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ABSTRACT

The principal diurnal anomalies in the maximum electron density of ionospheric F2 layer over Kodaikanal are discussed. From an analysis of data obtained over half a solar cycle, it has been found that the phenomena of rapid increase in the electron densities following sunrise, the diurnal asymmetry and the maintenance of abnormally high ionic densities after sunset undergo systematic changes during stormy conditions. In order to examine whether these changes are accounted for by additional movements during disturbed conditions, magnitudes of movement terms of the continuity equation at three heights, for the quiet as well as the disturbed days, have been computed and discussed. The changes in the pattern of diurnal variation of N_mF2 with solar activity and the mechanism responsible for these changes are also discussed. From an analysis of published F2 layer data obtained at a number of stations with magnetic dip between ± 40°, it has been shown that the ratio of morning to afternoon peak densities yields a fair measure of equatorial F2 layer distortion anomaly. From solar cycle variation in diurnal asymmetry, an attempt has been made to estimate the extent by which the anomalous belt widens during sunspot maximum.

1. INTRODUCTION

IT is well known that the morphology of the ionospheric F2 layer maximum ionic density is complex in space and time. The variation of maximum ionic density in the layer does not follow the solar zenith angle variation and is considerably subject to geomagnetic influence. On a world-wide basis, F2 layer ionization is found to be much more symmetric about the magnetic equator than the geographic equator. When the diurnal variation of the F2 layer maximum electron density at an equatorial station is considered, several anomalies are found to exist. The ionic density drops sharply during the pre-sunrise period and increases more rapidly following sunrise. Instead of an expected maximum at midday a dip is found to exist with a maximum in the late afternoon hours. There is also a tendency for high ionization to persist after sunset. These normal quiet day anomalies are found to be considerably altered during geomagnetically disturbed periods. In the present paper the magnitudes of these effects together with their diurnal, seasonal and solar activity cycle characteristics have been discussed for Kodaikanal (Geomagnetic Latitude: 0°·6 N; Dip. 3°·5 N). Vertical incidence day-time data since July 1952 and round-the-clock data since September 1955 have been utilized for this study.

2. Distortion Anomaly and Ionic Drifts

The geomagnetic distortion anomaly at low and moderate latitudes has been explained by Martyn (1954) in terms of his electrodynamic drift theory. According to this theory, the electrostatic (polarization) field E developed in the 'dynamo' region produces currents in the F region. These currents interact with the main magnetic field of the earth as a consequence of which vertical and horizontal drifts of ionization are caused. The vertical drift velocity v at a place with dip ϕ is given by:

$$v = \frac{E_y}{F} \cos \phi$$

where F is the main magnetic field and E_y is the eastward component of the electric field. Under the influence of the vertical drift loss of ionization takes place and the maximum divergence of the ionization occurs along the line of "zero" dip where the vertical transport velocity is directed upward during the day with maximum enhancement of its magnitude.

3. The Effect of Increased Magnetic Activity on Diurnal Variation in N_mF2

The influence of magnetic storminess on F2 layer maximum ionic density has been examined by Berkner and Seaton (1940), Appleton and Piggott (1952) and Wright and Skinner (1955). At Kodaikanal N_mF2 values on disturbed days are, generally, in excess of those observed on quiet days. It has also been noticed that the magnitude of the noon-'bite-out' effect progressively decreases with increasing geomagnetic activity. In order to examine these effects systematically, all internationally quiet and disturbed days from September 1955 to June 1958 were classified into four categories. These were designated Very Quiet (V.Q.), Quiet (Q), Disturbed (D) and Very Disturbed (V.D.). Very quiet days were selected out of all international quiet days and very disturbed days out of international disturbed days. The magnetic activity and percentage of days in each category are given in Table I.

TABLE I

Sl. No.	Magnetic activity	Symbol	Magnetic activity	Percentage number of days in each group
1.	Very quiet ..	V. Q.	$\Sigma K_p \leqslant 7$	≈ 15
2.	Quiet ..	Q.	All international quiet days	≈ 53
3.	Disturbed ..	D.	All international disturbed days	≈ 47
4.	Very disturbed ..	V. D.	$\Sigma K_p \geqslant 38$	≈ 11

The averages of mean hourly values of $(foF2)^2$ for all the days in each one of the four categories were obtained and these are plotted in Fig. 1. Both the characteristics of this station, *i.e.*, progressive increase in N_mF2, at all hours, with increased magnetic activity and reduced midday minimum are at once seen. The mean of 24-hourly values for very quiet and very disturbed days were also subjected to harmonic analysis and the results (Table II) indicate that the daily mean value of N_m is about 15% higher and the amplitude of the diurnal term lower on disturbed days. The amplitude of the semi-diurnal term is, however, considerably higher on disturbed days indicating that the perturbation of the quiet day (S_q) variations superposed on disturbed days (S_D) has not only a diurnal component but also a marked semi-diurnal component due to the effect of net disturbance current system. For equatorial latitudes, this current system is directed westwards at about noon and afternoon hours causing an increase in the magnitude of downward drift velocity associated with solar semi-diurnal tides in the ionosphere and pushing the region to lower levels at these times. Because of this contraction of the region on disturbed days, the ionization above the density peak descends to lower levels and adds to the ionization therein. Further, as seen in Fig. 1, night-time electron density is considerably enhanced on disturbed days.

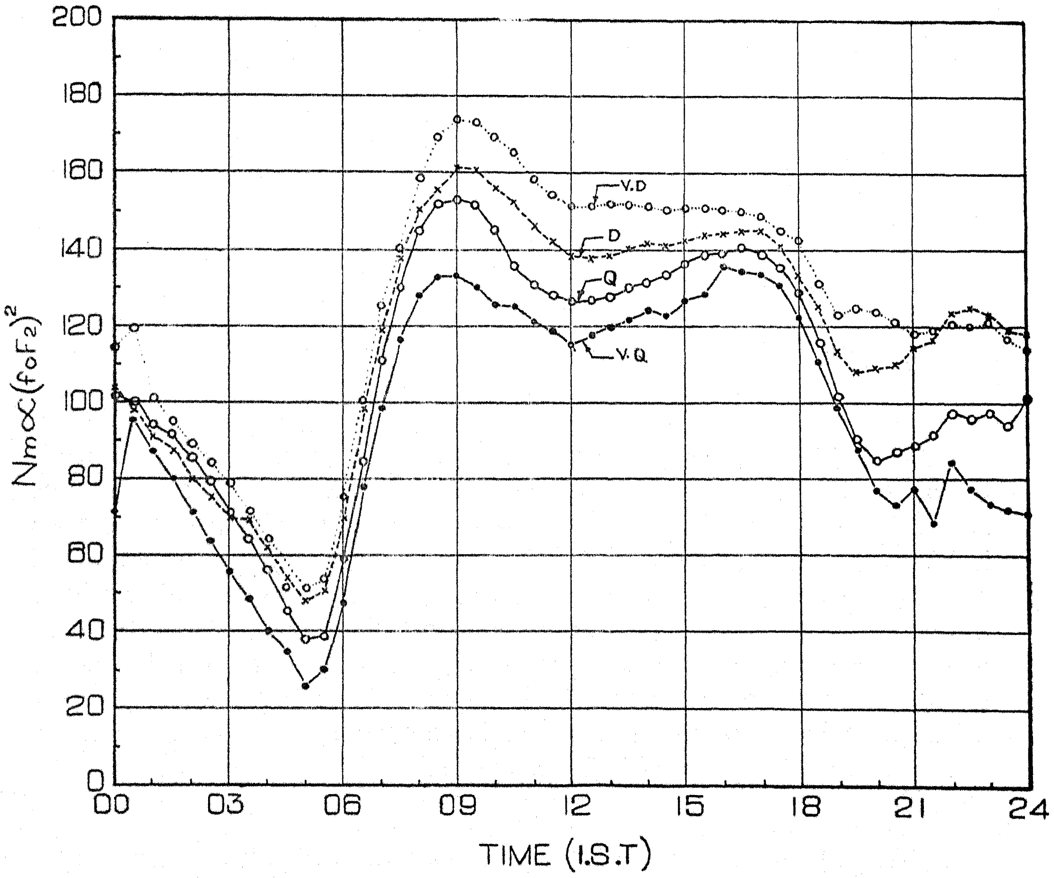

FIG. 1. Diurnal Variation of NmF2 for Different Stages of Magnetic Activity.

The basic continuity equation of electron density N is:

$$\frac{\partial N}{\partial t} = I(t) \cdot f(x, h) - \beta(h) \cdot N - \nabla \cdot (\bar{v}N) \qquad (\sigma)$$

where $I(t)$ represents the intensity of solar ionizing radiation, $f(x, h)$ represents the way in which the rate of ion production depends on solar zenithal angle x and height h, $\beta(h)$ is the attachment-like loss coefficient and $\nabla \cdot (\bar{v}N)$ is the movement term M, $\bar{v}$ being the transport velocity of electrons.

Immediately after sunset when $I(t) = 0$ and $\bar{v}$ is downwards, it can be shown that $\partial N/\partial t$ is positive if $(\partial/\partial z)(\bar{v}N)$ is $> \beta N$. At a given level z, therefore, the electron loss is more than compensated, on disturbed days, by an increase from enhanced downward drift. No significant differences are found to exist in the phases on quiet and disturbed days.

TABLE II

Summary of harmonic analyses of mean diurnal variation of foF2: (1) very quiet days and (2) very disturbed days

	R_0 Mc./sec.	R_1 Mc./sec.	t_1 (Hr.)	R_2 Mc./sec.	t_2 (Hr.)
(1) Very quiet days (Σ $K_p \leqslant 7$)	9·60	2·08	14·3	0·63	10·4
(2) Very disturbed days (Σ $K_p \geqslant 38$)	11·10	1·78	14·3	1·04	10·2

The midday characteristics can be visualized in terms of vertical spreading and horizontal diffusion in the layer. On quiet days the effects of intense equatorial current (electrojet) in spreading the layer are large and the layer is lifted up considerably at noon. Though vertical diffusion (proportional to $\sin^2\phi$) is likely to be absent at equatorial stations, horizontal diffusion at high levels could take place resulting in loss of ionization. On disturbed days, when geomagnetic H component is subnormal in this belt due to the effects of westward Dst currents, the height of the layer is considerably lower compared to quiet conditions and consequently the loss of ionization due to vertical divergence and horizontal diffusion does not appear to take place.

4. THE DIURNAL AND SEASONAL CHARACTERISTICS OF IONOSPHERIC STORMINESS

From data for the period September 1955 to June 1958 the ratios of foF2 for international disturbed days and quiet days are plotted in Fig. 2 for winter, equinoxes and summer conditions. It will be seen that the ratio D (foF2)/Q (foF2) exceeds unity during all seasons throughout the 24 hours except for a short night time period in summer. There is a marked increase in the ratio for the pre-sunrise and post-sunset periods. A moderate noon maximum also exists during all seasons. The values plotted in Fig. 2 were harmonically analyzed and the amplitudes and phases for the three seasons, given in Table III, indicate that the amplitude of the first harmonic is largest in winter. The second harmonic is higher than the first in summer and at the equinoxes but lower in winter. Significant phase differences exist in the semi-diurnal term between the equinoxes and summer on one hand and between the equinoxes and winter on the other.

These may be attributed to slight shift in the vertical tide in the F2 region due to seasonal changes in electrical conductivities and in quiet day magnetic variation (Sq.).

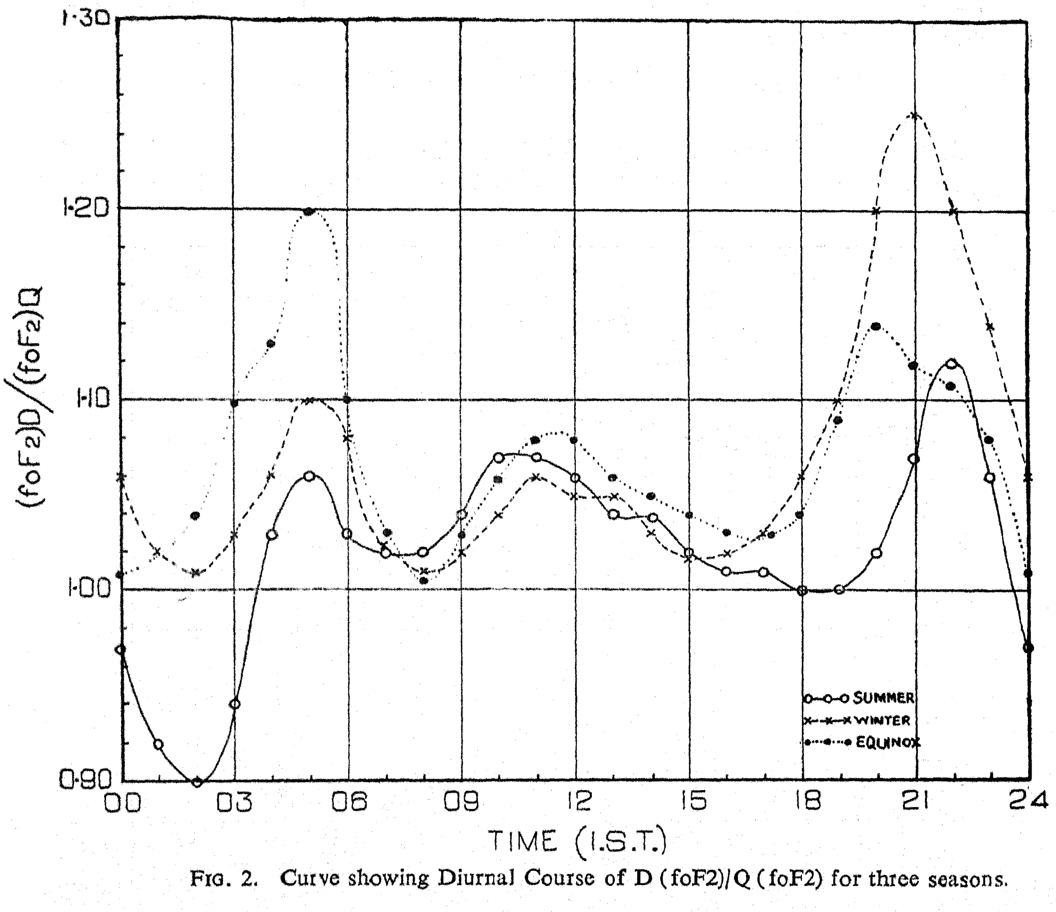

FIG. 2. Curve showing Diurnal Course of D (foF2)/Q (foF2) for three seasons.

TABLE III

	Summer Unit × 10^{-2} Mc./sec.					Equinoxes Unit × 10^{-2} Mc./sec.					Winter Unit × 10^{-2} Mc./sec.				
	R_0	R_1	ϕ_1	R_2	ϕ_2	R_0	R_1	ϕ_1	R_2	ϕ_2	R_0	R_1	ϕ_1	R_2	ϕ_2
$\frac{D}{Q}$(foF2) ..	102·4	2·61	209°	3·47	272°	106·5	2·49	31°	3·90	207°	106·1	4·42	311°	3·18	259°

5. IONOSPHERIC BEHAVIOUR DURING A SINGLE STORM

In order to find the magnitude and nature of movements during a typical storm, ionospheric data of September 4, 1958, when a severe magnetic storm of range 532 γ in H was recorded at Kodaikanal, were analysed together with similar data for a 'control' day, two days earlier to the storm, when the magnetic character figure Ci was 0·1. The selected 'control' day was preceded and followed by quiet conditions and, therefore, free of residual storminess.

For three selected heights of 250, 300 and 350 km., N—h profiles were obtained from $h'-f$ records using the appropriate coefficients given by Schmerling and Ventrice (1959) for both the storm and control days. The $(N - t)_h$ curves obtained from $N - h$ profiles are plotted in Fig. 3.

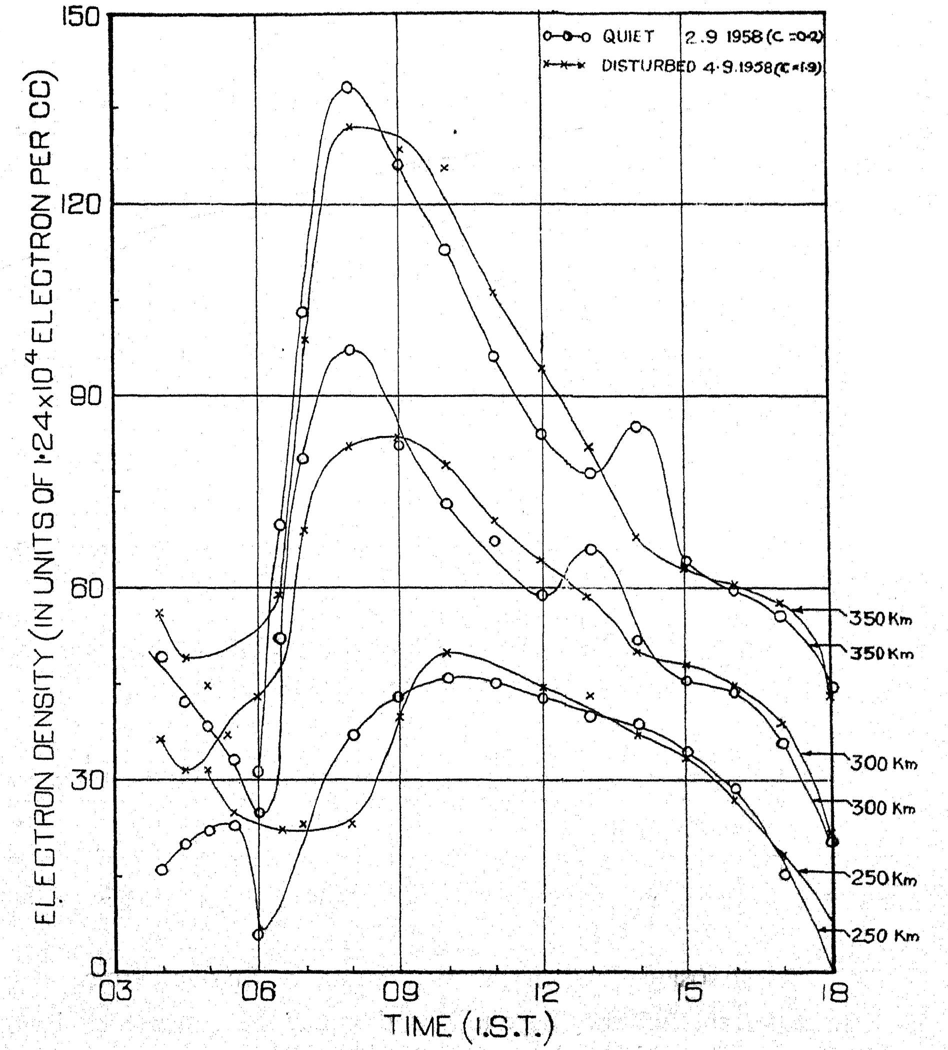

FIG. 3. Variation of Electron Density with Time at Fixed Heights during Sunspot Maximum for Disturbed and Quiet Days.

Using values of N and dN/dt from these curves and computing β (h) after Ratcliffe *et al.* (1956) and $f(x, h)$ and $I(t)$ from the usual expressions, the magnitudes of the movement terms were obtained, at intervals of one hour, from the continuity equation.

The control day movement term Mq for a selected true height of 300 km. together with the difference $\triangle M$ $(= M_Q - M_D)$ for the same level is plotted in Fig. 4. These curves together with $(N - t)h$ curves of Fig. 3 indicate

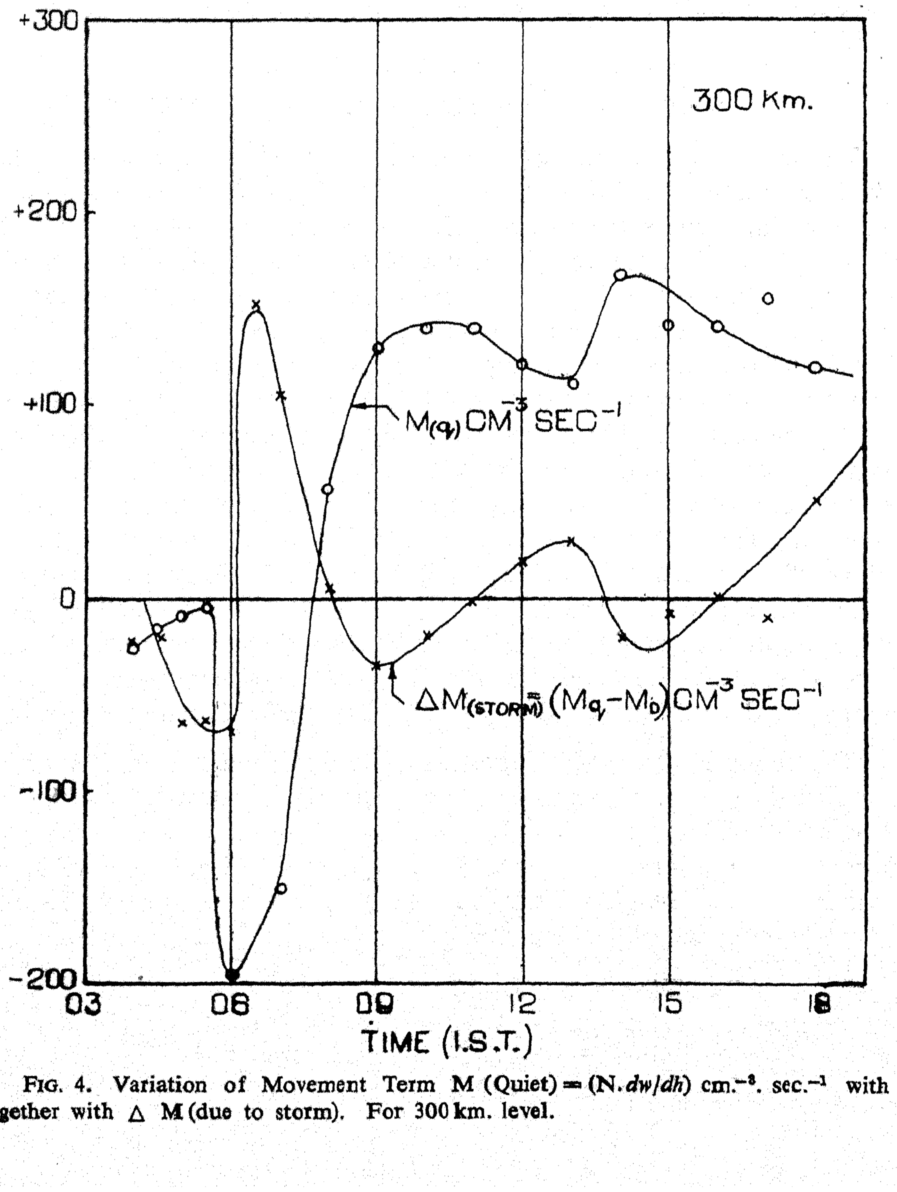

FIG. 4. Variation of Movement Term M (Quiet) = (N.dw/dh) cm.$^{-3}$. sec.$^{-1}$ with time together with $\triangle$ M (due to storm). For 300 km. level.

that normal quiet day N_mF2 characteristics were substantially modified due to the existence of additional movements on disturbed days; such movements also eliminated the midday decrease. According to Martyn (1953), the additional movement term during a storm is due to the electrostatic (polarisation) field created by currents set up in the auroral zone by incoming solar particles. This polarisation field spreads all over the earth during a storm and sets up currents in the F2 region; these currents, in turn, distort the region to a considerable extent through interaction with the earth's main magnetic field and the normal N_mF2 variations of a quiet day are, therefore, modified.

6. SOLAR CYCLE CHANGES IN DIURNAL ASYMMETRY

The variations in maximum electron densities of F2 layer at Kodaikanal have been obtained utilizing six years' data (1952–58) covering both a sunspot minimum and a maximum. The ratios $P_m = (f_1 - f_2)/f_2$ and $P_a = (f_3 - f_2)/f_2$ which represent the extent of the midday distortion in N_mF2 with respect to the morning and afternoon peaks respectively were computed from f_1, f_2 and f_3 which are the morning, midday and afternoon peak values of critical frequencies. From Fig. 5, where these ratios have been plotted as functions of sunspot number, it will be seen that P_m increases gradually and P_a decreases rapidly with increasing solar activity. A shift in the phases of vertical tide during the solar cycle (Hirono and Maeda, 1954) is perhaps responsible for these characteristics. This shift in phase is due to change in phase of diurnal variation of 'effective' conductivity, in the pattern of ion production and in the pattern of atmospheric oscillation due to irregular heating. The gradual increase in the morning peak with solar activity appears to be due to the lower heights of the layer in the forenoon hours when drift characteristics are likely to be of comparatively smaller importance than the production and loss terms of the continuity equation.

The ratios P_m/P_a which represent the extent of the diurnal asymmetry are plotted in Fig. 6 against sunspot number, separately for the three seasons. It will be seen that for all parts of the year, the morning peak approaches the afternoon peak and equals it at a definite value of sunspot number. This value, given below separately for the three seasons, is smallest in winter and largest in summer.

R_z (Winter) ≈ 89

R_z (Equinoxes) ≈ 142

R_z (Summer) ≈ 173

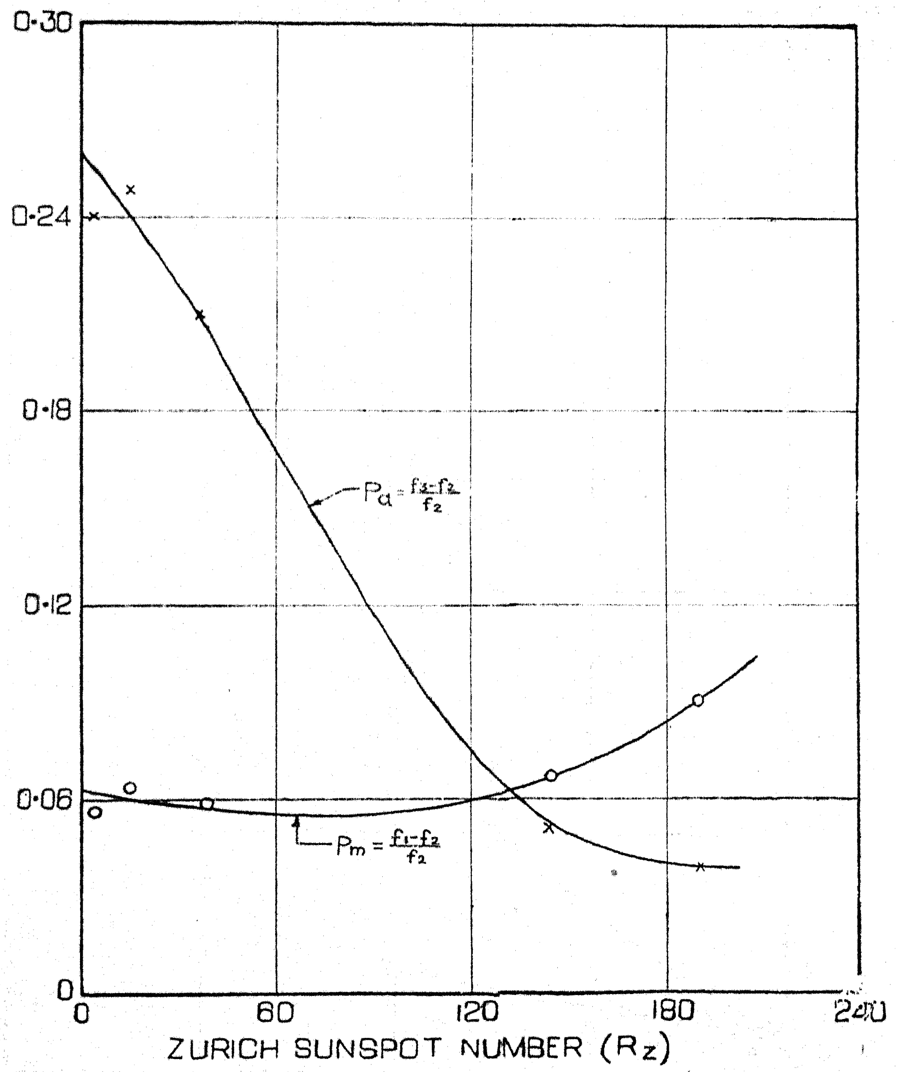

FIG. 5. Comparative Behaviour of Morning and Afternoon Peaks with Sunspot Activity.

At an equatorial station like Kodaikanal where the F2 region is lowest in winter months and highest in summer, the magnitude of drift effects in winter will be comparatively smaller than in summer because of the larger contribution from the electron production and loss terms of the continuity equation during the winter. As the diurnal asymmetry arises from vertical transport of ionization, the magnitudes of the drifts are of different orders during winter and summer. The large differences in the values of R_z for which the morning and afternoon peak ionization are equal are, therefore understandable.

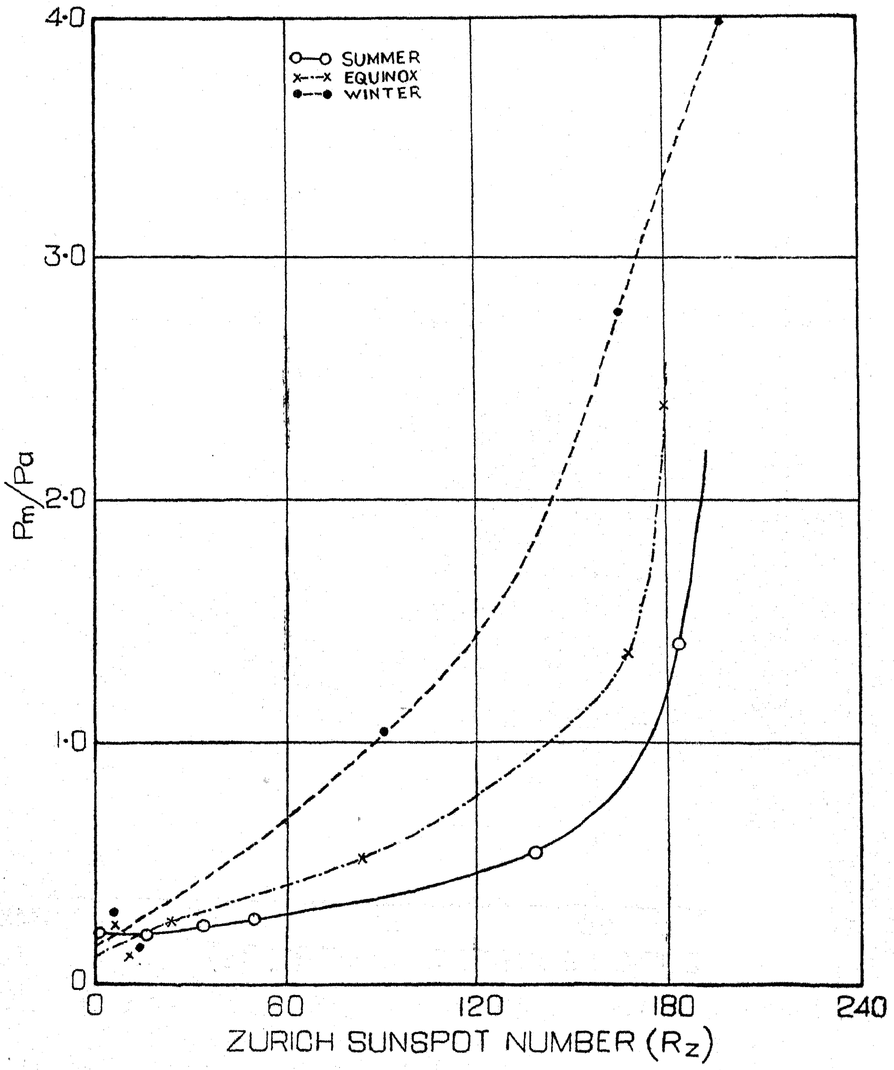

FIG. 6. Variation of P_m/P_a with Sunspot Activity for the Three Seasons.

7. THE VARIATION OF MIDDAY ANOMALY WITH MAGNETIC DIP

In order to obtain the variation in the noon anomaly with magnetic dip and in the extent of the anomalous belt from a sunspot minimum to a maximum, ionospheric data from several low latitude stations with their magnetic dip between 19°·0 N and 28°·5 S listed in Table IV, for the years

1954 and 1957 were examined. The plots of foF2 averaged over a year indicated that for the year 1954 it was possible to identify both the morning and the afternoon peaks only for stations which were located within a dip zone from 14°·0 N to 16°·0 S. For the year 1957, however, it was noticed that these peaks could be identified for stations substantially farther from the dip equator. The three frequencies f_1, f_2 and f_3 were read from the foF2 plots for each one of the stations and the values were utilised to obtain the magnitudes of the midday distortion, represented by the ratio P_m/P_a. The ratios are plotted against the respective dip of the station in Figs. 7 (*b*) and 7 (*c*) for the years 1954 and 1957 respectively.

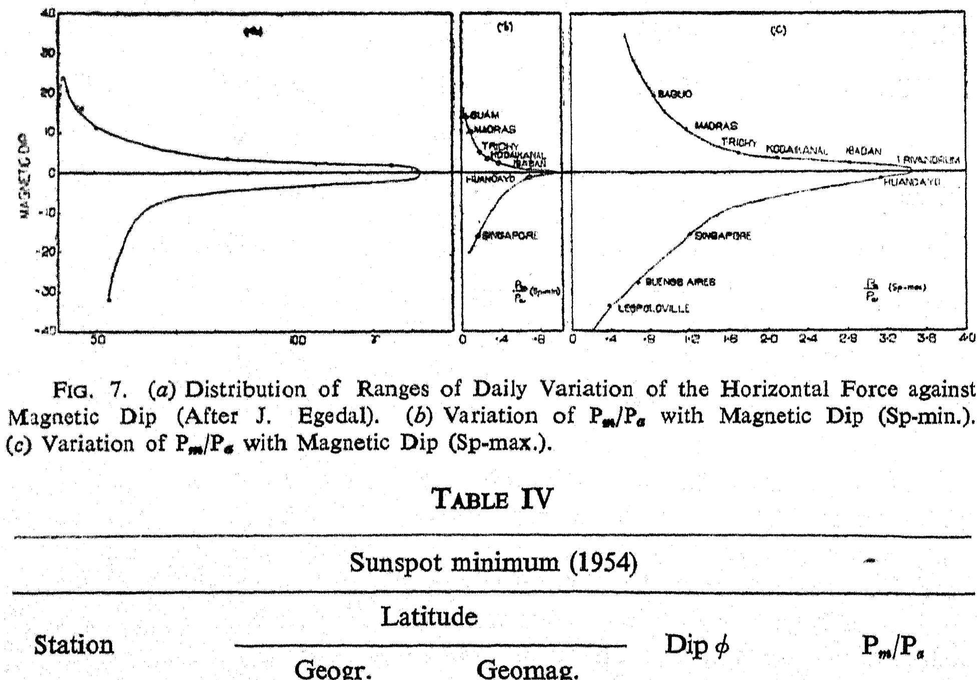

FIG. 7. (*a*) Distribution of Ranges of Daily Variation of the Horizontal Force against Magnetic Dip (After J. Egedal). (*b*) Variation of P_m/P_a with Magnetic Dip (Sp-min.). (*c*) Variation of P_m/P_a with Magnetic Dip (Sp-max.).

TABLE IV

Sunspot minimum (1954)				
Station	Latitude		Dip ϕ	P_m/P_a
	Geogr.	Geomag.		
	(°)	(°)	(°)	
Guam	13·5 N	3·9 N	14·0 N	0·06
Madras	13·0 N	3·1 N	10·5 N	0·10
Trichy	10·5 N	1·3 N	4·8 N	0·18
Kodaikanal	10·2 N	0·6 N	3·5 N	0·26
Ibadan	7·2 N	10·4 N	2·5 N	0·37
Huancayo	12·0 S	0·6 S	1·0 S	0·69
Singapore	1·2 N	10·1 S	16·0 S	0·18

TABLE IV—(*Contd.*)

Sunspot maximum (1957)

Station	Latitude		Dip ϕ	P_m/P_a
	Geogr.	Geomag.		
	(°)	(°)	(°)	
Baguio ..	16·2 N	7·0 N	19·0 N	0·83
Madras ..	13·0 N	3·1 N	10·5 N	1·18
Trichy ..	10·5 N	1·3 N	4·8 N	1·67
Kodaikanal ..	10·2 N	0·6 N	3·5 N	2·08
Ibadan ..	7·2 N	10·4 N	2·5 N	2·81
Trivandrum ..	8·4 N	0·5 S	0	3·43
Huancayo ..	12·0 S	0·6 S	1·0 S	3·18
Singapore ..	1·2 N	10·1 S	16·0 S	1·21
Buenos Aires ..	34·5 S	23·1 S	28·5 S	0·71
Leopoldville ..	4·3 S	3·1 S	33·5 S	0·39

It will be seen that the magnitude of the ratio P_m/P_a is largest along 'zero' dip and that it further increases rapidly with solar activity from about unity at sunspot minimum to about 3·4 at sunspot maximum. The variations also indicate that the distortion anomaly belt is much wider during periods of high solar activity than those of low activity. With increased solar activity, geomagnetic distortion appears at stations with comparatively large dip like Baguio (Dip: 19° N), Beunos Aires (Dip: 28°·5 S) and Leopoldville (Dip: 33°·5 S). This indicates that in spite of the downward movement of ionization due to vertical diffusion (Ferraro, 1945) the 'effective' conductivity becomes, during high solar activity, adequate for the occurrence of drifts and consequent divergence of ionization around noon at these stations. Recently, Appleton (1960), in his plots of equatorial foF2 data for 1958 (a year of sunspot maximum) with magnetic latitude for different hours of the day, found that the equatorial 'trough', centred on the magnetic equator, is more extensively exhibited at Sp-max. than at Sp-min. From curves (*b*) and (*c*) of Fig. 7 we have obtained values of dip at Sp-min. (1954) and close to Sp-max. (1957) corresponding to P_m/P_a ratios between 0·2 and 0·8 (Table V). It will be seen that from the point of view of F2 layer anomaly, the extent of the belt during Sp-max. covered stations whose magnitudes of dip were greater by about 25°.

TABLE V

P_m/P_a	1954	1957	Extension of geomagnetic anomalous belt Dip ϕ
	Dip ϕ	Dip ϕ	
	(°)	(°)	(°)
0·2	14·5	40·0	25·5
0·4	6·0	33·0	27·0
0·6	3·0	29·0	26·0
0·8	0·8	24·0	23·2
		Mean	25·4

8. DISTORTION ANOMALY AND EQUATORIAL ELECTROJET

In Fig. 7 *a*, Egedal's (1947) curve of the variation in daily range in horizontal force with dip is reproduced along with the variation of P_m/P_a. A remarkable similarity of the three curves is obvious. Similar variations with dip of intense sporadic E in the vicinity of magnetic equator was reported by Matsushita (1952). It appears that the ratio P_m/P_a which gives a measure of vertical divergence of N_mF2 around noon may be due to the effect of drifts associated with Hall polarisation field related to the intense eastward current—the so-called electrojet. The seasonal variation of this ratio appears to arise from possible movement of electrojet itself like that of the Sq. current system while the solar cycle variation of the ratio appears to be due to enhanced ionospheric conductivity resulting from increased solar activity to which the electrojet is sensitive.

9. ACKNOWLEDGEMENT

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