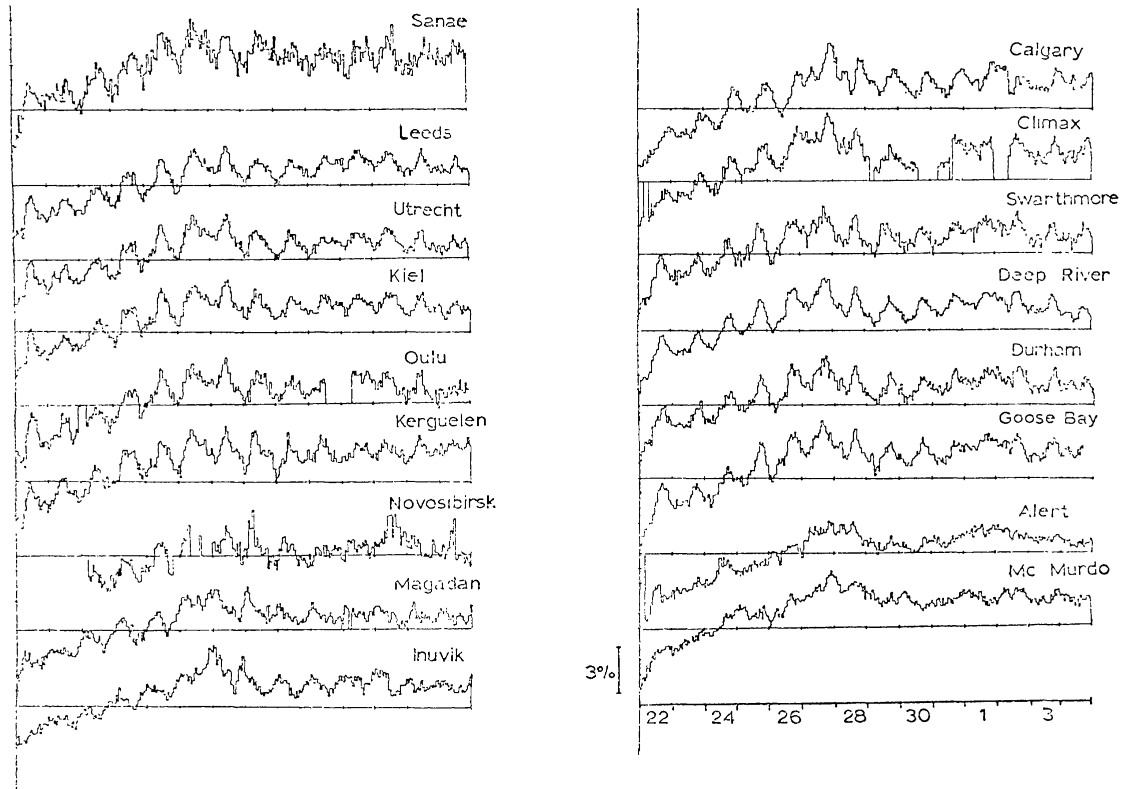

Fig. 1. Intensity–time profiles constructed using high-latitude neutron monitor data for the period 22 May–4 June, 1973.

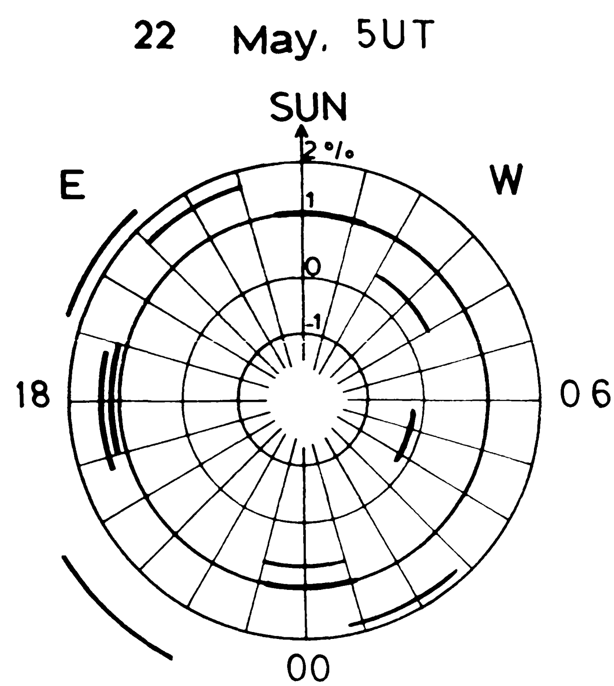

Fig. 2. A typical example of the intensity–direction diagrams during the 5th hour (UT) of 22 May, 1973.

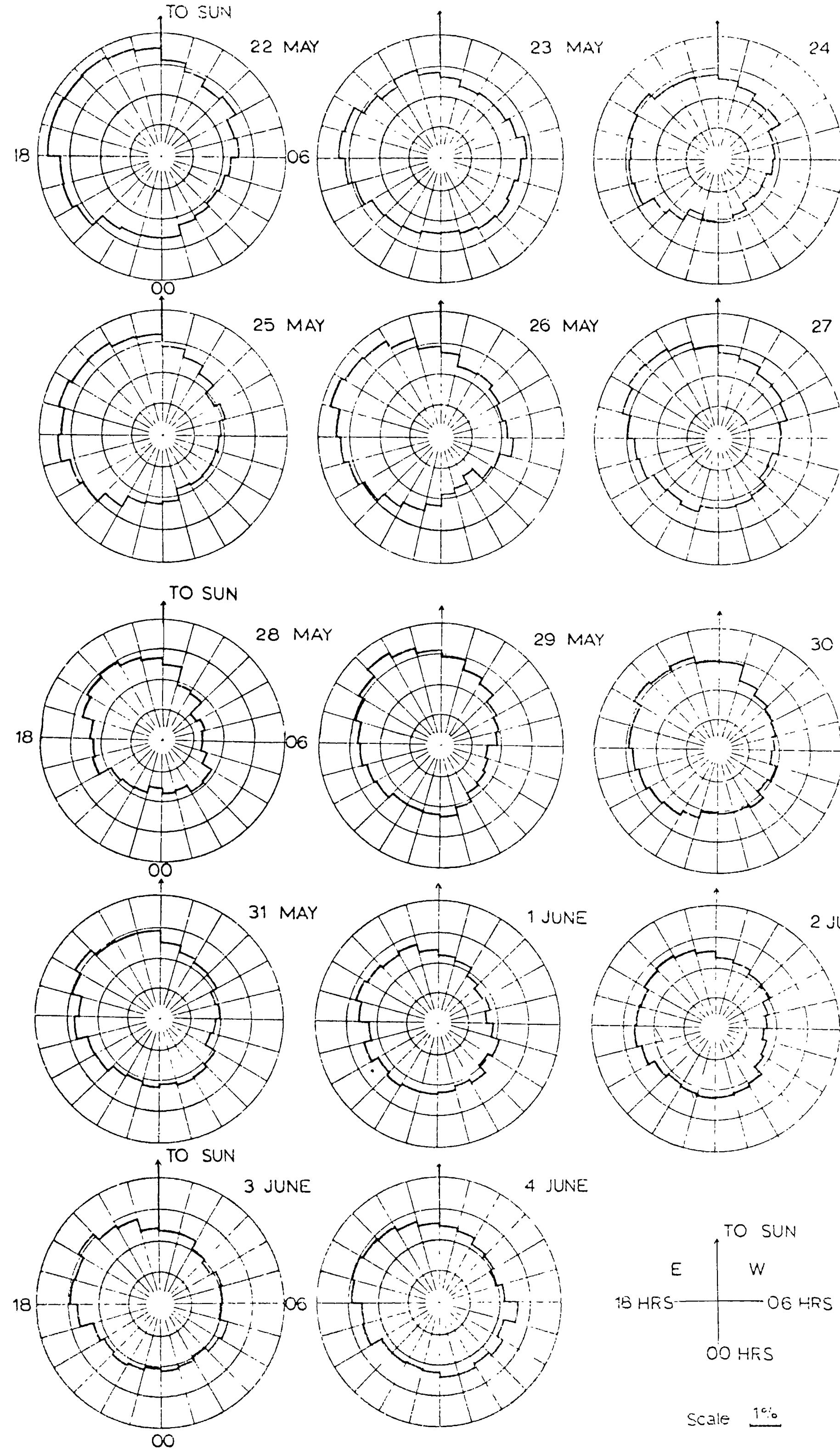

Fig. 3. Polar diagrams of the equatorial component of the diurnal anisotropy showing the evolution of the anisotropy.

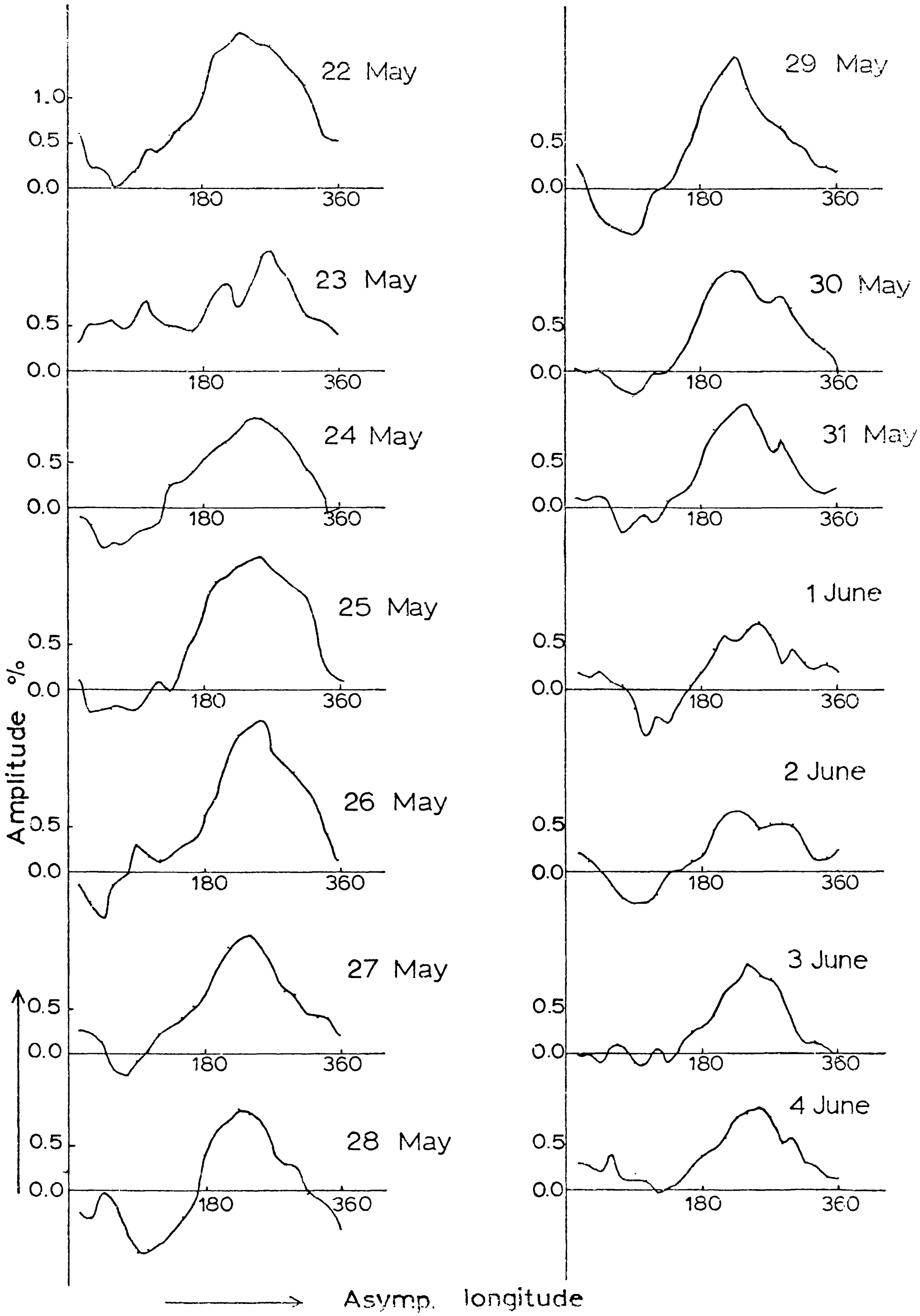

Fig. 4. 'Average diurnal waves' for the period 22 May–4 June, 1973.

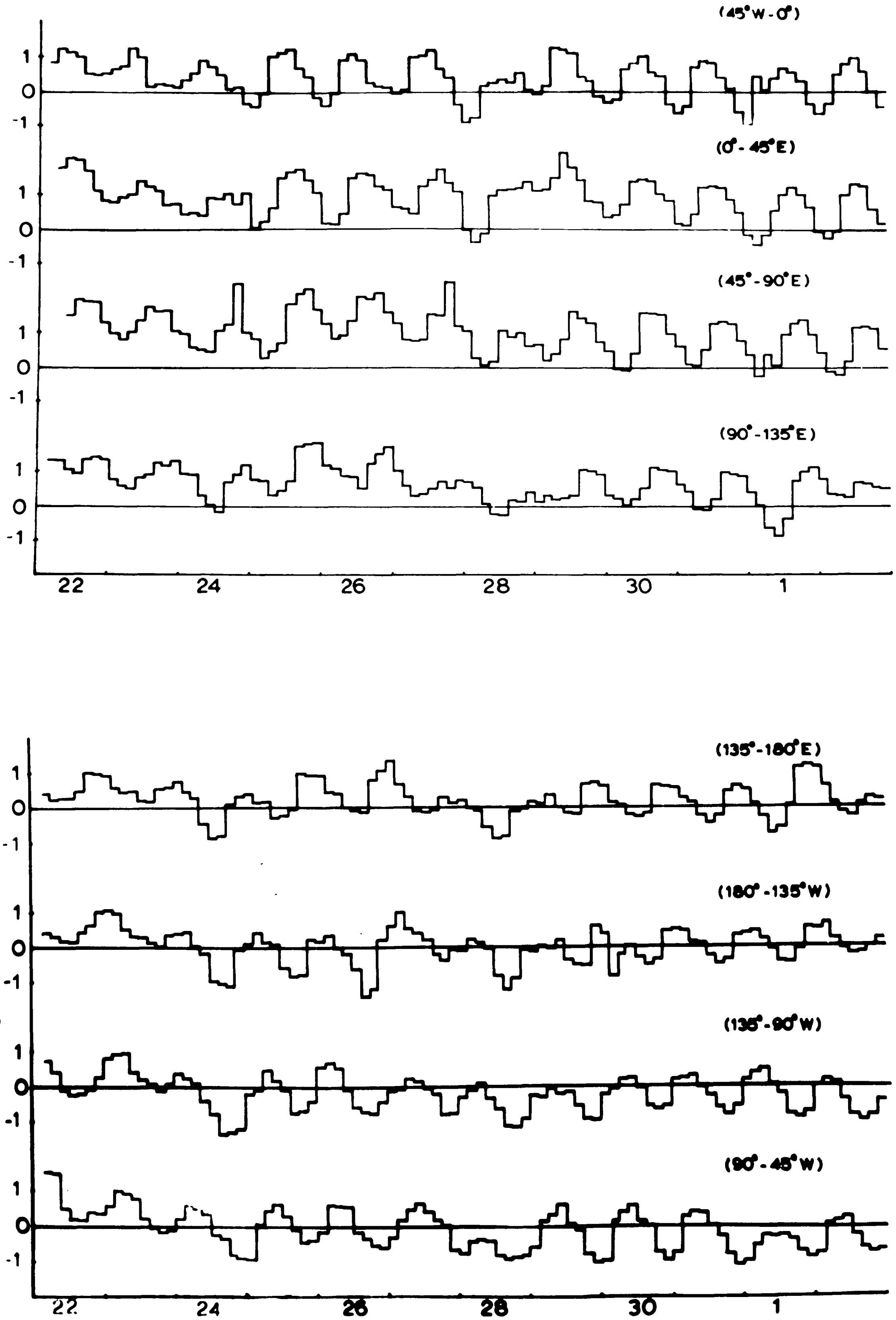

Fig. 5. Cosmic-ray intensity–direction–time diagrams during the period 22 May–2 June, 1973.

23 May an approximately isotropic flux appears. On 24, 25, 26, 27 May a depression of cosmic-ray intensity around 120° W of the Sun–Earth line to the normal level of 22 May is observed, but the intensity in the cone of directions centred around 60° E is almost unaffected. The most enhanced diurnal variation then appears. On 28 May the intensity is found to be depressed from all directions, especially 90° W of the Sun–Earth line. On the following days – 29, 30, 31 May and 1 and 2 June – a depression of intensity is observed in the western hemisphere. On 3, 4 June there is again an approximately isotropic flux. The intensity profile in different directions (1200 corresponding to the Sunward direction) for three-hourly intervals from 22 May to 4 June, 1973, is shown in Figure 5.

The intensity of this enhanced diurnal amplitude event of 22 May–4 June, 1973, shows a complex behaviour. During the early part of the event (between 22 and 27 May), cosmic-ray intensity shows an excess in the directions around 60° E of the Sun–Earth line. During the later part of the event (between 28 May and 2 June), cosmic-ray intensity is found to be depressed below the normal level in the directions around 120° W of the Sun–Earth line. It is noted that for this event the intensity in the garden-hose and anti-garden-hose directions is almost unaffected. The enhanced diurnal variation over all these days shows a maximum of about 1600 h in contrast to the 1300 h maximum observed in corotational anisotropy (Figure 6).

Previous analyses of such events (Hashim and Thambyahpillai, 1969; Rao *et al.*, 1972) had shown a maximum around 2000 h which was attributed to the depression of the intensity along the garden-hose direction or the increase of the intensity along the anti-garden-hose direction. The enhanced diurnal anisotropy maximum frequently presents an increased intensity along the corotational direction (Kane, 1970; Bussoletti, 1973). The phase shift of the enhanced diurnal anisotropy to earlier hours during the large amplitude event of May 1973 is obvious.

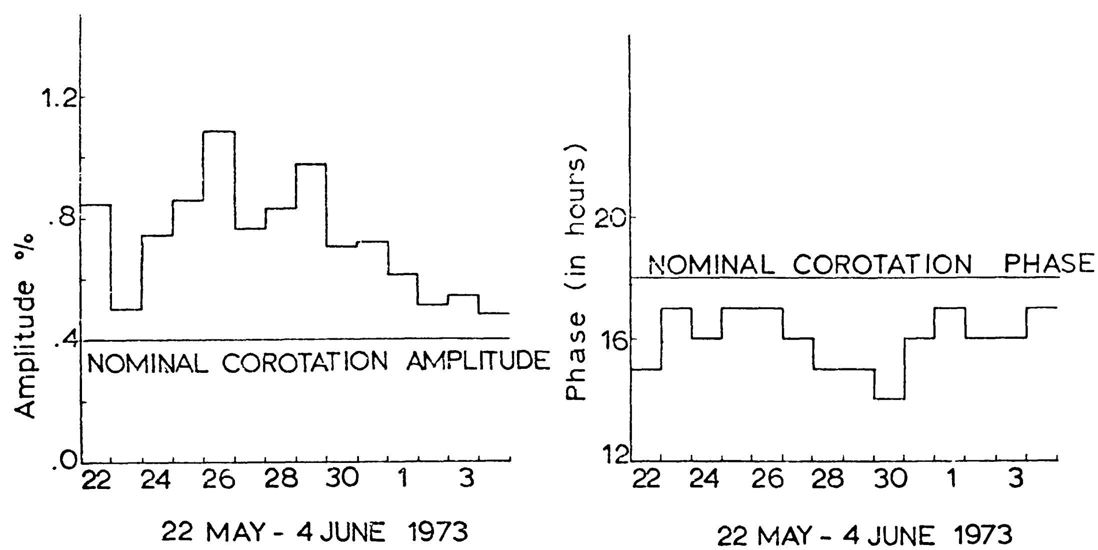

Fig. 6. The amplitude and phase of the diurnal anisotropy in space on each day during 22 May–4 June, 1973, from a number of neutron monitoring stations.

4. Relationship of the Enhanced Diurnal Variation with the Interplanetary Magnetic Field

Following the convective–diffusive concept the observed cosmic-ray diurnal anisotropy vector δ was resolved into two vectors: the convective vector (radially outward from the Sun) δ_c and the diffusive vector δ_d. The space anisotropy amplitude was not corrected as suggested by Subramanian (1971) because this correction will only increase the amplitude by a constant factor and will have no effect on the present analysis (Rao *et al.*, 1972). The magnitude of the convective vector was calculated with the expression

$$\delta_c = 3C \frac{V_p}{v} \tag{1}$$

where C is the Compton–Getting factor (which is ~ 1.5 for ~ 10 GeV particles), V_p the solar wind velocity, and v the particle velocity. The magnitude and direction of the diffusive vector was calculated by subtracting vectorially the convective vector from the observed diurnal anisotropy vector (Table II). The error of the diffusive anisotropy direction was typically small, ± 0.2 h.

To estimate the magnetic field data, hourly averages were taken from magnetometers in the HEOS-2 satellite. The daily average magnetic field vector in the ecliptic plane, $B\chi\psi$, was also calculated to within an accuracy of ± 1 h. On some days, however, it was considerably larger.

TABLE II

Diurnal anisotropy vector, convective vector, diffusive vector and interplanetary magnetic field vector (ecliptic component)
HEOS-2

Date	Diurnal anisotropy vector		Convective vector	Diffusive vector		Magnetic field vector	
	Amp (%)	Phase (deg)	Amp. (%)	Amp. (%)	Phase (deg)	Amp. (γ)	Phase (deg)
May 22	0.84	225	0.87	0.66	295	28.0	330
23	0.50	225	0.82	0.84	325	12.0	320
24	0.74	240	0.60	0.69	290	3.5	320
25	0.85	255	0.57	0.89	293	5.8	295
26	1.09	255	0.50	1.07	282	3.2	323
27	0.76	240	0.48	0.67	279	12.9	270
28	0.82	225					
29	0.97	225	0.63	0.68	268	3.9	120
30	0.69	210	0.51	0.36	257	4.5	115
31	0.72	240	0.48	0.63	281	5.4	115
June 1	0.61	255					
2	0.51	240	0.57	0.54	306	52.0	160
3	0.55	240	1.05	0.91	328	7.8	121
4	0.48	255	1.20	1.17	337	6.0	164

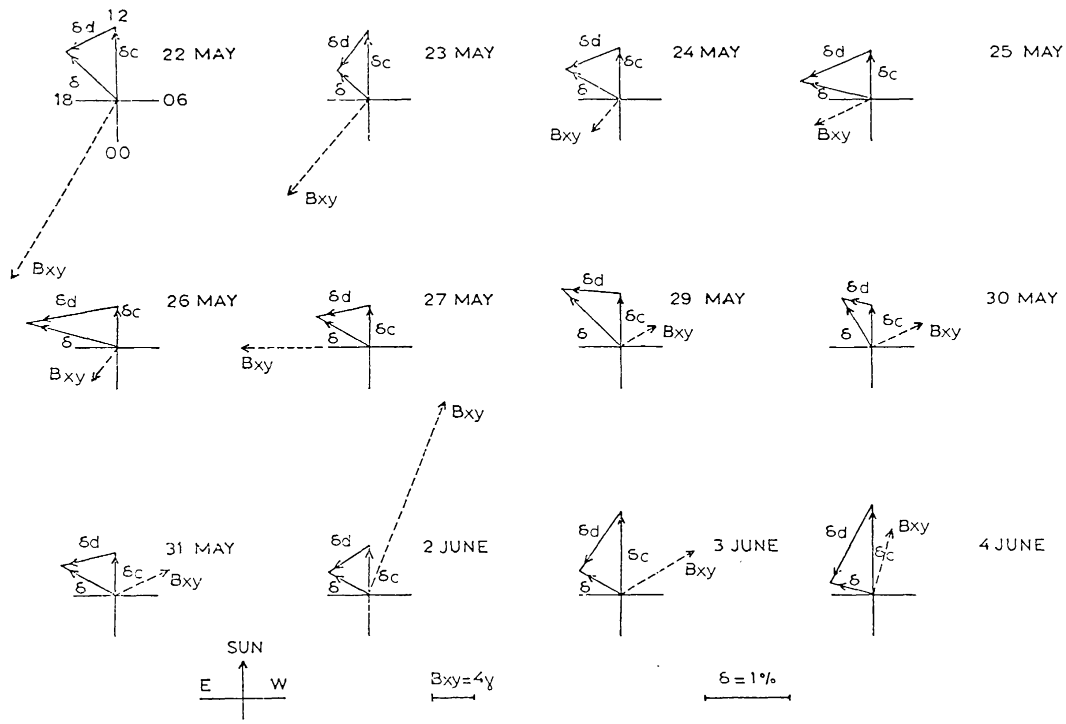

Fig. 7. Observed diurnal anisotropy vector (δ), convective vector (δ_c), diffusive vector (δ_d) and ecliptic component of the magnetic field vector ($B_{\chi\psi}$).

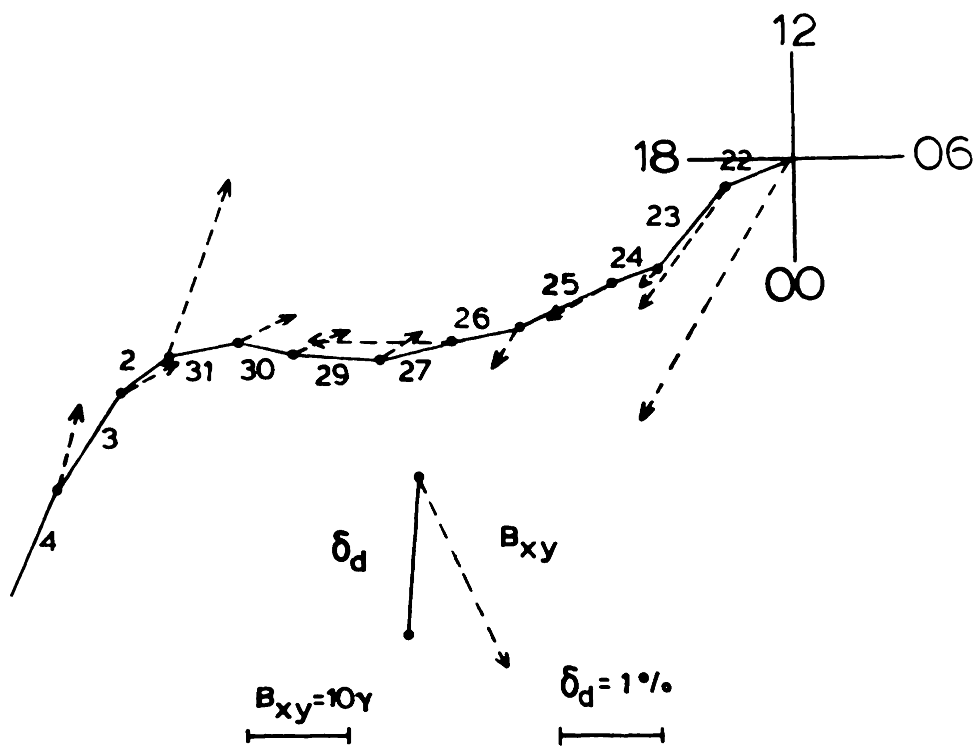

Fig. 8. Showing the cosmic-ray anisotropy diffusive vector (δ_d) and interplanetary magnetic field vector ($B_{\chi\psi}$) for each day end-by-end during 22 May–4 June, 1973.

The good agreement between the field azimuth and the direction of the diffusive vector throughout the duration of the event is shown in Figures 7 and 8. The diffusive vector is aligned parallel to the magnetic field vector. It maintains the anti-garden-hose direction whether the magnetic field vector is directed outwards from the Sun (22–27 May) or is directed towards the Sun (31 May–4 June). However, during the days 28–30 May, which are influenced by interplanetary magnetic sector passages (Owens and Kash, 1976), the diffusion vectors are not well field-aligned.

5. Discussion

According to the convective–diffusive mechanism of the diurnal anisotropy of cosmic rays the anisotropy A in the ecliptic plane is given (Kane, 1974) by

$$A = A_c - 3\frac{k_{\parallel}}{v}G_{\parallel} - 3\frac{k_{\perp}}{v}G_{\perp} - 3\frac{k_{\mathrm{T}}}{v}\frac{G \times B}{B} \qquad (2)$$

where the cosmic-ray gradient G has components $G_{\parallel}$ and $G_{\perp}$ in the ecliptic plane and G_p perpendicular to it; A_c is the convective component; $k_{\parallel}$ and $k_{\perp}$ are the diffusion coefficients parallel and perpendicular to $B\chi\psi$; and k_{T} is a transverse diffusion coefficient. When the diffusion vector is field aligned, $k_{\perp}/k_{\parallel}$ and k_{T} are negligible – the first two terms can adequately explain the anisotropy. In the present case the ratio of the average diffusion vectors is $k_{\perp}/k_{\parallel} \sim 0.2$ (Rao *et al.*, 1972). Ananth *et al.* (1974) have shown that on average this ratio is $\leqslant 0.05$ for field-aligned days and ~ 1.0 for non-field-aligned days.

During this period we have found that the observed average diffusive vector is 0.85%, which corresponds to an enhanced positive radial density gradient in the ecliptic plane of $\sim 8\%$ AU^{-1} (Rao *et al.*, 1972). (This gradient is sensitive to the value assumed for the diffusion coefficient.) This means that we have large cosmic-ray gradients which are seldom observed in satellites measurements, but are useful in an explanation of the diffusive phenomena. It is interesting to note that during the large amplitude event of May 1973 the density gradient did not reverse when the Earth crossed the sector boundary. Our results clearly show that the diffusive vector maintains the anti-garden-hose direction whether the interplanetary magnetic-field vector is positive or negative. There are therefore objections to believing that such large density gradients of cosmic rays take place over such long periods of time as two or three weeks. In the future this analysis must be extended to other events to see if this type of behaviour occurs regularly.

In order to explain the observed diurnal vectors for the days of non-field-aligned diffusivity (28–30 May), large values of perpendicular and transverse diffusion are needed (Kane, 1975), although during these days of sector boundaries the errors of the magnetic field vector are larger.

The shift of the time of maximum to earlier hours (1600 h) can be understood in terms of the simple convection–diffusion theory either as an enhancement in the convective vector or as a decrease in the diffusive vector. From the present set of observed diurnal vectors, one or both mechanisms may be operative. We have a significant convective flow due to the increase in the solar wind velocity. Also, a slight decrease of the diffusive vector has shifted the resulting diurnal variation to a time earlier than 1800 h because of the field-aligned nature of the diffusive flow (Agrawal and Singh, 1975).

6. Conclusions

From the data presented earlier, and the discussion, we conclude that:

(1) The enhanced diurnal variation cannot be attributed only to the decrease of cosmic-ray intensity in the garden-hose direction and increase in the anti-garden-hose direction or in the corotational direction. It may be caused by a source at about 60° E of the Sun–Earth line (1600 h) or by a sink at about 120° W of the Sun–Earth line (400 h). The relaxation time from a source to a sink is 4–5 days.

(2) The diurnal variation might be influenced by the polarity of the magnetic field. The largest diurnal variation is observed during days when the daily average magnetic field vector is directed outwards from the Sun (Venkatesan and Mathews, 1968). On days of enhanced diurnal variation the geomagnetic activity was low, and therefore interplanetary disturbances did not reach the Earth.

(3) The enhanced diurnal variation can be understood very well in terms of convection and field-aligned diffusion. The diffusive vector is aligned parallel or antiparallel to the interplanetary magnetic field. It maintains the anti-garden-hose direction even when the magnetic field vector presents a deviation from this direction, as if it was in its memory. On days which are influenced by magnetic sector boundaries the agreement is not very good. The average diffusive vector has an amplitude of 0.85%, which corresponds to an enhanced radial density gradient of $\sim 8\%$ AU^{-1}.

(4) The shift of the observed time from maximum to earlier (1600 h) can be understood in terms of the convective–diffusive mechanism either as an enhancement in the convective vector or as a decrease in the diffusive vector. On a day-to-day basis this mechanism offers a satisfactory explanation of the variability and times of maxima of this enhanced diurnal anisotropy.

Acknowledgements

Thanks are due to the Director of the World Data Center A for the data of neutron monitors, to the experimental groups which contributed these data, to Dr P. C. Hedgecock for interplanetary magnetic field data and to Dr H. Rosenbauer for solar wind data. Many thanks are also due to Dr T. Thambyahpillai and Dr A. Geranios for their kind assistance in evaluating the paper.

References

Agrawal, S. P. and Singh, R. L.: 1975, *Proc. 14th Int. Cosmic Ray Conf., München* **4**, 1193.
Ananth, A. G., Agrawal, S. P. and Rao, U. R.: 1974, *Pramana* **3**, 74.
Axford, W. I.: 1965, *Planet. Space Sci.* **13**, 115.
Bussoletti, E., Iucci, N. and Villoresi, G.: 1972, *Nuovo Cimento* **10B**, 43.
Bussoletti, E.: 1973, *Eldo-Cesles/Esro-Cers Sci. Tech. Rev.* **5**, 285.
Forman, M. A. and Gleeson, L. J.: 1975, *Astrophys. Space Sci.* **32**, 77.
Hashim, A. and Thambyahpillai, T.: 1969, *Planet. Space Sci.* **17**, 1879.
Kane, R. P.: 1970, *J. Geophys. Res.* **75**, 4350.
Kane, R. P.: 1974, *J. Geophys. Res.* **79**, 1321.
Kane, R. P.: 1975, *J. Geophys. Res.* **80**, 3509.
Mathews, T., Venkatesan, D. and Wilson, B. G.: 1969, *J. Geophys. Res.* **74**, 1218.
McCracken, K. G., Rao, U. R. and Ness, N. F.: 1968, *J. Geophys. Res.* **73**, 4159.
Owens, A. J. and Kash, M. M.: 1976, *J. Geophys. Res.* **81**, 3471.
Parker, E. N.: 1964, *Planet. Space Sci.* **12**, 735.
Rao, U. R., Ananth, A. G. and Agrawal, S. P.: 1972, *Planet. Space Sci.* **20**, 1799.
Subramanian, G.: 1971, *J. Geophys. Res.* **76**, 1093.
Venkatesan, D. and Mathews, T.: 1968, *Can. J. Phys.* **46**, 5794.