CHAPTER - IV
STUDIES OF THE DISTURBED F-REGION

4.1 Introduction

F-region disturbances manifest themselves differently at the different latitudes of the earth as has been shown by earlier workers. Most references of their work have been given in Ch. 3. Here the disturbance effects are shown by choosing an equatorial station and an example each in the northern and southern hemispheres, of a low-latitude, a mid-latitude, and a high-latitude station. Such a network of stations is selected for the East and the West zone separately so that longitudinal differences if any, are also shown.

It is known that the equatorial anomaly in \( f_{0} F_2 \) occurs between \( \pm 35^\circ \) magnetic dip and high latitude phenomena like aurora occur around \( 67^\circ \) dip. Hence in the present analysis the latitude zone of a station is classified on the basis of its dip thus

<table>
<thead>
<tr>
<th>LATITUDE ZONE</th>
<th>RANGE OF DIP ANGLE</th>
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<tbody>
<tr>
<td>Equatorial</td>
<td>0° - 10°</td>
</tr>
<tr>
<td>Low-Latitude</td>
<td>10° - 35°</td>
</tr>
<tr>
<td>Mid-Latitude</td>
<td>35° - 70°</td>
</tr>
<tr>
<td>High-Latitude</td>
<td>70° and above</td>
</tr>
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Disturbance storm-time variations of $f_0F_2$ $D_{st}$ ($f_0F_2$)

These studies use the method of analysis described in Section 3.1(a) of Chapter III. The time of storm commencement is taken as zero-time, and the ratios are computed for the period 4 hours before the commencement, to 72 hours after commencement of the storm. The period considered is IGY-IGC (1957-1959) and the total number of storms considered is over 100 for each station. Of these, about 40 storms occurred in the equinoxes, and about 30 each during the solstices. The storms are all strong ones with Ap exceeding 100 on any one of the 3 days following the storm.

4.2 Seasonal $D_{st}$ ($f_0F_2$) variations at equatorial, low, mid, and high latitudes.

Equatorial stations:

Fig. 4.1 (Pg. 80 (a) shows the seasonal behaviour of $D_{st}$ ($f_0F_2$) at Huancayo in the West, and Trivandrum in the East zone. The ordinate is the average ratio $f_0F_2$ storm/$f_0F_2$ for all the storms and the abscissa is the storm-time in hours. Some longitudinal differences in the variations are seen. The Annual variation is a 'positive' one in both cases (i.e. the ratio exceeds 1.00, implying disturbed $f_0F_2$ values are larger than the median $f_0F_2$). While the general pattern is the same, the recovery time seems longer for Trivandrum, the ratio not having returned to 1.00 even 72 hours after storm-commencement. In the
E-months too, the variations at both stations are positive; but at Huancayo while ratios on the 3rd day are of small magnitude, at Trivandrum they are still fairly large. In the D-months, Huancayo shows some 'negative' phase (i.e. the ratio $f_{oF_2}/F_{oF_2}$ is less than 1.00, implying that disturbed $f_{oF_2}$ values are less than the median $f_{oF_2}$). At Trivandrum there is a completely positive phase. In the J-months, the variation at Huancayo is completely positive, in keeping with its winter conditions while Trivandrum experiences negative phase in its summer conditions. It may be noted that though both these stations are equatorial from the point of view of magnetic dip, Huancayo has a geographic latitude of 12°S and is experiencing summer while Trivandrum with a geographic latitude of 10°N is having winter. The differing $D_{st}$ ($f_{oF_2}$) variations at these two stations may thus be a seasonal effect. The ratio-fluctuations at Trivandrum seem to be more than those at Huancayo.

(2) Low-latitude stations

We now compare Talara with a dip of 13°N and Tucuman with a dip of 22°S, both lying in the West zone, with Baguio (dip 19°N) and Singapore (dip 17°S) both lying in the East zone (Fig. 4,2) (Pg. 81 (a)). Such depiction also enables us to sort out asymmetry between the northern and southern hemisphere if any exists.
FIG 4.2
The annual and E-month variations at Talara and Bagiuo are both positive. In the D-months too, the variations at both stations are mainly positive. In the J-months more of a negative phase exists but both stations have some positive phase on the second day of the storm. The general behaviour at the two stations is not vastly different.

Now consider the southern hemisphere stations Tucuman, and Singapore. The Annual variations are negative on the first day, but positive on the second and third days. The E-months show a chiefly positive variation at Singapore, but at Tucuman, it is negative. In the D-months, the variation at Singapore is uncertain, but at Tucuman it is mostly negative. In the J-months, Tucuman shows a positive trend, whereas Singapore shows a positive trend only on the second day. A good amount of longitudinal difference is seen between these two stations, though geographically they experience the same seasons.

Comparing Baguio and Singapore in the East zone for north-south asymmetry, the Annual and E-month variations are alike at both stations. To obtain similar seasonal conditions, the D-month behaviour at Baguio has to be compared with the J-month behaviour at Singapore when 'winter' prevails. Despite the almost equal dip values of the stations, the winter $D_{st}$ ($f_0P_2$) behaviour is by no means alike, there being practically no negative phase at
Baguio, but a considerable amount of negative phase at Singapore. For local summer, the J-months at Baguio would compare with the D-months at Singapore. Here the variation of $D_{st} (f_0 F_2)$ differs only in the first few hours of the storm.

In the West zone, even the Annual and E-month behaviour at Talara and Tucuman differ, but this could be because of the fairly different dip values of the two stations.

(3) Mid-latitude stations

We now compare Puerto Rico (dip 51°N) and Port Stanley (dip 46°S) in the West zone with Akita (dip 53°N) and Townsville (dip 48°S) in the East zone (fig. 4.3)

It is interesting to compare the pair of mid-latitude stations, Puerto Rico (dip 51°N) and Akita (dip 53°N). The prominent feature about these is the small $D_{st} (f_0 F_2)$ variation shown in the Annual curve for both stations, the variation on the whole being a negative one. The E-month variation is clearly negative at Akita, and a similar type of variation is seen at Puerto Rico. In the D-months, both show a clear positive variation, while in the J-months both show a clear negative variation. Hardly any asymmetry in storm-behaviour exists between the two stations. It is
interesting to speculate whether the small Annual $D_{st} (f_{F_2})$ variations have anything to do with disturbed-time current foci locations in the two zones.

Comparing Port Stanley and Townsville, at Port Stanley the annual variation is clearly positive during the first 48 hours but at Townsville the variation is uncertain. In the E-months, the variation at Port Stanley is definitely positive, but at Townsville, it is clearly negative. In the D-months, the variation is negative at Stanley, and on the whole negative at Townsville. In the J-months Stanley shows a vastly positive variation with a peak value of 1.25; the variation at Townsville is less positive with pronounced 24 hour ratio peaks. Thus in spite of the similar dips of the two stations, a good amount of longitudinal asymmetry exists in the southern hemisphere.

Now we compare Puerto Rico and Port Stanley in the West zone for north-south asymmetry. While the Annual and E-month variations at Puerto Rico are negative, the variations at Stanley are decidedly positive. Local winter requires the comparison of the D-months at Puerto Rico with the J-months at Stanley; both show positive variations, but there is a slight difference in the pattern. For local summer conditions one compares the J-months at Puerto Rico with the D-months at Stanley. Both show a negative variation. There is not much north-south asymmetry in the solstices but the
asymmetry is marked in the E-months in the West zone.

We now compare Akita and Townsville in the East zone. The Annual and E-month variations are less negative at Townsville than at Akita. Local winter (D-months for Akita and J-months at Townsville) variations are positive at both places but a strong, 24-hour component is seen at Townsville. In local summer while the variation is a clear negative during the J-months at Akita, it is not so clear at Townsville in the D-months. Some amount of north-south asymmetry does exist in the East zone too.

(4) **High-latitude stations**

We now compare Resolute Bay (dip 89°N) and Pole Station (dip 75°S) in the West zone with Tixie Bay (dip 83°N) and Scott Base (dip 83°S) in the East zone (Fig. 4.4) (Pg. 85 (a)).

The outstanding point about the $D_{st}$ ($F_2$) variations at all these stations is that they exhibit large and rapid fluctuations. This clearly has something to do with high-latitude conditions. The later models of the magnetosphere believe that the geomagnetic field lines at high latitudes are directly connected to the interplanetary magnetic field lines (Dungey 1961) and charged particles emitted from the sun during disturbed conditions have easy and direct access to these regions of the earth. These sharp fluctuations in
(f₀F₂) behaviour may therefore be connected with these charged particles and the secondary ionisation they cause, each peak corresponding to a fresh quantum of ionisation. The overall behaviour of (f₀F₂) in spite of these peaks is a decrease during disturbed conditions. This may be due firstly, to the motion of field lines blowing ionospheric plasma into the tail of the magnetosphere (Banks and Holzer 1968) and secondly, to the enhanced recombination rates due to enhanced temperatures by corpuscular frictional heating and Joule current heating. These aspects are dealt with in detail in Chapter 7.

The overall variations of D₀ (f₀F₂) at Resolute Bay and Tixie Bay compare closely in all seasons. The same may be said of Pole Station and Scott Base. Very little longitudinal variation exists at high latitudes. North-south asymmetry too does not exist greatly in either zone when one compares similar seasons (i.e. D-months in the north with J-months in the south and vice-versa).

4.3 North - south Asymmetry in storm-time variation of f₀F₂

From this study of D₀ (f₀F₂) variations at equatorial, low-latitude, mid-latitude, and high-latitude stations, it seems as though north-south asymmetry in seasonal storm-time behaviour is most marked for mid-latitude, and little asymmetry exists for the other latitude zones.
A good deal of longitudinal difference does exist but this will be dealt with in Chapter 5. Some studies of ionospheric $F_2$ behaviour at conjugate places in low latitudes have been made by Matsushita (1968).

Here a detailed study of north-south storm-time asymmetry at middle latitudes was made by choosing suitable pairs of northern and southern stations in different longitude zones for low and high sunspot years. The behaviour for the low sunspot period (1951-1956) was studied for the Asian, African, American and Pacific zones, and is described in Paper (1) which follows. The high sunspot behaviour (1957-1961) was studied by using seasonal classification too, and the results are described in Paper (2).

The above-mentioned studies suggest that (1) North-south asymmetry is most marked in the American and Pacific mid-latitudes, and is less in the Asian and African zones. (2) In the American zone, the asymmetry is most prominent in the equinoxes; in the Pacific zone it is in local summer, while in the Asian zone it is in local winter.

(Papers 1 and 2 follow overleaf)
SHORT PAPER

North-South asymmetry in storm time variation of $f_0F_2$

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(Received 2 October 1967)

Abstract—The study of Dst ($f_0F_2$) variations at equatorial and subtropical stations at different longitude zones for 1951–1956, show that at equatorial stations of any in the zones the variation indicates an increase of $f_0F_2$ during the main phase. The northern subtropical stations in any of the zones indicate a decrease of $f_0F_2$ during the main phase. The southern subtropical stations show decreased $f_0F_2$ for Asian and African zones but at American and Pacific zones an increase of $f_0F_2$ during main phase of the storm is noted. It has been shown by earlier workers that the critical frequency of the $F_2$-layer, $f_0F_2$, at middle latitudes is reduced during the main phase of geomagnetic storms while at low latitudes there is an increase of $f_0F_2$ in the corresponding period (APPLETON and INGRAM, 1935; BERKNER and SEATON, 1940; MARTYN, 1953; and SKINNER and WRIGHT, 1955). Averaging over a large number of stations, MATSUSHITA (1959) found that at middle latitudes, storm time variation of $f_0F_2$ [i.e. Dst ($f_0F_2$)] is characterised by an initial increase followed by much larger decrease while at equatorial regions the phase of variation is reversed. Comparing the equatorial anomaly of the $F_2$-region of the ionosphere on quiet and disturbed days during the equinoxes of 1952, RASTOGI (1966) found that in the north subtropical region, $f_0F_2$ was lower on disturbed than on quiet days, but in south subtropical region, $f_0F_2$ was slightly greater on disturbed than on quiet days, suggesting some N–S asymmetry in the ionospheric storms.

The present paper describes the storm-time variation in $f_0F_2$ at stations near the magnetic equator, and at northern and southern subtropical latitudes along approximately the same longitudes. The longitude zones are (1) Asian zone where the geographic and magnetic equators are almost parallel to each other (2) African zone where the geomagnetic and magnetic equators are most separated (3) American zone where the magnetic equator is shifted maximum southward and (4) Pacific zone where the magnetic equator crosses the geographic equator. In each of the zones except the Pacific zone there existed some equatorial as well as northern and southern subtropical stations during 1951–1956. For the Asian zone the data of the equatorial station Nhatrang (dip. 6°N) for the period January 1951–December 1955 were combined with the data at Kodaikanal (dip. 4°N) for the period (January 1956–December 1956). The behaviour of $F_2$-region at these two stations has been found to be similar. As usual, the zero hour was taken as the hour nearest to the time of sudden commencement of a geomagnetic storm. Twenty-two strong SC storms were chosen in which in the succeeding 72 hr the maximum value of $A_s$ index was greater than 50. The same storms were used for all the stations.

It has been shown by earlier workers that the critical frequency of the $F_2$-layer, $f_0F_2$, at middle latitudes is reduced during the main phase of geomagnetic storms while at low latitudes there is an increase of $f_0F_2$ in the corresponding period (APPLETON and INGRAM, 1935; BERKNER and SEATON, 1940; MARTYN, 1953; and SKINNER and WRIGHT, 1955). Averaging over a large number of stations, MATSUSHITA (1959) found that at middle latitudes, storm time variation of $f_0F_2$ [i.e. Dst ($f_0F_2$)] is characterised by an initial increase followed by much larger decrease while at equatorial regions the phase of variation is reversed. Comparing the equatorial anomaly of the $F_2$-region of the ionosphere on quiet and disturbed days during the equinoxes of 1952, RASTOGI (1966) found that in the north subtropical region, $f_0F_2$ was lower on disturbed than on quiet days, but in south subtropical region, $f_0F_2$ was slightly greater on disturbed than on quiet days, suggesting some N–S asymmetry in the ionospheric storms.

The present paper describes the storm-time variation in $f_0F_2$ at stations near the magnetic equator, and at northern and southern subtropical latitudes along approximately the same longitudes. The longitude zones are (1) Asian zone where the geographic and magnetic equators are almost parallel to each other (2) African zone where the geomagnetic and magnetic equators are most separated (3) American zone where the magnetic equator is shifted maximum southward and (4) Pacific zone where the magnetic equator crosses the geographic equator. In each of the zones except the Pacific zone there existed some equatorial as well as northern and southern subtropical stations during 1951–1956. For the Asian zone the data of the equatorial station Nhatrang (dip. 6°N) for the period January 1951–December 1955 were combined with the data at Kodaikanal (dip. 4°N) for the period (January 1956–December 1956). The behaviour of $F_2$-region at these two stations has been found to be similar. As usual, the zero hour was taken as the hour nearest to the time of sudden commencement of a geomagnetic storm. Twenty-two strong SC storms were chosen in which in the succeeding 72 hr the maximum value of $A_s$ index was greater than 50. The same storms were used for all the stations.
Fig. 1. Storm-time variation of $f_0F2$ at north subtropical, equatorial and south subtropical stations in the Asian zone.

Fig. 2. Storm-time variation of $f_0F2$ at north subtropical, equatorial and south subtropical stations in the African zone.

Fig. 3. Storm-time variation of $f_0F2$ at north subtropical, equatorial and south subtropical stations in the American zone.

Fig. 4. Storm-time variation of $f_0F2$ at north subtropical, equatorial and south subtropical stations in the Pacific zone.
Figures 1, 2, 3 and 4 show the average storm-time variations at groups of stations in the Asian, African, American and Pacific zones respectively. The solid lines are the 5-hr running means of $f_0F2(f0F2)$ v. storm-time.

Referring to Fig. 1 it is seen that $\text{Dst}(f_0F2)$ at the equatorial station Kodaikanal-Nhatrang shows a small decrease followed by a large and prominent increase of $f_0F2$ on the second and third day of the storm. At the north and south subtropical stations Kokubunji and Watheroo, Dst ($f_0F2$) consists of a small initial rise followed by main decrease of $f_0F2$. Similar behaviour of $f_0F2$ is seen at equatorial and subtropical stations in the African zone (refer Fig. 2). These results are in conformity with the earlier results.

Referring to Fig. 3 for the stations in the American zone, one finds that the equatorial station Huancayo shows nearly normal behaviour. The $f_0F2$ at the northern subtropic station, Puerto Rico, shows an initial rise followed by a decrease of $f_0F2$. However at the southern station Buenos Aires the Dst variation is distinctly different showing increased $f_0F2$ during the 3 days following the SC storms. This is rather unexpected for a station near the region of daytime $f_0F2$ maximum.

Referring to $\text{Dst}(f_0F2)$ at stations in the Pacific zone (Fig. 4), the northern subtropical station Maui has a negative type of variation but at the southern station Rarotonga, $f_0F2$ during geomagnetic storms is greater than the normal $f_0F2$ value for the corresponding hours, somewhat similar to Buenos Aires. It may be noted that the geographic as well as the magnetic latitudes of the two stations Maui and Rarotonga are almost identical except that they are in opposite hemispheres.

MARTYN (1953) had shown that the storm time variation of $f_0F2$ depends upon the local time of the beginning of the storm. The present analysis refers to the same storms at pairs of stations almost along the same longitude and therefore the local times of the storms are identical. The different behaviour of the Dst ($f_0F2$) at the northern and southern stations cannot be attributed to solar time effect.

RASTOGI and RAJARAM (1965) have shown that in the December solstitial months during IGY/IGC period the disturbance daily variation of $f_0F2$ at the equatorial stations in the American zone was quite different from that at Ibadan or at Kodaikanal. These abnormalities seem to be related to the low value of the geomagnetic field and its North–South asymmetry in the American zone. A detailed analysis of the ionospheric storm effects at southern latitude stations is being undertaken to study this abnormal behaviour in relation to the morphology of the geomagnetic field.

Acknowledgement—The authors are pleased to thank Professor K. R. Ramanathan for stimulating discussions during the course of work.

References

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Journal/Reference</th>
</tr>
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<tbody>
<tr>
<td>Matsushita S.</td>
<td>1959</td>
<td>J. Geophys. Res. 64, 305.</td>
</tr>
</tbody>
</table>
North–South asymmetry of ionospheric storms—dependence on longitude and season

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(Received 20 May 1969)

Abstract—The study of ionospheric storms at pairs of north and south mid-latitude stations in different longitude zones, individually for each season, has shown asymmetry in their behaviour, most significantly in the Pacific zone, to some extent in the Asian and American zones. The decrease of $f_0 F_2$ which is found to occur during geomagnetic storms in Summer months is conspicuously absent at Rarotonga. This suggests that ionospheric storm variations are greatly affected by horizontal and vertical movements of ionisation, which are controlled by the asymmetric magnetic field of the Earth.

The earliest ionospheric observations showed that $F_2$-layer critical frequencies ($f_0 F_2$) were greatly affected by magnetic disturbances (APPLETON and INGRAM, 1935; BERKENH and SRATON, 1940). Following the method of analysis used by Moos and Chapman for studying magnetic storms, MARTYN (1963) studied both the disturbance diurnal (SD) and storm-time ($D_s t$) variations of ionospheric parameters at a few stations. MATSUHITA (1959) studied $D_s t$ variations at a large number of stations, and suggested that the $D_s t$ variation is similar at stations having comparable dipole latitudes N or S. The ratio of storm-time $f_0 F_2$ at any hour to the median $f_0 F_2$ for the same hour ($f_0 F_2/F_2$), for low-latitude stations is greater than unity for any of the seasons, i.e. the storms increase the value of $f_0 F_2$ and are called positive storms. At high latitudes the ratio is less than unity for any of the seasons, i.e. the storms decrease the value of $f_0 F_2$ and are called negative type. At mid-latitudes, the effect is more of equatorial type in Winter, and of high latitude type in Summer. RASTOGI (1962) showed that the character of $D_s (f_0 F_2)$ variation is controlled by the dip, and not by the dipole latitude of the station.

RAJARAM and RASTOGI (1968) found significant asymmetry in $D_s (f_0 F_2)$ variations at pairs of ionospheric stations of comparable dip angle for certain longitude zones. The results were based on the annual average $D_s t$ variations for the low sunspot period, 1951–1956. The present work describes $D_s (f_0 F_2)$ variations at pairs of stations in the N and S in different longitude zones for each of the seasons of the high sunspot period, 1957–61. Only strong magnetic storms of this period in which $A_p > 50$ on any of the 3 succeeding days were used. A total of about 100 storms have been studied for each station, which means an average of about 30 storms for each
season, the storms being the same, as far as availability of data allowed. The geographic coordinates and the magnetic dip of the stations studied in this article are given in Table 1.

Table 1. Geographic coordinates and the magnetic dips of stations studied

<table>
<thead>
<tr>
<th>Station</th>
<th>Geographic Lat.</th>
<th>Geographic Long.</th>
<th>Dip angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akita</td>
<td>39°N</td>
<td>140°E</td>
<td>53°N</td>
</tr>
<tr>
<td>Brisbane</td>
<td>27°S</td>
<td>158°E</td>
<td>57°N</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>18°N</td>
<td>67°W</td>
<td>51°N</td>
</tr>
<tr>
<td>Port Stanley</td>
<td>51°S</td>
<td>57°W</td>
<td>48°S</td>
</tr>
<tr>
<td>Buenos Aires</td>
<td>34°S</td>
<td>58°W</td>
<td>31°S</td>
</tr>
<tr>
<td>Maui</td>
<td>20°N</td>
<td>160°W</td>
<td>40°N</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>21°S</td>
<td>159°W</td>
<td>40°S</td>
</tr>
</tbody>
</table>

Figure 1 shows $D_n$ variations for pairs of stations in the Asian zone, namely Akita (Dip 53°N) and Brisbane (Dip 57°S). The annual average $D_n$ variations at either of the stations is of negative type, the change being larger at Brisbane than at Akita. During local Summer and equinoxes, the variations are almost identical at both the places, and definitely of the negative type. During local Winter months, $D_n$ is definitely positive at Akita, and rather uncertain at Brisbane indicating if at all some positivity; there are significantly large 24-hr oscillations in the $D_n$ variation at Brisbane.

![Fig. 1. Storm-time variation of $f_0F_2$ for each season at N and S sub-tropical stations of Asian zone.](image-url)
Figure 2 shows \( D_{st} \) variations at three stations in the American zone, namely, Puerto Rico (Dip 51°N), Port Stanley (Dip 48°S) and Buenos Aires (Dip 31°S). The annual \( D_{st} \) variation at Puerto Rico shows a very small positive at the beginning of the storm, followed by mainly negative phase. The annual \( D_{st} \) variation at Port Stanley shows a small negative, followed by a positive, ending with a slight negative phase. The annual average \( D_{st} \) variation at Buenos Aires is positive on the first day of the storm, and slightly negative on the second day, somewhat similar to that at Port Stanley. During local Summer, the \( D_{st} \) variation at all the three stations is of similar nature, the change being significantly smaller at Buenos Aires, than at the other two stations. During equinoxes, the variation at Puerto Rico is negative, while at Port Stanley, it is positive around 24 hr storm-time, the changes at Buenos Aires being small and uncertain. During local Winter, \( D_{st} \) is positive at any of the three stations, although the effects are stronger at Port Stanley and Buenos Aires than at Puerto Rico.
It is to be noted that $D_{st}$ variation during the equinoxes at either the N or S station in the Asian zone is strongly negative in character, almost of the same magnitude as in the Summer months. Consequently, the annual average $D_{st}$ variation in the Asian zone is negative. In the American zone, $D_{st}$ in the equinoxes is negative at Puerto Rico, slightly positive at Port Stanley, and almost negligible at Buenos Aires. This makes the annual average $D_{st}$ variation different in the north and south stations in this zone.

Figure 3 shows $D_{st}(f_0 F_2)$ variations at pairs of stations in the Pacific zone, namely Maui (Dip 40°N) and Rarotonga (Dip 40°S). The annual average $D_{st}(f_0 F_2)$ variation is generally negative at Maui, and positive at Rarotonga. At Maui, the $D_{st}$ variation is distinctly negative during local Summer and positive during local Winter. At Rarotonga, $D_{st}$ is distinctly positive during local Winter, but tends to be positive even during local Summer. During equinoxes, $D_{st}$ variation at Rarotonga is small, being slightly negative on the first, and slightly positive on the second day of the storm, while at Maui, variations have a large 24-hr component over a smooth variation which would be similar to that at Rarotonga. Thus during local Summer months, the $D_{st}$ variations at the two stations are completely dissimilar. It is to be noted that this pair of stations is a conjugate pair, and is located on the same longitude zone.
Instead of comparing $D_{st}$ variations for N and S stations for the same local season, one can compare the variations during the same groups of months. This has the advantage that the same magnetic disturbances are involved for the two stations. In Fig. 4 are shown $D_{st}$ variations for the same month-groups at pairs of N–S stations in all the three zones; full lines represent the northern stations, and the dotted lines the southern stations. Since during the same months, the local seasons are opposite at the N and S stations, the $D_{st}$ variations at the two stations should be opposite in nature, if N–S asymmetry is absent.

Referring to the variations during the $D$-months at N–S stations, one finds that the curves are opposite in character in the Asian and American zones and not so in the Pacific zone. Examining the smaller fluctuations, one notices that up to about 36 hr these are opposite in character at the Asian and American zones. The smaller fluctuations are almost in phase at the two stations during 36–72 hr in Asian and American zones, and during the entire 0–72 hr in the Pacific zone.
During the equinoxes, one finds that the variations are almost similar for the two stations both for the general behaviour as well as for the shorter fluctuations. For the American zone the variations seem to be opposite in character for the first 6 hr. The magnitude of $D_t$ variations is very small at American and Pacific stations, and large (negative type) at Asian stations.

During the $J$-months the variations are in general opposite in nature at the two stations in the American and Pacific zones, while in the Asian zone, there is no distinct relationship between the two.

It is suggested that the effect of magnetic storms at middle and high latitudes is controlled by both horizontal and vertical movements and other dynamical processes in the $F$-region which are not symmetric in the N and S hemispheres due to the asymmetry of the Earth’s magnetic field and which seem to depend a good deal on the season. Further studies of this asymmetry are being continued.

Acknowledgements—The authors are grateful to Professor K. R. Ramanathan for stimulating discussions and the authorities of the respective observatories and WDC ‘A’ at Boulder, for the data used in this study.

References

MATSUSHITA S. 1959 J. geophys. Res. 64, 305.
Explanation of North-South asymmetry in \( D_{st}(f_{o}F_{2}) \)

This asymmetry in storm-time \( f_{o}F_{2} \) variation could be due to the uneven configuration of the earth's geomagnetic field described in detail in Chapter 1.

Surface anomalies are irregularities in the field caused by uneven deposits of ferromagnetic materials in the thin crust of the earth. These exist only in localised areas (Handbook of Geophysics 1961). One such anomalous area is the South American zone, with its very low field intensity of only 0.25 gauss at the centre. In fact there is a girdle of low field intensity over a large area extending from the South Pacific, through South America to South Africa.

This low field intensity will have considerable effect on the mirror points of charged particles drifting in the inner radiation belt. As described in Section 1.9, the mirror altitudes of the particles are considerably lowered as they drift towards the longitude of this low-field anomaly region. Those whose mirror altitudes come down low enough are lost in the atmosphere (Cladis and Dossier 1961; Williams and Kohl 1965; Imhof and Smith 1965; Paulikas and Froden 1964; Gledhill and Van Rooyen 1962; Sharp et al., 1966). It may be the secondary ionisation caused by these particles which is observed as the enhanced storm-time \( F_2 \) ionisation in the South Pacific and South American temperate latitudes.
Satellite studies have shown the enhanced concentration of ionisation over such anomalous zones. Knudsen and Sharp (1968) found a region of enhanced electron concentration at F$_2$ peak heights from a study of flux distribution of 10 eV electrons measured from the satellite 1962 A1. They carried out another flight in 1963 and found that besides an anomalous F$_2$ region in the south Pacific, there is a second region of enhanced concentration extending approximately from the South Atlantic magnetic anomaly to the eastern edge of Africa. These results support the observations of storm-time f$_0$F$_2$ made here in the S. Pacific and S. American zones.

4.5 $D_{st}$ ($f_0F_2$) dependence on time of storm commencement

Some workers believe that the shape of the $D_{st}$ ($f_0F_2$) curve depends on the local time at which a storm starts. Harang (1937) from studies at Tromso, a high-latitude station, found that the major depression of $f_0F_2$ was seen the day after the magnetically disturbed day. Appleton and Piggott (1952) showed that the form of the $N_mF_2$ variations depends on the local time of start of the storm. L. Thomas and Venables (1966) found that the major changes in $N_mF_2$ in mid-latitudes depend on the local time at which the main phase of the magnetic storm begins. If it occurred at night, there was an immediate depression of $N_mF_2$, but not if it occurred by day. Kotadia and Ramanathan (1961) from a study of disturbances at Ahmedabad
found that the changes in $f_{o}F_2$ are chiefly governed by the local time of sudden commencement of a magnetic storm.

Here a detailed study of the dependence of the $D_{st} (f_{o}F_2)$ variation on the local time of commencement of the storm is made for the IGY-IGC period for the same stations chosen for seasonal studies. Again the storms are all strong ones, with $Ap > 50$ on any of the 3 days following the storm. They are broadly classified into two categories - one with commencement in the daytime (between 06 hr. and 18 hr.) and the other with commencement in the night-time (between 18 hr. and 06 hr.). A further classification into storms with commencement in the pre-noon (06-12) hr. post-noon (12-18) hr., pre-midnight (18-00) hr, and post-midnight (00-06) hr, periods was tried but the number of storms in each of the four categories was insufficient and statistically-significant results could not be obtained.

(1) **Equatorial stations** (fig. 4.5) (Pg. 90 (a))

For storms which have their commencement in the daytime, after a slight drop of $f_{o}F_2$, there is a clear positive type of $D_{st} (f_{o}F_2)$ variation. This is so at both Huancayo (West zone) and Trivandrum (East zone). Storms with night-time commencement show larger fluctuations of ratio such that sometimes the ratio is less than 1.00.
(2) Low-latitude stations (Fig. 4.6) (Pg. 91(a))

Daytime commencement storms show an uncertain variation at Talara (13°N dip), but the night-time ones show a clear positive variation. At Baguio, both night-time and daytime commencement show a positive variation. At Tucuman, (22°S dip) there seems to be an anti-correlation between the $D_{st}$ ($f_0 F_2$) variations with daytime commencement and night-time commencement. At Singapore, both daytime and night-time commencement storms start with a drop, and a positive phase is shown mainly on the second day of the storm. Not much north-south asymmetry is seen when northern and southern stations in the same zone are compared.

(3) Mid-latitude stations (Fig. 4.7) (Pg. 91(b))

We now study the variations at mid-latitude stations Puerto Rico (dip 51°N) and Port Stanley (dip 46°S) in the West zone, and Akita (dip 53°N) and Townsville (dip 48°S) in the East zone. The striking point about all these stations is that storms with daytime commencement and night-time commencement have clear anti-correlation. Daytime commencement storms begin with a rise in $f_0 F_2$ on the first day, a drop in $f_0 F_2$ from 20 hr to 36 hr and then a rise. Night-time commencement storms begin with a clear drop in ($f_0 F_2$), a rise around 24 hr to 36 hr and then a drop.
FIG - 4.6
Fig. 4.7
The opposite tendency is very clear and there is even some correlation between the peaks of one with the troughs of the other. Some north-south asymmetry is seen between northern and southern stations in the same zone, but this is more in the magnitude than in the shape of the variation.

(4) High-latitude stations (Fig. 4.8) (Pg. 92 (a))

Both daytime commencement storms and night-time commencement storms show large and rapid ratio-fluctuations at high-latitudes. In the northern hemisphere at both Resolute Bay (dip 89°N) and Tixie Bay (dip 83°N), the ratio \( \frac{f_{oF2}}{f_{o'F2}} \) is well below 1.00 even at the zero-hour of the storm. This aspect is rather puzzling as after a depression of \( f_{o'F2} \) around 24 hours (this is the time when the peak effect on \( f_{oF2} \) occurs) the \( f_{oF2} \) values return to normal in the following 48 hours. In the southern hemisphere, the characteristic feature of depressed \( f_{oF2} \) at zero hour is not seen at either South Pole (dip 75°S) or Scott Base (dip 83°S) for either the daytime commencement or night-time commencement storms. Again the peak effect of disturbances on \( f_{oF2} \) occurs around 24 hours, and then normal values are reached in the next 48 hours. The variations are chiefly negative. Little North-south asymmetry is seen.
RESOLUTE BAY DIP 89° N
1957-1959

AVERAGE RATIO $F_{o2}/F_{o2}$

DAY TIME

SOUTH POLE-DIP 75° S
1957-1959

NIGHT TIME

TIXIE BAY - DIP 83° N
1957 - 1959

AVERAGE RATIO $F_{o2}/F_{o2}$

DAY TIME

SCOTTSBASE - DIP 83° S
1957 - 1959

NIGHT TIME

STORM-TIME IN HOURS

STORM TIME IN HOURS.

Fig 4.8
Conclusions

From this study, one comes to the conclusion that the behaviour of \( D_{st} \left( f_0 F_2 \right) \) for daytime commencement storms and night-time commencement storms is not remarkably different at equatorial, low-latitude, and high-latitude stations. At mid-latitude stations, they are vastly different, the \( D_{st} \left( f_0 F_2 \right) \) variation for daytime commencement storms being exactly opposite to variation of night-time commencement storms. This is borne out by the \( f_0 F_2 \) variations of daytime and night time commencement storms at three other mid-latitude stations - Wakkanai (dip 59°N), Concepcion (dip 36°S) and Port Lockroy (58°S dip) as shown in Fig. 4.9 (Pg. 92(b)).

4.6 \( f_0 F_2 \) variations on magnetically Quiet and Disturbed days \( S_q \left( f_0 F_2 \right) \) and \( S_d \left( f_0 F_2 \right) \).

Detailed studies of \( D_{st} \left( f_0 F_2 \right) \), and \( S_q \left( f_0 F_2 \right) \) and \( S_d \left( f_0 F_2 \right) \), are given in the Papers (3,4,5) following this page. Such variations are for individual stations in the Asian zone (Rajaram and Rastogi 1969), Australian zone (Rajaram and Rastogi 1970) and the American zone (Rajaram and Rastogi 1971) for the high sunspot period of IGY-IGC.

(Papers 3,4,5 follow overleaf)
A synoptic study of the disturbed ionosphere during IGY-IGC-
(1) the Asian Zone

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Abstract. — A systematic study of the solar daily variation $S_0(f_0F_2)$ and the storm-time disturbance variation $D_d(f_0F_2)$ has been made for stations in the Asian zone for each of the seasons of the IGY-IGC period. The latitude of change-over of the equatorial to the high-latitude type of ionospheric storm, varies appreciably with season. This may cause the consideration of ionospheric storms on an annual basis to lead to erroneous conclusions. During local winter months, all the stations in the Asian zone, except those between 10° and 20° dip latitude, and above 60° dip latitude, have positive type of ionospheric disturbances. It is suggested that the ionospheric storm effects at stations within 0° — 20° dip, are due to the modification of the diurnal development of the equatorial anomaly, caused by the geomagnetic disturbance. The mid-latitudes are affected by the combined effect of disturbances arising at the equator as well as at the high latitudes, especially during the local winter months.

Introduction

Since the epic work of Appleton and Ingram [1935] on the effect of magnetic storms on the ionosphere, studies have been made for many workers, to name a few, Berkner and Seaton [1940], Martyn [1953], Obayashi [1954], Nagata [1954], Skinner and Wkight [1955], Sato [1956], Maeda [1959], Matsushita [1959] and Thomas and Venables [1966]. The higher latitudes have been studied by Ignatov [1962], Kiyanovskiy and Mednikova [1963], Dolgova [1965], Feldsheyn [1965] and others. Bhargava [1959] and Kotadia [1961] have made a study of the Indian stations.

The understanding on the basis of all this work is, that a magnetic disturbance generally increases $f_0F_2$ at equatorial latitudes, and decreases $f_0F_2$ at high latitudes. Mid-latitudes seem to show a seasonal
change-over, exhibiting equatorial behaviour in local winter, and high latitude behaviour in local summer.

The daily variation of $f_0F_2$ at a station has been shown to depend on the ionisation locally produced, as well as on that transported from the equator, along the lines of the earth’s magnetic field [RASTOGI, 1959, 1960]. The daily variation of $f_0F_2$ thus greatly depends on the spatial distribution of the magnetic field in the region concerned. The Asian zone is for this reason, simple to study, as the isodip lines are parallel to the lines of geographic latitude. The synoptic study of the variation of the $F_2$ region in the Asian zone has already been described by RASTOGI [1960], and it was therefore decided to study the ionospheric storm behaviour for the same zone within the longitudes 75°E and 150°E.

### Table I

**Stations studied in the Asian zone with their geographic and magnetic coordinates.**

<table>
<thead>
<tr>
<th>Station</th>
<th>Abreviation used</th>
<th>Geographic</th>
<th>Magnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude</td>
<td>Longitude</td>
</tr>
<tr>
<td>Trivandrum</td>
<td>TVD</td>
<td>8°25'N</td>
<td>77°0'E</td>
</tr>
<tr>
<td>Kodaikanal</td>
<td>KOD</td>
<td>10°14'N</td>
<td>77°29'E</td>
</tr>
<tr>
<td>Tiruchi</td>
<td>TIR</td>
<td>10°50'N</td>
<td>78°50'E</td>
</tr>
<tr>
<td>Madras</td>
<td>MAD</td>
<td>13°00'N</td>
<td>80°15'E</td>
</tr>
<tr>
<td>Baguio</td>
<td>BAG</td>
<td>16°25'N</td>
<td>120°35'E</td>
</tr>
<tr>
<td>Ahmedabad</td>
<td>AHM</td>
<td>23°01'N</td>
<td>72°36'E</td>
</tr>
<tr>
<td>Okinawa</td>
<td>OKI</td>
<td>26°19'N</td>
<td>127°47'E</td>
</tr>
<tr>
<td>Delhi</td>
<td>DEL</td>
<td>28°35'N</td>
<td>77°13'E</td>
</tr>
<tr>
<td>Yamagawa</td>
<td>YAM</td>
<td>31°13'N</td>
<td>130°38'E</td>
</tr>
<tr>
<td>Kokubunji</td>
<td>KOK</td>
<td>35°42'N</td>
<td>139°29'E</td>
</tr>
<tr>
<td>Akita</td>
<td>AKT</td>
<td>39°44'N</td>
<td>148°08'E</td>
</tr>
<tr>
<td>Wakkanai</td>
<td>WAK</td>
<td>45°24'N</td>
<td>141°41'E</td>
</tr>
<tr>
<td>Alma Ata</td>
<td>ALM</td>
<td>43°12'N</td>
<td>76°55'E</td>
</tr>
<tr>
<td>Irkutsk</td>
<td>IRK</td>
<td>52°28'N</td>
<td>104°02'E</td>
</tr>
<tr>
<td>Tomsk</td>
<td>TOM</td>
<td>56°28'N</td>
<td>84°58'E</td>
</tr>
<tr>
<td>Yakutsk</td>
<td>YAK</td>
<td>62°01'N</td>
<td>129°43'E</td>
</tr>
<tr>
<td>Salekhard</td>
<td>SKD</td>
<td>66°35'N</td>
<td>66°40'E</td>
</tr>
<tr>
<td>Tixie Bay</td>
<td>TIX</td>
<td>71°34'N</td>
<td>128°54'E</td>
</tr>
</tbody>
</table>

The stations chosen for the analysis are given in Table 1 with their respective geographic and magnetic coordinates, and their alphabetical abbreviations, which have been used throughout the paper. The positions of these stations are shown in Figure 1, on which lines of same dip latitude are also drawn. It is seen that the combination of Indian, Japanese and Russian stations, forms a systematic and close distribution of stations from the magnetic equator to about 80° dip.

The annual average noon value of $f_0F_2$ at these stations has been plotted against the dip angle of the stations in Figure 2, showing the well-known equatorial anomaly. The high-latitude spur discussed by THOMAS [1964] is also evident around 70° dip. The maximum $f_0F_2$ is seen to occur at Ahmedabad. The stations, TVD, KOD, TIR and MAD are within the equatorial trough, while all the Japanese stations are beyond the tropical peak. The Russian stations are very close to the spur region, while Tixie Bay seems to be almost outside the spur, and is in the Arctic region. The effect of the magnetic disturbance would naturally depend on the position of the station on the curve in Figure 2.

**Disturbance solar daily variation $S_D(f_0F_2)$**

The disturbance solar daily variation for all these stations, during each season, has been studied by comparing the solar daily variation of $f_0F_2$ averaged on 5 International Quiet days ($Q$) and 5 International Disturbed days ($D$) of each month, as published in the IAGA bulletins.
Figure 1
Map showing the geographic and magnetic locations of stations studied in Asian zone.

Fig. 2
Equatorial anomaly in noon $f_0F_2$ for Asian zone.

Fig. 3
Annual average solar daily variation of $f_0F_2$ at the different stations on $Q$ and $D$ days of IGY-IGC.

Figure 3 shows the IGY-IGC behaviour of solar daily variations on $D$ as well as $Q$ days for each of the stations. It is seen that at TVD and KOD which are closest to the magnetic equator, the values on $D$ days are larger than the corresponding values on $Q$ days, for any of the solar hours. The same is true at TIR, MAD and BAG, for most hours of the day. This confirms that at stations within the equatorial trough, at least in the daytime, magnetic disturbances cause an increase of $f_0F_2$ above the normal values. It is seen too, that normally, the maximum increase happens near midday, which is also the time of the well-known bite-out of $f_0F_2$ at equatorial stations. At AHM, OKI and DEL, the $D$ values are smaller than the corresponding $Q$ values for most of the hours except forenoon, and the maximum storm effect occurs in the evening. These observations indicate that the disturbance daily variation within these latitudes is just a modification of the daily development of the equatorial anomaly. At stations,
Figure 4 shows these curves for the Equinoxes. D values are greater than Q for all hours at TVD, KOD and TIR, but for only daytime hours at MAD and BAG. At AHM a reversal in disturbance behaviour occurs, with the D values being generally smaller than Q values, for almost all hours of day and night.

The daily variations on Q and D days during the June months are shown in Figure 5. The behaviour at equatorial stations is similar to that described earlier. At stations above the latitude of AHM, a reversal in disturbance — behaviour occurs, as before, with the D values being generally smaller than Q values, for almost all hours of day and night.

The variations during the December months are shown in Figure 6. Again at stations, TVD, KOD, TIR and MAD, D values are greater than Q values for almost all hours, while at BAG, the D and Q values of $f_0F_2$ are almost the same for most hours, except for a few hours around 06 hr. and 22 hr. At AHM, OKI and DEL, D is less than Q for afternoon and
lost part of the night. At all the Japanese stations as well as at ALM and IRK, the $D$ values are greater than $Q$ values, for most of the daytime and for the early half of the night. This increase is rather unexpected. At higher latitude stations, $D$ values are again less than $Q$ values, at least for all daytime ours.

Those stations having similar variations have been grouped together, and the average difference of $f_0F_2$ on $D$ and $Q$ days have been shown in Figure 7 for six such groups during each of the seasons. The shaded portions denote excess of $D(f_0F_2)$ over $Q(f_0F_2)$.

It is seen that at stations within $0^\circ — 5^\circ$ dip, $(D — Q) f_0F_2$ is positive for all hours, during $D$ and $E$-months and for 5 hr. to 21 hr. during $J$-months. At stations between $10^\circ$ and $18^\circ$ the variations are similar except that the positive phase during June happens only during 09 hr. and 16 hr. At stations between $34^\circ$-$44^\circ$, $(D — Q) f_0F_2$ is positive between 05 hr. to 12 hr. during $D$ and $E$-months, and is negative for all hours of day and night during $J$-months. At station between $48^\circ$-$59^\circ$, $(D — Q) f_0F_2$ is negative for all hours during $E$ and $J$ months and is positive for hours between 09 and 24 hr. during $D$ months. At still higher latitudes between $71^\circ$ and $75^\circ$, $(D — Q) f_0F_2$ is strongly negative during the day and positive during the night for the $D$-months. During $E$ and $J$-months, it is strongly negative for all hours.

Taken as a whole, the curves show that during the $J$-months, the positive phase of the ionospheric storms occurs between 09 — 18$^\circ$ dip, during $E$-months the positive storm-effect extends up to 44$^\circ$, while during $D$-months, the positive phase of $(D — Q) f_0F_2$ variation occurs at almost all latitudes, although the time of occurrence shifts uniformly from forenoon at low latitudes to night hours at high latitudes. This suggests that during the $D$-months, the ionospheric storm is affected by phenomena originating at the equator as well as at high latitudes.

To study the ionospheric disturbance in relation to the equatorial anomaly, the ratio, $f_0F_2$ on $D$ days/$f_0F_2$ on $Q$ days, as well as average $f_0F_2$ have
Fig. 8

Variation of average $f_0F_2$ and $\frac{\partial (f_0F_2)}{\partial f_0}$ with dip latitude for different seasons of IGY-IGC for mid-day and mid-night hours.
been plotted against dip latitude separately for mid-day hours (10 hr. — 14 hr.) and mid-night hours (22 hr. — 03 hr.). These are shown in Figure 8. Studying this relationship for the mid-day hours, it is seen that the annual average latitude variation of mean $f_0F_2$ shows the well-known peak at 20° dip latitude. The ratio $\frac{D}{Q}(f_0F_2)$ is greater than 1.0 below 20°, is almost equal to 1.0 between 20° and 35°, and decreases below 1.0 with further rise in latitude. Thus the change-over of the disturbance effect from positive at the equator to negative at high latitudes occurs at the region close to the tropical $f_0F_2$ peak. It is to be noted that phase reversal of lunar tide in $f_0F_2$ from equatorial type to high-latitude type occurs at 11° dip latitude which is almost half way between the equator and the tropical $f_0F_2$ peak. During the J- and E-months, the features are similar to that described above, the change-over of disturbance effect occurring at a latitude slightly below 20° during J-months, and slightly above 20° during E-months. The decrease of this ratio with latitude is much faster during E-months. During the D-months, the average $f_0F_2$ shows a broad maximum around 60° dip latitude — this is the winter spur referred to earlier. The average $\frac{D}{Q}(f_0F_2)$ ratio is greater than 1.0 for a few degrees near the equator. During the J-months, the ratio is less than 1.0 for any of the stations, and decreases uniformly with increasing latitude. During E-months, the ratio is greater than 1.0 between 3° — 5° latitude, and is less than 1.0 for higher latitudes. During D-months, it is less than 1.0 at a small region around 20° latitude which is close to the peak $f_0F_2$ region. At latitudes below 10° and above 20° the ratio is greater than 1.0. Thus the abnormal disturbed behaviour of $f_0F_2$ exists during both the mid-day and mid-night hours of the D-months.

**Storm-time variation of $f_0F_2$ — $D_{st}(f_0F_2)$.**

To further understand the disturbance behaviour, it was decided to study the storm-time variations of $f_0F_2$ in this zone for the stations mentioned before. The method of analysis is the superposed epoch one in which the degree of disturbance — the ratio, storm $f_0F_2$/median $f_0F_2$ for the same hour — has been averaged for 4 hours preceding the storm-commencement, and 72 hours following it. All the storms of the IGY-IGC period, with $A_p \geq 50$ have been used in the analysis. As there are nearly 80 storms, it was assumed that the storms would be distributed evenly over the different times of the day, and hence the diurnal variation would disappear.

The annual average picture of these storm-time variations is given in Figure 9. This reflects the same behaviour as that of the annual $S_{st}(f_0F_2)$ variation, the ratio, storm $f_0F_2$/Median $f_0F_2$, during the main phase being greater than 1.0 up to BAG, and changing to less than 1.0, at higher latitudes. The ratio continues to decrease with increasing latitude. It is interesting to note the one-to-one correspondence of the predominant peaks, at almost all the latitudes. The strong 24-hour component at WAK may be due to a particular storm-time component showing itself strongly at this particular latitude. The stations, DEL, YAM, KOK and AKT seem to show very small amplitude of ratios as compared to the other stations.

**ANNUAL- IGY-IGC**

![Annual average $D_{st}(f_0F_2)$ variation at different stations during IGY-IGC.](image-url)
Fig. 10

$D_n (f_0 F_2)$ variation during Equinoxes of IGY-IGC.
The $D_s(f_0F_2)$ behaviour during the Equinoxes and June solstices is shown in Figure 10 and Figure 11 respectively. The change-over of the ratio, storm $f_0F_2$/median $f_0F_2$ from greater than 1.0 to less
than 1.0 occurs north of BAG in the E-months, and almost at BAG in the J-months. This is similar to the annual average behaviour described above.

It is in the winter months that the picture changes, and this is shown in Figure 12. Here the equatorial stations, TVD, KOD, TIR and MAD clearly show values of storm $f_0F_2$/median $f_0F_2$ to be greater than 1.0 during the main phase. At BAG too, this is so. At stations, AHM, OKI and DEL, this ratio is rather uncertain, but higher north, right up to TOM at a dip of 74°, it is definitely greater than 1.0. Very high latitude stations, YAK, SKD and TIX of course show ratios less than 1.0. Thus the abnormality exhibited by $S_g(f_0F_2)$ in the winter months shows itself in $D_s(f_0F_2)$ variation too. Another point to be noted is the large amount of fluctuation in the curves for the winter months, which is remarkably absent in those for the summer months.

The effect of geomagnetic activity on the $F_2$ layer at stations in other zones is being studied.

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The authors are grateful to Professor K. R. Ramanathan for his valuable discussions and suggestions during the course of the work.

Manuscrit reçu le 26 août 1969.
NORTHERN WINTER IGY-IGC

$D_s(\sqrt{f_0F_2})$ variation during December Solstices (local winter) of IGY-IGC.
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F-region Disturbances in the Australasian Zone during IGY-IGC

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Physical Research Laboratory, Ahmedabad

A study of $f_0F_2$ in the east zone (i.e. Australasian zone) during magnetically disturbed conditions shows the existence of some asymmetry between the northern and southern hemispheres. During the day-time hours of the winter months, there is a prominent increase in $D/Q(f_0F_2)$, the ratio of disturbed to quiet values of $f_0F_2$, between 40°N and 70°N dip. Similar but rather a flatter hump is observed in the southern hemisphere in the day-time in the local winter months. These humps seem to get stronger during the night hours of the local winter months. The $D_n(f_0F_2)$ variations show an unexpected positive phase at the Japanese stations together with the region of reduced disturbed $f_0F_2$ values around 30° dip. The effect of storms on $f_0F_2$ seems more enhanced in the northern hemisphere than in the southern hemisphere. Within ±40° dip the disturbance effects in $f_0F_2$ are associated with the normal solar daily variation of $f_0F_2$, which in turn is controlled by the equatorial electrojet current.

The effect of magnetic disturbances on the F-region of the ionosphere has been the subject of much investigation by workers all over the world since the earliest studies by Appleton et al., who found a strong negative correlation between magnetic activity and the critical frequency of the $F_2$ layer at high latitude stations, Slough and Tromso. Berkner and Seaton showed that the daily average electron density of $F_2$ at an equatorial station Huancayo increased continuously with increase of magnetic activity, whereas at a temperate latitude station Watheroo, the summer months showed a negative correlation between the two, and the winter months a positive correlation. Martyn showed that, during disturbances, there is a tendency for the electron density to be raised at low latitudes and lowered at high latitudes; at medium latitudes the mean values of $f_0F_2$ were depressed in summer and equinoxes, while the effect was much smaller in winter. Matsushita studied the $D_n(f_0F_2)$ variations at a large number of stations round the world, grouping them into different geomagnetic latitude zones. He found that irrespective of the season, stations in the equatorial belt show a positive phase, and stations in the high latitudes a negative phase; in the intermediate zone, the variation resembled that for equatorial stations in winter, and high latitude stations in summer. Rastogi showed that the effect of magnetic storms on $f_0F_2$ is governed by the dip angle of the station and not by its geographic or geomagnetic latitude.

In this paper, the results of a study of the effect of magnetic disturbances on $F_2$ critical frequencies separately, at stations in the east zone (i.e. the Australasian zone) between ±35° dip during the IGY-IGC period have been presented.

The solar daily variations of $f_0F_2$ on quiet (Q) and disturbed (D) days for both the D-months (November, December, January and February) and the J-months (May, June, July and August) at some of the stations are shown in Fig. 1. Kodaikanal is a typical equatorial station at which disturbed $f_0F_2$ always exceeds quiet $f_0F_2$, the effect being most pronounced during mid-day, thereby decreasing the noon bite-out of $f_0F_2$. Baguio (dip, 19°N) and Singapore (dip, 17°S) are in the transition region where the disturbance effects are rather small and uncertain. Ahmedabad (dip, 33°N) seems to lie in the region where disturbed $f_0F_2$ values are less than quiet $f_0F_2$ values in both seasons. It may be noted that the effect of the disturbances is most pronounced in the post-sunset period when $f_0F_2$ value is normally greatest. No corresponding station is available in the south for comparison with Ahmedabad. Both Akita (dip, 53°N) and Watheroo (dip, 65°S) show the seasonal change-over of disturbed $f_0F_2$ values, from an enhancement in local winter to a decrease in local summer. Salekhard (dip, 79°N) and Hobart (dip, 72°S) lie in the high latitude region where disturbances decrease $F_2$ critical frequencies in all seasons. Thus, in the northern hemisphere, the latitude of change-over from the positive to the negative type of disturbed $f_0F_2$ varies appreciably with season. There seems to exist a trough at the mid-latitude region where disturbances always decrease $f_0F_2$ values irrespective of the season, and then a 'hump' at higher latitudes with increased $f_0F_2$ values during local winter. This hump disappears at the polar latitudes where disturbances decrease $f_0F_2$ at all seasons.

The variations with dip of the degree of disturbance in $f_0F_2$, i.e. the ratio $f_0F_2$ on D days and on Q days, are shown in Fig. 2 for the mid-day and midnight hours of each season. The corresponding variation of the average $f_0F_2$ values are also shown on the diagrams. Thus, a comparison between the geomagnetic anomaly in $f_0F_2$ and the disturbance effect can be made. During any of the seasons, the noon bite-out at the equator, shown in average $f_0F_2$, is replaced by an enhancement of $f_0F_2$ during disturbed conditions. In the day-time of the
D-months, the $D/Q(F_p)$ curve shows, apart from the equatorial enhancement, another enhancement between 40° and 70° dip with a minimum in between. This is shown to some extent in the average $F_p$ in the 'spur' occurring beyond 60° dip. In the night-time hours, the features in the $D/Q$ variation mentioned above are even more enhanced, but all evidence of the spur in the average $F_p$ curve vanishes. During the J-months, the $D/(Q/F_p)$ ratio is greater than unity for the day-time and less than unity during night-time. During the day-time the ratio $D/(Q/F_p)$ decreases continuously with latitude in the northern hemisphere while in the southern hemisphere a hump around 60° is seen with a trough around 30°. Thus, the day-time behaviour in the S and N hemispheres is similar in the same local season. During the night a southern hump at 60° is seen with no trough around 30°. Thus, the night-time behaviour differs between N and S hemispheres primarily due to the decrease of $f_p$ at the equator during the J-months while an increase occurs during the D-months. Fig. 3 shows the annual average $D_m(F_p)$ variation (the storm-time variation of $F_p$) for the east zone. About 80 strong storms, i.e. storms with $A_p$ exceeding 50 on any of the 3 days following the commencement of the storm, of the IGY-IGC period have been averaged to obtain the average ratio $f_pF_p/F_p$ (i.e. storm value of $F_p$ at a particular hour/median $F_p$ for the same hour) for each of the 72 hr following the storm. Pairs of stations of approximately same dip N and S have been used for this study. Trivandrum and Kodai-kanal as typical equatorial stations show chiefly a positive phase (i.e. values of these ratios are greater than 1-00). Singapore and Baguio with dip of about 18° show mainly positive values between 24 and 48 hr storm-time. Townsville and Akita are mid-latitude stations, and show no uncertainty in the variation. A feature worth noticing is the pronounced 24 hr repetition frequency of the ratio peaks at Townsville. Brisbane and Wakkalai lie in the higher latitude region, and show a negative phase (i.e. values of the ratio are less than 1-00). Wakkalai shows the repetitive 24 hr period ratio-peaks. The pairs of stations Canberra-Alma Ata and Hobart-Irkutsk have clearly negative peaks. Ratio values for Canberra are lower than for Alma Ata and ratios for Hobart are lower than those for Irkutsk. A sharp dip in ratios around 24 hr storm-time characterizes both Hobart and Irkutsk; Scott Base and Tixie Bay both have the very high value of dip of 83°, and show clear negative phase marked by rapid ratio fluctuations. This is probably a polar region effect, and may be related to the periodic dumping-in of charged particles along the favourably aligned geomagnetic lines of force. Taken on the whole, Fig. 3 shows that the storm-time variations follow approximately the same N and S pattern except for slight differences in the mid-latitude regions.

Fig. 4 shows the $D_m(F_p)$ variation with dip N and S. This is the mean of the ratios $f_pF_p/F_p$ taken over 00-48 hours. It represents the net effect on $F_p$ critical frequencies of the storm-time ring-current (DR) which is supposed to encircle the earth at a distance of about 4 earth radii. This is shown for the D-, E- and J-months in Fig. 4.

The ring-current effects in the E-months show a fair symmetry in the variation in the N and S hemispheres. The annual picture is much the same. In the D-months, the ring-current appears to cause enhancements of $D/(Q/F_p)$ in the equatorial and northern high latitudes with a trough in between. In the J-months the equatorial enhancement is not pronounced, but there does seem to be an enhancement of ratios around 60° dip. Whether there is a trough of lesser ratios around 30° dip cannot be ascertained owing to the absence of an operating station in this critical region during IGY-IGC. The enhancement of these disturbance ratios in local winter is certainly more in the northern hemisphere than in the southern hemisphere.
Fig. 2 — Variation of $D/Q(f_0F_a)$ and average $f_0F_a$ with dip angle for day-time and night-time hours.

Fig. 3 — $D_m(f_0F_a)$ variations for northern and southern dip-conjugate stations in the east zone.

Fig. 4 — Variation of mean value of the ratio $f_0F_a/f_0F_s$ during main phase of storms, with dip angle.

Conclusion

The enhancement of disturbed $f_0F_s$ values in the equatorial region seems to be associated with a weakening of the equatorial electrojet current during geomagnetic disturbances. This is suggested by the decrease of the mid-day bite-out in $f_0F_s$ observed at equatorial stations on D days as compared to Q days. Further, the disturbance effect (decrease during disturbance) at tropical peak $f_0F_s$ regions is most pronounced during the evening hours. These two features are complementary to each other. A decrease of the electrojet would mean a smaller ($E \times B$) lifting force on the F-region.
ionization at the equator resulting in the decreased bite-out. Consequently, there is less transport of ionization along the geomagnetic lines of force to the mid-latitudes, resulting in lesser $f_0F_2$ at these latitudes on the D than on the Q days. This is also supported by the flattening of the $F_2$ geomagnetic anomaly crests on D days as compared to Q days.

The high latitude ‘hump’ of disturbed $f_0F_2$ around 60° dip in the winter hemisphere may be associated with the preferential precipitation of charged particles into the auroral zone. It is well known that the auroral belt shifts equatorward during geomagnetic disturbances. Its appearance only in the winter hemisphere bears a resemblance to the ‘spur’ occurrence mentioned by Thomas. Why this does not happen in the summer hemisphere is rather puzzling. Further investigation of this problem is being carried out.

References

A synoptic study of the Disturbed Ionosphere during IGY-IGC

(2) The American Zone

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Physical Research Laboratory
Ahmedabad-9, India.

INTRODUCTION

The earliest studies of the ionospheric changes following a magnetic storm were generally of individual stations. Matsushita [1959] described the ionospheric storms at a large number of ionospheric stations grouping them into different geomagnetic latitude zones. It has been shown that the behaviour of ionospheric storms at low latitudes is governed by the actual magnetic dip of the station rather than by its geomagnetic latitude [Rastogi, 1962]. Significant longitudinal differences have been shown to exist in ionospheric disturbances during the IGY-IGC period by Rastogi and Rajaram [1965]. With these points in view, a study of ionospheric storms for different seasons was undertaken; the results for the stations in the Asian Zone have been described in an earlier paper by Rajaram and Rastogi [1969]. This paper shall, henceforth, be referred to as Ref. 1.

The present paper describes the results of a study of ionospheric storms during the IGY-IGC period at stations situated over the complete American zone. The method of analysis is the same as in the earlier papers. The list of stations chosen for the analyses with their geographic and magnetic co-ordinates, as also their alphabetical abbreviations which have
been used in the paper are given in Table I. The positions of these stations with respect to the isodip lines are shown on the map in Figure 1. It can be seen that most of the stations lie in the longitude belt 45°W to 105°W and thus cover the complete latitude range from 89°N dip to 75°S dip; the southernmost station South Pole (75°S dip and 90°S geographic) could not be depicted on the map. It may be noted that the isodip lines have a strong tendency to show a convexity to the south; this is more marked in the southern hemisphere. In this respect this zone differs from the Australasian zone where the isodip lines are almost parallel to the lines of constant geographic latitude.

The Annual Average midday values of $f_0F_2$ plotted against the dip angle of the stations are shown in Figure 2. The equatorial anomaly is clearly seen in the diagram, HUA, LAP and TAL being situated within the anomaly trough; PMR and PAN lie very close to the northern crest, and TUC, SAO lie close to the southern crest of the anomaly. Beyond the crests there is a gradual and steady decrease of $f_0F_2$ towards the poles, and stations with dips greater than 30° lie on these declines. It may be seen that the high-latitude "spur" [THOMAS, 1964] which was prominent at a latitude of 70°—80°N dip in the Asian zone (Ref. 1, Fig. 2) is not clearly defined in the American zone. It may also be noted that the

<table>
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<tr>
<th>Station</th>
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<th>Magnetic</th>
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<td>52°47'W</td>
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<td>- 49°</td>
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<td>90°00'S</td>
<td>0°0'</td>
<td>- 75°</td>
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**Caption:** Stations studied in the American zone with the abbreviations used, and their geographic and magnetic coordinates.
critical frequencies outside the anomaly region are lower in the southern hemisphere than at a corresponding latitude in the northern hemisphere. This may be due to the abnormal distribution of the geomagnetic field, and its associated effects on the transport of electrons from the equator to the mid-latitude regions [Rastogi, 1960].

**Disturbance solar daily variation** $S_0(f_0F_2)$

The annual average daily variation of $f_0F_2$ on the five International Quiet ($Q$) and five International Disturbed ($D$) days of the IGY-IGC period are shown in Figure 3 for each of the stations. The full lines indicate the $D(f_0F_2)$ variations as compared to the dotted curves which indicate the $Q(f_0F_2)$ variations. In the paragraphs which follow the figures in brackets given against the stations refer to the dip angle of the station, + indicating North and — indicating South. At the equatorial stations, TAL, HUA and LAP, $f_0F_2$ is greater on $D$ than on $Q$ days for any

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**AMERICAN ZONE IGY-IGC**

**ANNUAL AVERAGE**

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**Fig. 1**
Map showing the geographic and magnetic dip angle locations of stations in the American zone.

**Fig. 2**
Equatorial anomaly in noon $f_0F_2$ for the American zone.

**Fig. 3**
Annual average solar daily variation of $f_0F_2$ at different stations on $Q$ and $D$ days of IGY-IGC.
hour of the day. The change-over region in the north occurs at PMR and PAN (about +35°); here the difference between \( D(f_0F_2) \) and \( Q(f_0F_2) \) is uncertain. Beyond +65° till +89° all stations show \( D(f_0F_2) \) less than \( Q(f_0F_2) \), for all hours of the day, the difference between the two getting larger with increasing latitude. In the southern hemisphere, day-time \( f_0F_2 \) is greater on \( D \) than on \( Q \) days, even at non-equatorial stations SAO, TUC, BNA, and CON, which are close to, or just outside the southern anomaly crest. PST (-46°) could be regarded as a change-over region showing uncertainty between \( D(f_0F_2) \) and \( Q(f_0F_2) \). Further south, PLO, ELL and SPO shows \( D(f_0F_2) \) less than \( Q(f_0F_2) \) though the difference is not as much as for the corresponding high latitude stations in the northern hemisphere.

The seasonal behaviour of \( D(f_0F_2) \) and \( Q(f_0F_2) \) for these stations is shown in Figure 4. Considering first the D-months (November, December, January and February) one finds that at the equatorial stations TAL, HUA and LAP, \( f_0F_2 \) around midday is lower on \( D \) than on \( Q \) days. This behaviour is different from that shown by the equatorial stations in the African and Asian zones, where midday \( f_0F_2 \) on \( D \)-days is greater than on \( Q \) days for all seasons [Rastogi and Rajaram, 1965]. In the northern hemisphere \( D(f_0F_2) \) is greater than \( Q(f_0F_2) \) within a small dip region, around PUE and GBH (+60°).

Beyond this, right till RES (+89°) \( D(f_0F_2) \) is less than \( Q(f_0F_2) \), once again the decrease in \( D(f_0F_2) \) increasing with increasing dip. In the southern hemisphere too, there is a narrow region around SAO and TUC (-22°) where \( D(f_0F_2) \) is greater than \( Q(f_0F_2) \). The stations BNA (-31°) and CON (-36°) show an uncertainty, but beyond this till SPO (-75°) \( D(f_0F_2) \) is less than \( Q(f_0F_2) \), as is expected of high-latitude stations.

It may be noticed that the high latitude stations of the northern hemisphere (winter hemisphere) show a sharper diurnal variation of \( f_0F_2 \) than the high-latitude stations of the summer hemisphere (southern hemisphere) (Antarctic Research Series, Vol. 4, 1965). A point worth noticing for the high-latitude stations is that in the northern hemisphere the maximum difference between \( D(f_0F_2) \) and \( Q(f_0F_2) \) occurs in the day-time hours when \( Q(f_0F_2) \) itself attains its highest value. In the southern hemisphere the difference between \( D(f_0F_2) \) and \( Q(f_0F_2) \) is maximum at night when \( Q(f_0F_2) \) here attains its highest values.

Considering the E-months (March, April, September and October), the equatorial stations LAP, HUA, TAL show the expected \( D(f_0F_2) \) greater than \( Q(f_0F_2) \). In the northern hemisphere the change-over occurs at PMR (+33°). At all higher latitude stations up to RES (+89°) \( D(f_0F_2) \) is less than \( Q(f_0F_2) \). In the southern hemisphere, the change-over region is rather broad with TUC, BNA and CON all showing some uncertainty; in fact at CON (-36°), \( D(f_0F_2) \) is greater than \( Q(f_0F_2) \). Beyond this, till SPO (-75°) \( D(f_0F_2) \) is less than \( Q(f_0F_2) \). It may be noted that the difference between \( D(f_0F_2) \) and \( Q(f_0F_2) \) is less for the southern high-latitude stations than for the northern high-latitude stations; also the abnormal daily variation of \( f_0F_2 \) observed at ELL, and PLO in winter, with night \( f_0F_2 \) exceeding daytime \( f_0F_2 \) is absent in the equinoxes. The post-sunset increase of \( f_0F_2 \) at around 33°N dip and 33°S dip remains. This has been attributed to thermal cooling of electrons arising from collisions [Evans, 1965]. The character of the \( f_0F_2 \) variation curves in the N and S hemisphere does not differ much in the equinoxes, there being no flat variations anywhere; this suggests that any ionisation locally produced at the equator in the equinoxes directly under solar influence is symmetrically distributed between the two hemispheres.

Considering the J-months (May, June, July and August), the equatorial stations, LAP, HUA, and TAL all show the expected \( D(f_0F_2) \) greater than \( Q(f_0F_2) \). In the northern hemisphere all stations north of this region show \( D(f_0F_2) \) less than \( Q(f_0F_2) \). In the southern hemisphere SAO (-23°) and TUC (-22°) show an uncertainty, while BNA, CON, PST, PLO and ELL (-66°) all clearly show \( D(f_0F_2) \) greater than \( Q(f_0F_2) \). Nowhere right until this region of +66° dip does any station show \( D(f_0F_2) \) less than \( Q(f_0F_2) \) as expected of high-latitude stations. Even
A SYNOPTIC STUDY OF THE DISTURBED IONOSPHERE DURING IGY-IGC

The southernmost station SPO (—75° dip) one cannot definitely say that \( D(f_0F_2) \) is less than 2 \( (f_0F_2) \), there existing an uncertainty between the two. In this respect the South American zone differs from the North American zone in which the high-altitude decrease of \( D(f_0F_2) \) is clearly shown in all seasons from WAS (+71°) to RES (+89°).

In the southern hemisphere only SPO (—76°) retains its flat diurnal variation of \( f_0F_2 \). None of the northern high-latitude stations show the abnormal feature of maximum \( f_0F_2 \) occurring at night as was seen in some of the southern stations in the corresponding season.

Also, the difference between \( D(f_0F_2) \) and \( Q(f_0F_2) \) is more in the northern hemisphere than in the southern hemisphere; in the southern hemisphere itself his difference is larger in the \( D \) and \( E \) months and less in the \( J \) months. This suggests that the South American zone seems to experience enhanced electron densities during magnetically disturbed conditions, particularly in the local winter months.

In Figure 5 is shown the average difference of \( f_0F_2 \) between \( D \) and \( Q \) days for the different hours of the day for the different seasons. Stations having similar variations of \( f_0F_2 \) have been grouped together giving total coverage from north to south in 10 dip zones as shown in the diagram. The shaded portions denote excess of \( D(f_0F_2) \) over \( Q(f_0F_2) \).

Considering the variation of \( (D — Q)f_0F_2 \), in the dip zone (0°—5°) S—that is, at equatorial latitudes, the value of \( (D — Q)f_0F_2 \) is higher in the night than at day, in each of the seasons. This is so especially in the \( D \) months when there are negative midday values of \( (D — Q)f_0F_2 \); this implies that the effect of disturbances in this zone in this season has been to decrease \( f_0F_2 \) as compared to the quiet day values. This is an unusual feature for the equator. Almost the same observations hold for the dip zone 13°N. This zone has the positive phase of \( (D — Q)f_0F_2 \) during \( D \) months again may be noted. In the dip zone, 31°—7°N, negative values occur in the night hours, and in the \( D \) months higher values of \( (D — Q)f_0F_2 \) are entred around the sunrise and sunset hours, with comparatively smaller values around midday. The coud peak centred around sunset disappears in the \( J \) months, and the one centred around sunrise too. The last two zones are marked by negative values of \( (D — Q)f_0F_2 \) in the \( D \) months and the \( J \) months.

To summarise all this, in the northern hemisphere the positive phase of \( (D — Q)f_0F_2 \) occurs upto 51°—61° N dip in the \( D \) months, to 31°—37° in the \( E \) months, and only till dip 13°N in the \( J \) months. In the \( S \) hemisphere some positive phase occurs till 32°—36°S in the \( D \) and \( E \) months, and only till dip 13°N in the \( J \) months. The mean value of \( D(f_0F_2)/Q(f_0F_2) \) for the midnight hours (22-02) and for the midday hours (10-14), also the average \( f_0F_2 \) for the corresponding hours, are plotted against magnetic dip in Figure 6. This was done with a view to study the \( f_0F_2 \) effect in relation to the normal equatorial anomaly.
G. RAJARAM AND R. G. RASTOGI

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Fig. 6
Variation of average \( f_0F_2 \) and \( D(f_0F_2)/Q(f_0F_2) \) with magnetic dip for different seasons of IGY-IGC for mid-day and midnight hours.

Considering the \( D \) months in the midday hours, the ratio \( D/Q(f_0F_2) \) is less than 1.00 between \( \pm 20^\circ \) dip giving a decrease in \( f_0F_2 \) during disturbed conditions even at the equator where normally only an increase is expected. This is unusual. Positive regions of \( D/Q(f_0F_2) \) occur around \( 40^\circ \) dip both N and S, these peaks occurring at higher dip value than the normal \( f_0F_2 \) anomaly crests. Beyond \( 60^\circ \) dip, the ratio \( D/Q(f_0F_2) \) falls off below 1.00 gradually with increase in dip. In the night the equatorial trough of \( D/Q(f_0F_2) \) is filled up and replaced by a positive peak, the southern peak disappears, while the northern peak around \( 60^\circ \) dip becomes normal and sharper. A mid-latitude trough in \( D/Q(f_0F_2) \) is now centred around \( 30^\circ \) S. The normal anomaly crests of \( f_0F_2 \) are sharper and more pronounced in the night than at day.

In the midday hours of the \( E \) months, the ratio \( D/Q(f_0F_2) \) is greater than 1.00 between \( 50^\circ \) dip and \( 50^\circ \) dip with an indication of a slight trough around the equator. Beyond these dip values, the value of \( D/Q(f_0F_2) \) gradually falls off with increasing dip. The appearance of the \( D/Q(f_0F_2) \) curve is not very different from the normal \( f_0F_2 \) curve. In the night hours, again a prominent peak in \( D/Q(f_0F_2) \) is centred around the equator, with a suggestion of a secondary peak around \( 50^\circ \) dip, although beyond \( 20^\circ \) dip N and S, the values of \( D/Q(f_0F_2) \) are all negative.

In the midday hours of the \( J \)-months, there is a region of positive \( D/Q(f_0F_2) \) centred around the equator, with a second and stronger peak occurring around \( 40^\circ \) dip S. Beyond \( 30^\circ \) dip and \( 60^\circ \) dip, \( D/Q(f_0F_2) \) falls off below 1.00 with increasing dip. There is no resemblance between the \( D/Q(f_0F_2) \) curve and the normal anomaly curve. In the night the equatorial peak in \( f_0F_2 \) vanishes, and a vast peak of \( D/Q(f_0F_2) \) forms in almost the whole southern hemisphere with its centre around \( 40^\circ \) dip. Negative values of \( D/Q(f_0F_2) \) occur throughout the N hemisphere. Again there is no resemblance to the normal anomaly curve.

The annual behaviour is the average of the 3 seasons, and is characterised by \( D/Q(f_0F_2) \) values exceeding 1.00 around \( 40^\circ \) dip in the day, while the equatorial peak gains prominence at night. Several interesting features are:

1. The normal equatorial anomaly is more pronounced in the night than by day, particularly in the \( D \) and \( E \) months.

2. In the day-time of the \( D \)-months, there seems to be decreased ionisation at the equator during disturbances, with peaks in both hemispheres around \( 45^\circ \) N and \( 45^\circ \) S dip. Classically, disturbances are supposed to fill up the equatorial anomaly trough.

3. The southern \( 50^\circ \) dip peak in the \( J \)-months (winter months) is stronger than the corresponding equatorial peak or the northern \( 50^\circ \) dip of the \( D \)-months. This again shows a marked enhancement of \( F \)-region electron densities over the South American zone during disturbed conditions. This feature may be connected with the low geomagnetic field intensity in this zone.

STORM-TIME VARIATION OF \( f_0F_2 \) — \( D_a(f_0F_2) \)

The storm-time (i.e. universal time) variations of \( f_0F_2 \) were studied with a view to further understanding the \( F \)-region disturbance behaviour in this zone. The strong storms of the IGY-IGC period with \( A_p \geq 50 \) have been chosen, and their seasonal behaviour as well as the annual picture obtained for each station.

The method of obtaining \( D_a(f_0F_2) \) from the ratio (storm-time value of \( f_0F_2 \) corresponding median value of \( f_0F_2 \)) is the same as described in Reference 1.

Figure 7 shows the annual average \( D_a(f_0F_2) \) variations. In the northern hemisphere the positive phase of \( f_0F_2 \) is greater than 1.00, which occurs at equatorial HUA (+2°) gradually decreases as dip increases. A change-over occurs at (PAN + PMB + BOG) the region of \( +35^\circ \) dip where the variation is uncertain. Beyond this a negative phase (i.e. the value of \( f_0F_2 \) less than 1.00) takes over. This supports the general belief that the effect of magnetic storms is to increase \( f_0F_2 \) at the low-latitude regions, and decrease \( f_0F_2 \) at the high latitudes. A region such as PUE (+51°) which is at the \( Sq \) current focus does not seem to be affected much by disturbances. In the southern hemisphere the change-over, from the equatorial positive phase to the high-latitude negative phase does not occur at the region of least disturbance,
which is around TUC, SAO (—22°). The positive phase continues lower down till PST (—46°). Beyond this the negative phase occurs right till SPO (—75°). PLO (—58°) shows an unusual variation with almost uniform negative values of \( f_0 F_2 \); there does not seem to be a clearly defined main phase or recovery phase for \( F_2 \) disturbances in this region. The 24 hour repetition frequency of the disturbance peaks which was seen in the Asian Zone (Ref. 1) is not prominent in the American zone. The southern high-latitude stations SPO (—75°) and ELL (—66°) show very rapid fluctuations of the ratio \( f_0 F_2 \). The maximum \( F_2 \) disturbance in higher latitudes, both north and south, seems to occur 20-24 hr after the storm commencement.

The \( D_s f_0 F_2 \) variations during the equinoxes are shown in Figure 8. They do not differ much in character from the annual average behaviour, the regions of change-over being almost the same. The variations at the different stations resemble the annual picture.

In Figure 9 are shown the \( D_s f_0 F_2 \) variations for the December Solstice which is the northern winter. Here, in the Northern hemisphere the positive phase of \( D_s f_0 F_2 \) exists from equatorial HUA to WHT (+61°). The region of least change in \( f_0 F_2 \) now seems to have shifted to WAS (+71°), and beyond this right till RES (+89°), negative variations of \( f_0 F_2 \) are shown by all stations. In the southern hemisphere negative variations seem to start at the latitude of TUC (—22°) itself, the decrease in \( f_0 F_2 \) continuing to SPO (—75°). The 24-hour peaks are seen in the \( D_s f_0 F_2 \) variation at WHT (+61°) in the north. The northern high latitude stations now show very large and rapid fluctuations of the ratio but these are not seen in the southern high latitude stations; this suggests these fluctuations to be a local winter-time feature.
The $D_{st}$ ($f_0F_2$) variations for the June Solstice (i.e. northern summer) are shown in Figure 10. Now it is the southern high latitude stations SPO and ELL lying in the winter hemisphere which show large and rapid fluctuations of the ratio $f_0F_2/f_2$. The northern high latitude stations, RES, BAK, CHR, WIN, OTT, etc. show comparatively smoother and smaller variations. In this season, in the northern hemisphere, the positive phase of $D_{st}$ ($f_0F_2$) occurs at the equatorial stations HUA and TAL; the changeover region of little fluctuation occurs at BOG, PMR (+33°) and then with increasing dip, the variation becomes more and more negative. In the southern hemisphere, the positive $D_{st}$ ($f_0F_2$) continues right down till ELL (—66°), and even at SPO (—75°) the variation cannot be called a clearly negative one. The 24 hour peaks in $D_{st}f_0F_2$ are not clearly shown at any of the stations.

**Conclusions**

Several deviations from the classical knowledge of $f_0F_2$ disturbance effects have been brought out in this study. The equatorial decrease of disturbed $f_0F_2$ in the day-time hours of the IGY-IGC is an unexpected feature and has been dealt with more detail in previous papers [RASTOGI and RAJARAM (1965); RAJARAM and RASTOGI, 1968]. The formation of a peak of disturbed $F_2$ ionisation in the winter mid-latitudes is a feature of other longitude zones too [RAJARAM and RASTOGI, 1969, 1970]. The physical implications of this are being studied.

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On the pattern of the work published in the attached papers, the analysis was extended to cover the East Zone for the low sunspot years. In the sections which follow, a summary of these results has been made for some selected stations, namely those near the magnetic equator, the subtropical peak, at mid-latitudes, and the polar latitudes. Longitudinal differences are studied by comparing the West and East zones for high sunspot (IGY-IGC). The solar cycle effects are seen by comparing the East zone for high sunspot (IGY-IGC) and low sunspot (IQSY + 1953-1955).

The solar daily variations of $f_0F_2$ at these stations on International Quiet Days (Q) and International Disturbed Days (D) of the different seasons are shown in Fig. 4.10. (Pg. 95 (a)).

The abscissa is the local time in hours while the ordinate is $f_0F_2$ in MHz. $f_0F_2$ variations on quiet days are shown by full lines while the variations on disturbed days are shown by dashed lines.

In any one zone it is generally clear that –

(1) The annual behaviour and 1-month behaviour is rather alike. This happens at the equatorial and high-latitude stations because the change in disturbed $f_0F_2$ during equinox, summer and winter is in the same sense and additive; at high
latitudes, it is always a decrease of $f_{oF_2}$ on D days in all seasons as compared to Q days, while at equatorial stations it is always an increase.

The exceptions to the above are (1) during IGY-IGC, at the equatorial zone of the West zone in the D-months where there is a decrease of midday ($f_{oF_2}$) on D days; this is not seen in the East zone. (2) The northern high latitudes of the East zone in the low sunspot years, when a decrease of $f_{oF_2}$ on D-days occurs only in the J-months (local summer), but the D-months, E-months and Annual average all show $f_{oF_2}$ on D days almost equal to Q days. This is unlike the East zone (high sunspot).

Low and mid-latitude stations show opposite behaviour between local summer and winter, but the magnitude of changes being equal and opposite, they annul out, and render the Annual variation similar to the equinoctial variation.

(2) There is a post-sunset rise in $f_{oF_2}$ at the dip locations of about 33° north and south (more in the north than in the south) in the high sunspot years in both East and West zones (Evans 1965 b). This rise is certainly less on D days than on Q days. (Huang Y.N. 1964; Huang Y.N. and C.Y. Leh 1970).

(3) The high-latitude stations both north and south show a sharper daily variation of $f_{oF_2}$ in local winter when
FIG. 4.10

95(a)
ionising solar radiation is totally absent, and an almost flat daily variation of \( f_0 F_2 \) in local summer when solar ionising radiation is present. This suggests that \( F_2 \) ionisation at these latitudes is primarily governed by transport effects (from the magnetosphere or from other latitudes) rather than by processes connected with solar electromagnetic radiation alone (Rastogi 1960; Antarctic Research Series 1965). The anomalous variation of \( f_0 F_2 \) at Port Lockroy (\(-56^\circ\) dip) in the West zone, with night \( f_0 F_2 \) larger than daytime \( f_0 F_2 \) may be noted. It has been pointed out that this feature is due to the ionospheric drift produced by atmospheric wind systems (King J.W. et al., 1967). This anomalous variation is considerably less on D days, the difference in \( f_0 F_2 \) between day and night being less as compared to Q days. It looks as though magnetic disturbances have a tendency to smoothen out this \( F_2 \)-region Antarctic anomaly.

(a) **Solar cycle differences**

Comparing the \( S_q \), \( S_d \) curves for different sunspot periods it appears that:

(1) The absolute difference in MHz between \( f_0 F_2 \) on D days and Q days in low sunspot years is less than in high sunspot years; percentage-wise this difference is as much if not more in low sunspot years, as will be
shown in Section 5.4.

(2) The post-sunset rise in \( f_{o}F_2 \) seen at Ahmedabad (+ 33° dip) in high sunspot is absent in low sunspot. It should be noted that the post-sunset height rise of the \( F_2 \) layer at equatorial stations is also absent in low sunspot years. This establishes a relationship between the two features. The dependence of the post-sunset rise in \( f_{o}F_2 \) at a mid-latitude station on the post-sunset rise in \( h'F \) at an equatorial station has been studied for quiet conditions by Narasinga Rao (1966).

While Ahmedabad experiences decreased \( f_{o}F_2 \) in all seasons on D days in high sunspot, this is seen only in the D-months in low sunspot. In fact, E-months and J-months both show increased \( f_{o}F_2 \) on D days at Ahmedabad. In low sunspot years, all latitudes except the highest southern latitudes experience increase in \( f_{o}F_2 \) during D days. This goes against the classical belief of storm-time behaviour. In high sunspot years, this range of latitudes experiencing \( f_{o}F_2 \) increase on D-days in considerably reduced.

(3) At equatorial stations (Trivandrum -0.6° dip) in high sunspot years, the forenoon peak in midday \( f_{o}F_2 \) is stronger than the afternoon peak; in low sunspot years the afternoon peak is higher than the forenoon peak (Rastogi and Sanatani 1963).
(4) In the northern hemisphere of the East zone, in both high and low sunspot periods, Wakkanai (+59° dip) seems to experience its peak $f_0F_2$ before midday, while Ahmedabad (+33° dip) lying south of it, and Tixie Bay (+83° dip) lying north of it, both experience peak $f_0F_2$ after 12 hr. This suggests that some agent responsible (may be partly) for peak ionisation at 59° dip travels both north and south, taking about 3 hr. to influence locations at +83° dip and +33° dip.

(5) In the J-months, the $f_0F_2$ variation at Wakkanai (+59°) is remarkably flat on both Q and D days. This is true for both high and low sunspot.

(6) At high latitudes, the local winter feature of sharper $f_0F_2$ variation, and a flat summer variation persists in both high and low sunspot years. It is equally true of Q and D days.

(b) **Longitudinal differences**

Comparing the East and West zone for high sunspot, we find:

(1) The extremely flat variation of $f_0F_2$ at Wakkanai (+59° dip East zone) in the J-months is not found at Whitesands (+60° dip, West zone). The difference between D ($f_0F_2$) and Q ($f_0F_2$) is much larger at the latter station. However the variation of $f_0F_2$ in the D-months is
extremely similar at the two stations; the similarity is seen even in D ($f_{o,F_2}$) being greater than Q($f_{o,F_2}$) only from noon onwards.

(2) The post-sunset rise in $f_{o,F_2}$ at +33° dip in the West zone is much larger than in the East zone. It is interesting to see that this post-sunset rise in $f_{o,F_2}$ is less on D days than on Q days in both zones and both hemispheres.

(3) The abnormal decrease of D ($f_{o,F_2}$) in D-months at equatorial Huancayo (+2° dip) in the West zone is not seen at equatorial Trivandrum (-0.6° dip) in the East zone. Also the midday bite-out in $f_{o,F_2}$ seen at Trivandrum is absent at Huancayo; at the latter it is observed on the disturbed days of the D-months.

(4) The difference between D ($f_{o,F_2}$) and Q ($f_{o,F_2}$) at southern mid and high latitudes is much greater in the West zone than in the East zone. Also the anomalous feature of night $f_{o,F_2}$ exceeding daytime $f_{o,F_2}$ in D-months seen at -56° dip (Port Lockroy) in the West zone is not seen at the corresponding dip (Brisbane) in the East zone.
The anomaly at equatorial Huancayo of $D(f_0F_2)$ being less than $Q(f_0F_2)$ in the D-months is treated in detail in the two Papers (6,7) which follow. The first paper is a study in terms of $f_0F_2$, while in the second one, the electron density distribution at true heights are studied during the anomalous periods.

( Papers 6, 7 follow overleaf )
SHORT PAPER

Abnormal behaviour of \( f_0F2 \) at Huancayo in magnetically active periods of IGY-IGC

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Abstract—The way in which \( f_0F2 \) near noon varies with magnetic activity at different epochs of solar activity is studied. In the American zone, the normal equatorial increase in noon \( f_0F2 \) for disturbed days is replaced by a decrease in \( f_0F2 \) during the December solstice (local summer) of years with large solar and magnetic activity.

Appleton et al. (1937) had found a strong negative correlation between the critical frequency of the \( F2 \)-layer \( (f0F2) \) and the magnetic activity at high latitude stations, Slough and Tromso. Berkner and Shon (1940) showed that the electron density averaged for the whole day at equatorial station, Huancayo, increased continuously with the increase of magnetic activity during any of the seasons. Whereas, at temperate latitude station Watheroo, the electron density during summer months decreased continuously with the increase of magnetic activity but during the winter months it increased for small magnetic activities and then decreased as the activity became more severe.

Appleton and Progott (1955) found that the ratio of noon \( f_0F2 \) during disturbed and quiet days of the equinoxes at various ionospheric stations of the world when plotted against geomagnetic latitude, showed negative phase at both northern and southern high latitudes and a positive phase over a belt at the magnetic equator. Skinner and Wright (1955) found that the mean value of the maximum electron density of the \( F2 \)-layer between 1000 and 1400 hours at Ibadan showed monotonic increase with the daily sum of magnetic \( Kp \) index. Ranch (1962) showed that the mean value of \( (f_0F2)^3 \) for 11, 12 and 13 hr at equatorial stations Ibadan, Huancayo and Djibouti increased with increasing daily sum of \( Kp \) index during the June as well as December solstices. On the other hand, at temperate latitude stations Lwiro, Leopoldville and Tananarive the increasing \( Kp \) index increased mean \( (f_0F2)^3 \) during local winter months but decreased it during local summer months.

Oyabashi (1952) found that the daily variation on magnetically disturbed minus that on quiet days, called disturbance daily (SD) variation of the \( F2 \)-layer at Wakkanai consisted of an increase of the virtual height and the decrease of the critical frequency of the \( F2 \)-layer, the effect being much more pronounced in summer than in winter months. Comparing SD\( (f_0F2) \) variation at a number of stations, Matsuoka (1953a) found that there is a general tendency for the electron density to be lowered on the average at high latitudes and raised at low latitudes. The SD \( (f_0F2) \) variation at Huancayo was positive for any time of the day. In a later paper Matsuoka (1953b) studied SD\( (f_0F2) \) variation at temperate latitude stations Washington, Canberra and Watheroo and found that the mean values of \( f_0F2 \) were depressed in summer and equinoxes but the effect was very much smaller in winter: actually \( f_0F2 \) was slightly raised for Canberra and Watheroo. Mannar (1955) studied SD\( (f_0F2) \) variation at Huancayo from January 1951 to July 1952 and found that the variation was not too clear, a maximum seemed to occur at dawn and the maximum for harmonic results occurred in the daytime. Skinner and Wright (1955) found that the effect of magnetic activity at Ibadan consisted of an increase of \( f_0F2 \) at all hours of the day with a corresponding lowering of the height of the layer. Ranch (1962) studied SD\( (f_0F2) \) variation at stations in Central African regions and showed that the values of
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$f_0 F_2$ at Ibadan, Djibouti and Huancayo were generally higher during the disturbed than the quiet days of the June as well as the December solstices whereas at Leiro, Leopoldville and Tananarive the disturbed day values were greater than the quiet day values during the June solstice (local winter) and smaller during the December solstice (local summer). It was concluded that the magnetic disturbance generally increases the $f_0 F_2$ at low dip latitude (not geomagnetic latitude) stations during any of the seasons while at temperate latitudes the disturbance produces a decrease during local summer and an increase during local winter months.

Rastogi (1964) showed that the lunar perturbations in $f_0 F_2$ and in the horizontal component of earth's magnetic field, $H$, at equatorial stations are closely related being almost opposite in phase to each other. It was attempted to study if there exists similar relations between the perturbations of $f_0 F_2$ and $H$ caused by magnetic disturbances. Contrary to the expectations, the variations in $f_0 F_2$ and $H$ at Huancayo were found to be very similar to each other during certain periods of IGY and IGC. A detailed study of the simultaneous variations in $f_0 F_2$ and $H$ at Huancayo during magnetically active periods was therefore undertaken.

To examine the relation of noon value of $f_0 F_2$ and the degree of geomagnetic activity at Huancayo during the maximum sunspot year of 1958, the days are divided into groups with the daily sum of Huancayo magnetic index, $K$ figure being between 0-4, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34 and 35-39. The average value of $f_0 F_2$ at noon for each group of days so formed is computed separately for the June solstices (May, June, July and August months) and for the December solstices (November, December, January and February months). Figure 1 shows the relation between noon $f_0 F_2$ and the daily sum $K$ index for the two seasons. During June solstice (local winter), one finds the monotonic increase of $f_0 F_2$ with $K$ index. But during December solstice (local summer), $f_0 F_2$ decreases monotonously with increasing $K$ index. Rastogi (1962) has shown that the mean mid-day value of $f_0 F_2$ at Huancayo and other equatorial stations for the low sunspot period (1952-1963) increased with increasing interplanetary $K_p$ index during either of the solstices. Thus the effect of geomagnetic activity in noon $f_0 F_2$ at Huancayo during local summer months is opposite during the low and high sunspot years.

To further elucidate the effect of magnetic activity on $f_0 F_2$, the average solar daily variation of $f_0 F_2$ and $H$ at Huancayo are computed for the International Five Quiet (Q) and Five Disturbed (D) days of the two solstices of IGY and IGC and are shown in Fig. 2. The disturbance daily (SD) variations of $f_0 F_2$ and $H$ are also shown in the Fig 2.

During June solstice (local winter) the value of $f_0 F_2$ at Huancayo is greater on disturbed than on quiet days for any hour of the day. The SD($f_0 F_2$) variation is positive for any hour of the day, shows slightly higher values during the forenoon than the afternoon hours and a peak at about dawn period. During December solstice (local summer), $f_0 F_2$ is greater on disturbed than on quiet days for the night time hours only; but the values between about 0800 and 1600 hours are lower on disturbed than on quiet days. The SD($f_0 F_2$) variation is strongly diurnal in character with a minimum around mid-day hours.

Regarding the horizontal component of earth's magnetic field, $H$, its value for any hour of the day and for either of the solstices is markedly lower on disturbed than on quiet days,

Fig. 1. The relation between the noon value of $f_0 F_2$ and the daily sum of the $K$ index at Huancayo for the June and December solstices of the year 1958.
During the June solstice, the values of $f_0 F_2$ during the daytime hours at the equatorial stations Huancayo, Chimbote, Chiclayo and Talara are greater on disturbed than on quiet days. At Bogota there is little difference between the quiet and disturbed day values of $f_0 F_2$ while at temperate latitude station Panama (not shown in the diagram) and Puerto Rico, the value of $f_0 F_2$ for any hour is smaller on the disturbed than on quiet days. This decrease of $f_0 F_2$ due to magnetic disturbance, is much larger at high latitude station, Washington. The SD($f_0 F_2$) variation at southern latitude station Sao Paulo is very small during the daytime hours. At Buenos Aires and Port Stanley the value of $f_0 F_2$ is greater on disturbed than on quiet days. At Port Lockroy (not shown in the diagram), the SD($f_0 F_2$) was similar to that at Port Stanley. It is interesting to note that in spite of high geographic latitude of Port Lockroy (65° S), the SD($f_0 F_2$) variation at this station is similar to that at southern temperate latitude stations Leopoldville and Lwiro (Raemdonck, 1962) and opposite to that at northern temperate latitude stations Panama and Puerto Rico.

During the December solstice, the value of $f_0 F_2$ between 0800 and 1600 hours at any of the equatorial stations Huancayo, Chimbote, Chiclayo and Talara is markedly smaller on disturbed
Fig. 3. Average daily variations of $f_0F2$ on international quiet and disturbed days of June and December solstices of 1958 at the various stations in the American zone.
than on quiet days. At Bogota, the daytime $f_{0}F_2$ is slightly greater on disturbed than on quiet days while at Panama and Puerto Rico the increase of $f_{0}F_2$ on disturbed days is quite large and distinct. At Washington disturbed day values are smaller than the quiet day values. At southern stations Sao Paulo and Buenos Aires, there is very little difference between $f_{0}F_2$ on quiet and disturbed days. At Port Stanley, $f_{0}F_2$ for any hour is significantly smaller on disturbed than on quiet days. Thus excepting Panama and Puerto Rico all other stations in the American zone show a decrease of $f_{0}F_2$ due to magnetic disturbance during the December solstice of 1958.

Comparing the daily variations of $f_{0}F_2$ at local summer and winter months, it is seen that Washington behaves like a high latitude station experiencing decreased $f_{0}F_2$ on disturbed days at both the solstices. Puerto Rico, Panama and Port Stanley behave as a temperate latitude station, magnetic disturbances causing an increase of $f_{0}F_2$ during local winter and decrease of $f_{0}F_2$ during local summer months. The abnormality exists in the behaviour of $f_{0}F_2$ at equatorial stations Huancayo, Chimbote, Chiclayo and Talara where the magnetic disturbance causes an increase of daytime $f_{0}F_2$ during local winter and decrease of the same during local summer months in the same way as at any temperate latitude station.

To find out the extent of the years during which the decrease of daytime $f_{0}F_2$ at Huancayo during disturbed periods are found, the mid-day (1100, 1200 and 1300 hour mean) value of $f_{0}F_2$ at Huancayo averaged for the quiet and disturbed days of the June and December solstices of the years 1953-1961 are collected in Table 1. The ratio of $f_{0}F_2$ on D and Q days for each solstice is also given. During the June solstices of any of the years the mid-day $f_{0}F_2$ value is greater on disturbed than on quiet days. The ratio $D(f_{0}F_2)/Q(f_{0}F_2)$ ranges between 1.03 and 1.16. During the December solstices $f_{0}F_2$ is greater on disturbed than on the quiet days for the years 1953-1954 to 1956-1957, the ratio $D(f_{0}F_2)/Q(f_{0}F_2)$ being only between 1.01 and 1.06. During the December solstices of 1957-1958 to 1960-1961 the $f_{0}F_2$ is smaller on disturbed than on quiet days, the ratio $D(f_{0}F_2)/Q(f_{0}F_2)$ being between 0.94 and 1.00. During the November-December months of 1961 the $f_{0}F_2$ is again larger on disturbed than on quiet days.

To find out the $SD(f_{0}F_2)$ variation at different stages of solar activity, the average daily variations of $f_{0}F_2$ on disturbed and quiet days of each of the June and December solstices between the years 1953 and 1961 are shown in Fig. 4.

During the June solstice of any of the years 1953-1961, the value of $f_{0}F_2$ is greater on the disturbed than on the quiet days for almost any hour of the day or night. The difference in $f_{0}F_2$ on D and Q days is small for the years 1953 and 1954 but quite large for the years 1957 and 1958.

<table>
<thead>
<tr>
<th>Year</th>
<th>$D(f_{0}F_2)$ (Mc/s)</th>
<th>$Q(f_{0}F_2)$ (Mc/s)</th>
<th>Ratio $D(f_{0}F_2)/Q(f_{0}F_2)$</th>
<th>Year</th>
<th>$D(f_{0}F_2)$ (Mc/s)</th>
<th>$Q(f_{0}F_2)$ (Mc/s)</th>
<th>Ratio $D(f_{0}F_2)/Q(f_{0}F_2)$</th>
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<td>1.08</td>
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<td>1961</td>
<td>7.89</td>
<td>6.83</td>
<td>1.16</td>
<td>1961</td>
<td>9.95</td>
<td>8.95</td>
<td>1.11</td>
</tr>
</tbody>
</table>
During the December solstice, $f_a F2$ is larger on disturbed than on quiet days for almost all hours of the day in the years 1953-1954 and 1954-1955. In the season 1955-1956 few of the afternoon values of $f_a F2$ tend to be smaller on disturbed days, while the forenoon values are still larger on disturbed than on quiet days. In the season 1956-1957 the values of $f_a F2$ between 1600 and 1900 hours are decreased on disturbed days. The depression of the values of $f_a F2$ on disturbed days is found to be during 1000-1600 hours in 1957-1958. This depression of mid-day value of $f_a F2$ is very pronounced in 1958-1959 and 1959-1960, but the effect is very much reduced in 1960-1961. During the months of November-December 1961, SD variation seems to have been reversed, the values of $f_a F2$ are significantly larger on disturbed than on quiet days. Thus within the period of 1953-1961 studied at present the abnormal SDO($f_a F2$) variation at Huancayo is found during the December solstices of the years 1957-1958 to 1959-1960 and to a smaller extent in 1960-1961, i.e., during the period of maximum solar activity.

To find out the longitudinal extent of the anomalous behaviour of $f_a F2$ on disturbed days, the solar daily variations of $f_a F2$ on quiet and disturbed days of 1958 are computed for other equatorial stations, Ibadan and Kodaikanal. These curves are compared with those for Huancayo in Fig. 5. It is seen that the daytime values of $f_a F2$ at Ibadan and Kodaikanal are...
greater on disturbed than on quiet days of either of the seasons and are thus similar to the results for the low sunspot years. It is only at Huancayo during the December solstice when the values of $f_0F_2$ are decreased during the daytime on magnetically disturbed days. Thus the anomaly seems to be restricted to the equatorial stations in the American zone during the maximum sunspot years 1957–1958.

Acknowledgements—The authors are thankful to Dr A. A. Gershdeke and to World Data Centre A for Ionosphere and Airglow, Boulder for supplying the data of Huancayo. Thanks are also due to Prof. K. R. Ramanathan for stimulating discussions and to Mr. M. C. Sharma and Mrs. S. P. Jant for assistance in the preparation of the paper.

References


Abnormal electron density distributions over Huancayo on disturbed days of IGY/IGC

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Abstract. — Studying the midday value of $f_0F_2$ at Huancayo during 1938 to 1962, it has been found that $f_0F_2$ is higher on disturbed (D) than on (Q) quiet days during either of the solstices, except during the December solstices of 1957 to 1960. The ratio of midday $f_0F_2$ on D and Q days shows inverse relationship with sunspot number during December solstices. The $N_h$ profiles at Huancayo, Puerto Rico and Fort Monmouth during D and Q days indicate that the changes occur generally above the level of 200 km; the electron density is increased at Huancayo and decreased at Fort Monmouth, for either of the seasons, while at Puerto Rico, the electron density increases during winter, and decreases during summer months of 1961. Disturbance daily variation during 1961 shows that the major changes occurred around the midday hours. During November months of 1957-58 at Huancayo and Chimbote, the electron density at any height above 300 km was lower on disturbed than on quiet days, while during July months the electron density was higher on D than on Q days. The $D_s$ variations of $f_0F_2$ in any of the seasons of low, as well as high sunspot years, show a positive type of variation, $f_0F_2$ on storm days being higher than normal. The $D_s$ variation seems to be more prominent during the low sunspot years, and continues for a longer period than during high sunspot years, indicating some kind of saturation effect on the equatorial ionosphere during high sunspot years.
INTRODUCTION

It has been long known that magnetic disturbances decrease the critical frequency of the F\textsubscript{2} layer (f\textsubscript{0}F\textsubscript{2}) at high latitudes [APPLETON and INGRAM, 1935; HARANG, 1937; APPLETON, NAISMITH and INGRAM, 1937; APPLETON and PIGGOTT, 1950]. At the equatorial stations, it was found that the magnetic storms had an opposite effect, the critical frequency being increased during any of the seasons [BERKNER and SEATON, 1940; SKINNER and WRIGHT, 1955; MARTYN, 1959].

To find out exactly the periods during which the abnormal behaviour of ionospheric storms was observed, the ratios of midday critical frequency on Five International Disturbed and Five International Quiet Days were computed for the D-months (November, December, January and February) and for J-months (May, June, July and August) for all the years 1938 to 1962. Figure 1 shows the variations of these ratios compared with the yearly mean sunspot number. It is seen from the diagram that D/Q ratio during the J-months is always greater than unity for any of the years, the values being generally around 1.08, and there being no apparent solar cycle variation.

Solar cycle variation of the ratio of midday mean f\textsubscript{0}F\textsubscript{2} on Disturbed and Quiet days of J and D months at Huancayo for the period 1938-1962.

To study the behaviour of the F\textsubscript{2} region at different heights during comparatively low sunspot years, N-h profiles were computed for midday hours of five International Quiet days and five International Disturbed days of winter and summer months at the equatorial station, Huancayo, medium latitude station, Puerto Rico, and at high latitude station, Fort Monmouth, and these are shown in figure 2.

Fig. 1.

Solar cycle variation of the ratio of midday mean f\textsubscript{0}F\textsubscript{2} on Disturbed and Quiet days of J and D months at Huancayo for the period 1938-1962.
ABNORMAL ELECTRON DENSITY DISTRIBUTIONS OVER HUANCAYO

The profiles of electron density versus true height N-h in the ionosphere during the midday hours on Quiet and Disturbed days of a northern and a southern solsticial month of 1961 at equatorial (Huancayo), tropical (Puerto Rico), and high-latitude (Fort Monmouth) stations.

At Fort Monmouth, the average electron densities are higher during November than during May. This represents the well-known seasonal anomaly of higher foF2 occurring during winter than during summer. It is interesting to note that the heights of maximum electron density are not appreciably different during the two seasons, indicating that the electron density at any of the heights, are lower during summer than in winter, at high latitudes. Comparing the profiles on quiet and disturbed days, it is seen that the values are not significantly different from each other for levels ranging from 100 to 180 km. At heights above 200 km there is a definite decrease of electron density during the disturbed days, than during quiet days in either of the two seasons, maximum change occurring at the height of F2 peak. Regarding the profiles at Huancayo, we again find that the average electron density at any particular height is greater during November than during the July month. This indicates that besides abnormal seasonal variation, there is an annual effect causing greater ionisation during December solstices than during June solstices [Rastogi, 1960]. Comparing the profiles during quiet and disturbed days, one finds little change below the levels of 180 km while at any of the higher levels the ionisation is much larger on disturbed than on quiet days.

Regarding the variations at mid-latitude station, Puerto Rico, it is seen that again the magnetic disturbances affect the ionosphere only above 180 km. During the winter month of November 1961, the electron density seems to increase during disturbances, while during summer months there is a prominent decrease of electron density during disturbed days from about 200 km height. These changes in the electron densities at any of the stations and during any of the seasons are noticeable for the heights above 180 km, which means above the height of the F1 peak. This confirms Matsushita’s result [1962] for Puerto Rico, that the change during magnetic storms occurs at levels only above 200 km.

It is thus concluded that the results of previous investigators based on \( f_0 F_2 \) (proportional to maximum electron density) is confirmed for electron density at individual heights of the F1 region. Thus the magnetic disturbance causes the decrease of electron density at each height of the F2 layer during summer as well as winter at high latitudes; it increases the electron density at all heights during winter or summer for equatorial stations; while at medium latitude stations the magnetic storm effect on N-h profiles is of the equatorial type during winter, and of high latitude type during summer.

The maximum ionisation of the F2 layer \( (N_{\text{max}}F_2) \) the height of maximum ionisation \( (h_{\text{max}}F_2) \) and the totally integrated electrons over a vertical column of unit cross section \( (N_p) \), for each of the solar hours on the quiet and disturbed days of summer and winter months were studied at Fort Monmouth, Puerto Rico and Huancayo. The daily variation of these parameters on quiet and disturbed days is shown in figure 3. The circles indicate the quiet days, while the crosses indicate the disturbed day values.

The height of maximum ionisation \( (h_{\text{max}}F_2) \) shows a maximum during midnight, and minimum during midday hours at medium and high latitude stations (Puerto Rico and Fort Monmouth) while at equatorial stations, it is maximum in the afternoon hours and is lower during the night hours, in conformity with the conclusions of Wray [1962]. The maximum electron density at Fort Monmouth shows a maximum during midday, this being sharper in winter, and relatively flatter during the summer months. At Puerto Rico, the daytime maximum is close to midday during winter, but is shifted to the evening hours during summer months. At Huancayo there is a pronounced broad daytime maximum and the well-known bite-out effect at the equatorial stations is not evident.

Referring to Fort Monmouth it is seen that \( N_{\text{max}}F_2 \) is lower on disturbed days than on quiet days of winter for the hours, 06 to 12, while during the summer months on disturbed days, it is very significantly lower than that on quiet days for almost all the hours from 06 to 24. The height \( h_{\text{max}}F_2 \) is slightly higher on disturbed days during winter months, and smaller during summer months, the changes being very small. The total electron content \( N_p \) shows very small effect during winter and significant decrease during the disturbed days of summer. Thus, the effects of magnetic storms on high latitude F2 region seem to be most pronounced during the daylight hours and especially during the summer months. Regarding the profiles of Puerto Rico, it is seen that during the winter months of November 1961, both \( N_{\text{max}} \) and \( N_p \) are much larger on disturbed days than on quiet days for the daylight hours, the effect being too small for night hours 00 to 06 hours. The height \( h_{\text{max}}F_2 \) seems to have increased during the magnetic storms. During summer months of June 1961 the \( N_{\text{max}}F_2 \)
Fig. 3.
Daily variations of height of maximum ionisation ($h_{\text{max}}F_2$), maximum electron density ($N_{\text{max}}F_2$), and total electron content in a vertical column of unit cross-section ($N_T$) on Quiet and Disturbed days of a northern and a southern solstitial month of 1961 at Huancayo, Puerto Rico and Fort Monmouth.
as well as $N_T$ have decreased for the hours 06 to 20. The slight increase during the night hours 20 to 06 is also clear. There is no distinct effect in $h_{\text{max}}F_2$.

Regarding Huancayo it is seen that in general there is an increase of $N_{\text{max}}F_2$ during disturbed days of either summer or winter, although the effect is more pronounced during the daytime hours. The effect on $h_{\text{max}}F_2$ is again small and uncertain.

Skinner and Wright [1955] have studied the variations of parameters of the $F_2$ layer at Ibadan during magnetically quiet and disturbed days, and they have found that $N_{\text{max}}F_2$ is larger on disturbed than on quiet days. For any of the hours correspondingly, $N_T$ is also greater on disturbed than on quiet days. They have found that the base of the $F_2$ layer $h'F_2$ is lowered during the daytime hours of disturbed days, but $h_{\text{max}}F_2$ is decreased on disturbed days, between 08 to 13 hours and increased between 13 to 19 hours. The midday minimum of $N_{\text{max}}F_2$ seemed to disappear as magnetic conditions became more disturbed. Thus the variations of the $F_2$ layer parameters at Huancayo during 1961, are very similar to that found at the equatorial station, Ibadan.

Having found the normal expected variation of the disturbed $F_2$ layer during the relatively quiet period of 1961, the electron density profiles of one summer and one winter month were computed from the ionograms for the equatorial stations, Huancayo and Chimbote. The mean $N-h$ profiles over 11, 12 and 13 hours are shown in figure 4. The diagram shows profiles of July and November 1957 for Huancayo, and July and November 1958 for Chimbote. It is seen that the $N_{\text{max}}F_2$ at both Huancayo and Chimbote are larger during November than during July months. Comparing the mean profiles during July and November months, it seems that during 1957 at Huancayo, the electron densities were not appreciably different during the two seasons upto 300 km and there was additional ionisation till about 400 km which gave rise to much higher $N_{\text{max}}F_2$. During 1958 at Chimbote, the electron density seems to be higher in November than in July for any of the heights, the change being more at greater heights. Thus, the larger cri-
Storm-time variations of \( f_0F_2 \) during \( D, E, J \) and all months at Huancayo during years of low and high solar activity.

In figure 5 are compared the solar daily variations of \( h_{\text{max}}F_2 \), \( N_{\text{max}}F_2 \) and \( N_T \) during the July-November months at Huancayo and Chimbote. Referring to the curves for the July months it is seen that \( N_{\text{max}} \) and \( N_T \) during the daytime hours are higher on disturbed than on quiet days, and the effect is small and uncertain during the night hours. The height \( h_{\text{max}}F_2 \) has a tendency to be slightly higher on the disturbed than on the quiet days. During the November months the decrease in \( N_T \) and \( N_{\text{max}}F_2 \) during the disturbed days is again significant during the midday hours while changes in \( h_{\text{max}}F_2 \) during the daytime are uncertain. These results indicate that the decrease or the increase in \( N_{\text{max}}F_2 \) is not basically due to the change in the level of peak \( f_0F_2 \) but all the heights near the peak are affected similarly.
It was felt desirable to see the effect of abnormal disturbed daily variations, and the storm time variation, and hence $D_n$ variations in $f_0F_2$ at Huancayo were computed for the three seasons D-months (November, December, January and February), E-months (March, April, September and October) and J-months (May, June, July and August) both for the low sunspot years 1956, 1960 and 1961, and for the high sunspot years 1957, 1958 and 1959 (fig. 6). It is seen that during any of the seasons and epochs, the $D_n$ variation of $f_0F_2$ at Huancayo is basically of a positive type. There are, however, large variations during the D-months of the high sunspot years, there being a small negative phase on the 2nd and 3rd days which could be due to remnant disturbance daily variation.

It is however interesting to note that the annual average $D_n$ variation, expressed here in terms of the ratio of $f_0F_2$ on the disturbed day over the corresponding mean value, is more pronounced during the low, than during the high sunspot years. This means that the magnetic storm effects produce comparatively larger proportional changes in the electron density of the $F_2$ layer at the equatorial stations, during the low than during the high sunspot years. Further the positive phase of the storm seems to remain for a larger period i.e. up to about 2 1/2 days during the low sunspot years, whereas it comes to normal value in about 1 1/2 days during the high sunspot period. Further analyses are contemplated to study the solar cycle variations of $D_n$ in $f_0F_2$ at equatorial stations.

ACKNOWLEDGMENTS

Sincere thanks are due to the Institute of Telecommunication Sciences and Aeronomy at Boulder, for making available the ionograms and other data, which have been used for this study, and to Professor K. R. Ramanathan, for suggestions and discussions during the course of the study.

Manuscrit reçu le 9 septembre 1968.

REFERENCES


4.7 EQUATORIAL ELECTRON DENSITY DISTRIBUTIONS DURING QUIET AND DISTURBED CONDITIONS

Comparisons of electron density distributions on International Quiet and Disturbed days for different seasons and different solar cycle epochs have been made by considering the following equatorial stations:

- Huancayo - dip + 2° (West Zone)
- Thumba - dip 0.6° (East Zone)
- Kodaikanal - dip + 3.5° (East Zone)

The true height profiles were computed from the ionograms for the stations by using Budden's Matrix method. The diurnal variations of $h_{max}$, $y_m$, $N_T$, and $N_{max}$, the contours of constant electron density, and electron density distributions at constant heights, have been taken into consideration in making comparisons between magnetically Quiet and Disturbed days.

(a) Studies at Thumba

1) Variations of $h_{max}$, $F_2$, $y_m$, $N_T$, $N_{max}$, $F_2$

Fig. 4.11 (Pg. 101 (a)) shows the variations of $h_{max}$, $y_m$, $N_T$, and $N_{max}$ on quiet (Q) and Disturbed (D) days for 3 typical seasons - January (winter), April (Equinox), and July (Summer). The variations are shown for 1967 (a high sunspot year $R_z = 96$) and 1965 (a low sunspot year $R_z = 15$).
It is clearly seen that:

(1) In Jan. and April 1967, there is a post-sunset rise in $h_{\text{max}} F_2$ which seems slightly less on D days than that on Q days. This point could be significant in throwing light on the cause of the equatorial post-sunset height rise. In July 1967, this feature is not seen on either Q or D days. It is not seen in any season of 1965. In 1967 January and July, $h_{\text{max}} F_2$ on D days is less than on Q days, but this is not clear in April. In 1965 the reverse seems to occur, true heights on D days being greater than on Q days. Overall values of $h_{\text{max}} F_2$ are larger in 1967 than in 1965.

(2) The variations of $y_m$ show that the semi-thickness reaches its maximum values shortly before midday, during both Q and D conditions in every season in both years.

In the low sunspot year of 1965, there are clear differences in $y_m$ between Q and D. In April and July, the semi-thickness on D days is greater than on Q days, but in January in the daytime hours, values of $y_m$ on D days are less than those on Q days. Overall values of $y_m$ too are larger in 1967 than in 1965.

(3) Variations of $N_T$ differ more between Q and D days in 1965 than in 1967. In general, in 1965, $N_T$ on D days is more than on Q days in all seasons. The same is true of
Since both $N_T$ and $N_{max}$ show an increase, the $F_2$ layer is not merely being compressed so as to increase peak ionisation densities. A real absolute increase in the total number of electrons is taking place during disturbed conditions.

In 1967, the variations of $N_T$ and $N_{max}$ do not differ much between $Q$ and $D$ conditions in any season. Only in the equinox (April) does it appear clearly that both $N_T$ and $N_{max}$ are greater on $D$ than on $Q$ days. In January, $D$ values seem slightly less than $Q$ values in the daytime hours, while nothing can be said of July. The midday bite-out feature in $N_{max}$ is seen in all seasons of 1967, and April and July 1965, but it is not clear in January 1965. Clearly absolute values of $N_T$ and $N_{max}$ are more in 1967 than in 1965.

(ii) Iso-electron density contours during quiet ($Q$) and Disturbed ($D$) days.

These studies are made for the $Q$ and $D$ days of the same three representative months at Thumba and are shown in Fig. 4.12 (Pg. 105 (a)).

Considering overall behaviour of the two sunspots, it is seen that:
(1) There is a greater crowding together of contour lines because of larger electron densities in high sunspot than in low sunspot. This is true of all heights above 200 km; levels below this are not appreciably affected. The change in peak electron density from low to high sunspot can be seen from the diagrams and differs almost by a factor of 2.

During Quiet conditions afternoon peak values change thus -

<table>
<thead>
<tr>
<th>Electron density in el/cm³</th>
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<td>Month</td>
</tr>
<tr>
<td>January</td>
</tr>
<tr>
<td>April</td>
</tr>
<tr>
<td>July</td>
</tr>
</tbody>
</table>

During Disturbed conditions the changes are -

<table>
<thead>
<tr>
<th>Electron density in el/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
</tr>
<tr>
<td>January</td>
</tr>
<tr>
<td>April</td>
</tr>
<tr>
<td>July</td>
</tr>
</tbody>
</table>
The sharp height gradient of iso-electron density contours around sunrise and sunset (around 06 hr and 18 hr) is more marked in high sunspot than in low. The steep post-sunset rise in heights is absent in the low sunspot years, and is more marked in January and April of high sunspot, not in July.

In low sunspot years, particularly on Q days, ionisation before sunrise falls to levels too low to be detected by the ionosonde. This feature is not so in high sunspot years when a good amount of ionisation persists even before sunrise.

In low sunspot years, both on Q and D days, peak heights of ionisation are attained in the midday hours. In high sunspot years, they occur after sunset.

These are a few of the solar cycle differences in electron density distributions at Thumba. A detailed study of these solar cycle differences on Q days at Thumba is presented by Chandra (1969) in his Ph.D. thesis.

Comparing the density distribution on Q and D days from the same figure, the salient features are:–

There are greater electron densities on D days as compared to Q days. This is true of both high and low
sunspot years at heights above 200 km - levels below this seem unaffected by magnetic disturbances. An exception to these observations are the D days of July 1965, where the contours are farther apart than on Q days. This may be due to greater height distributions of ionisation on D days in July. It may be noted that $h_{\text{max}} F_2$ on D days is on an average greater than on Q days by almost 50 km.

(2) There has been an enormous and sudden height rise after 18 hr in the Q days of April 1967 followed by spread-F conditions. It may be noted that in the D days of the same month, the post-sunset height rise is less sudden and of less magnitude, and no spread-F is seen. It is known that at equatorial stations, spread-F is less on D Days than on Q days; hence its occurrence may be related to this height rise.

(iii) Electron density distribution at constant heights.

In Fig. 4.13 (Pg.106 (a) ) the electron density distributions at constant heights at Thumba are compared between Q and D days for the January, April, and July months of 1967 and 1965. On the average, electron densities on D days are greater than on Q days, in each season of both sunspots (except in January 1967) and the midday bite-out feature too seems to be reduced on D days. The afternoon peak seems to broaden out on D days as compared to Q days.
particularly at greater heights. Some of the more minute differences can be observed from the figure itself. The markedly lower electron densities in 1965 (a low sunspot year) as compared to 1967 (a high sunspot year) can be clearly seen. It is clear that in 1967, up to a height of 180 km the electron density varies with a simple Chapman behaviour with peak values around midday. At heights above this the day time bite-out in electron density starts manifesting itself. In 1965, such bite-out is seen only at levels above 220 km. The level at which bite-out commences therefore, seems to be a function of solar cycle, being lower in high sunspot, and higher in low sunspot.

(b) Electron density studies on O and D days at Huancayo.

(i) Variations of $h_{\text{max}}$, $F_2$, $y_m$, $N_T$, $N_{\text{max}}$, $F_2$

Variations of $h_{\text{max}}$, $y_m$, $N_T$ and $N_{\text{max}}$ for the same seasons - January (summer), April (equinox), and July (winter), are shown for Huancayo (12°S geographic) in the American zone. The years chosen are 1961 - a medium sunspot year ($R_z = 5$) and 1964 - a low sunspot year ($R_z = 10$) and the variations are shown in Fig. 1.14 (Pg. 107(a)).
Fig 4.14
A study of the variations reveals:

(1) In January and April of both 1961 and 1964 there is a post-sunset rise in $h_{\text{max}} F_2$. It is not present in July of either year; the sharp rise on D days of July 1961 seems spurious, and may be due to insufficient data. It is difficult to come to any conclusions on the variations in $h_{\text{max}} F_2$ between Q and D days. In both years in April and July, heights on D days seem to exceed heights on Q days, while in January, overall heights seem to be less on D days except for a few hours around midday in 1964. It is difficult to say anything about the relative magnitudes of the post-sunset rise on Q and D days. Overall $h_{\text{max}} F_2$ is larger in 1961 than in 1964.

(2) Variations of $y_m$ show more differences between Q and D in 1961 than in 1964. The trend is the same, with semi-thickness reaching minimum values around 06 hr. and maximum values at or shortly before midday. One gains a general impression that $y_m$ is slightly greater on D days than on Q days in all seasons of 1961, while in 1964 there seems little difference between the two.

(3) Both $N_{\text{max}} F_2$ and $N_T$ are larger in 1961 than in 1964. It is difficult to say much about the trend of $N_T$ and $N_{\text{max}}$ on Q and D days. In 1961 in January, D values are less than Q; in April D values exceed Q. There is
uncertainty in July. In 1964, D values exceed Q in April (equinox), but uncertainty prevails in both January and July. As far as $N_{\text{max}} F_2$ is concerned, only the equinoctial months of both years follow the accepted ideas of disturbances increasing $F_2$ electron densities at the equator. The behaviour in Jan. 1961 of disturbed $N_{\text{max}} F_2$ being less than quiet $N_{\text{max}} F_2$ is rather unexpected. The fact that $N_T$ has also decreased shows that the decrease has been due to a real loss of ionisation, and not merely to changes in the ionisation peak height. It may be noted that Disturbed $N_{\text{max}}$ and $N_T$ were less than Quiet $N_{\text{max}}$ and $N_T$ in January 1967 at Thumba too. This arouses a feeling that equatorial stations have a tendency to show a decrease in ionisation during disturbed conditions notably in the December solstitial months. Why this should be is not understood, and needs investigation.

(ii) Iso-electron density contours on Q and D days.

These studies are made for Huancayo for the Q and D days of the three months January, April and July of the low sunspot year 1964 (Fig. 4.15) (Pg. 109 (a)) and the outstanding features are:

1. Least crowding of contours and smallest electron densities occur in July; this is true of both Q and D days.

2. The sharp increase in ionisation at sunrise (around 06 hr.) is seen in all seasons on both Q and D days. A sharp drop in ionisation at sunset (around 18 hr) is however seen only in April.
Fig. 4.14 (Pg. 107 (a)) showed that a substantial change in $N_{\text{max}} F_2$ between Q and D days is clear only in April 1964, but is not obvious in January and July 1964. A closer look at Fig. 4.15 (Pg. 109 (a)) shows that even in 1964 the change is in the forenoon peak rather than in the afternoon peak. The forenoon peak electron densities change thus

<table>
<thead>
<tr>
<th>Month</th>
<th>Quiet</th>
<th>Disturbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>$6 \times 10^5$</td>
<td>$8 \times 10^5$</td>
</tr>
<tr>
<td>April</td>
<td>$7 \times 10^5$</td>
<td>$8 \times 10^5$</td>
</tr>
<tr>
<td>July</td>
<td>$4 \times 10^5$</td>
<td>$5 \times 10^5$</td>
</tr>
</tbody>
</table>

Afternoon peak electron densities change only in April between Q and D days in 1961.

(4) No post-sunset rise in ionisation height is seen in any season either on Q and D days for this year. Clearly this feature is characteristic of high sunspot only.

(iii) Electron density distributions at constant height during Q and D conditions.

These variations at Huancayo are compared for Q and D days for the same three seasons of 1961 and 1964 in Fig. 4.16 (Pg. 109 (a)).
The electron densities on D days are larger than on Q days particularly in the afternoon hours; in January 1961 the forenoon peak has decreased on Q days. The finer details can be seen from the diagram itself. The feature of lower electron densities in 1964 (a low sunspot year) as compared to 1961 (a medium sunspot year) is clear. The midday bite-out in $N_{\text{max}} F_2$ is more prominent in 1964; in 1961, there is an unconventional midday peak in $N_{\text{max}} F_2$. The daytime bite-out in electron density commences above heights of 200 km in January and April. In July there is no clear bite-out even at the $N_{\text{max}} F_2$ level in 1964, and very little in 1961. Specific differences between the two years in the levels at which bite-out commences are not obvious.

4.8 Longitudinal differences in Quiet and Disturbed-day behaviour of equatorial electron density distributions (Kodaikanal and Huancayo)

Comparisons of magnetically Quiet and Disturbed conditions for identical periods of high sunspot were made for the equatorial stations Kodaikanal (East zone) and Huancayo (West zone), to see how the widely differing geomagnetic field characteristics at the two locations would affect the electron density distributions with height.
(a) Comparison of \( h_{\text{max}} F_2 \), \( y_m \), \( N_T \), \( N_{\text{max}} F_2 \)

Fig 4.17 (Pg. 112 (a)) shows the variations of \( h_{\text{max}} F_2 \), \( y_m \), \( N_T \), and \( N_{\text{max}} F_2 \) on Q and D days at these two stations for July 1957, 1958, and November 1957, 1958. Being equatorial stations it was believed that seasonal effects would not enter too much in the picture.

(1) \( h_{\text{max}} F_2 \) variations

Peak \( F_2 \) heights seem larger at Kodaikanal than at Huancayo, and the difference is larger in July (almost 100 km) and less in November (about 50 km) of both years. The post-sunset rise in height too is more prominent at Kodaikanal than at Huancayo. This fact could be of importance in deciding the part played by electric fields in the height-rise. At both places, minimum \( h_{\text{max}} F_2 \) values occur around 06 hr. and maximum after 18 hr. In 1958, there is little difference in \( h_{\text{max}} F_2 \) between Q and D days, at both places - only Kodaikanal in July 1958 shows D values to be slightly greater than Q. In 1957, differences are clear at both locations. In July 1957 D values of \( h_{\text{max}} F_2 \) are greater than Q values at almost all hours of day at both stations. In November 1957, D values of \( h_{\text{max}} F_2 \) are less than on Q days at both stations, and it is accompanied by a decrease in both \( N_{\text{max}} F_2 \) and \( N_T \) on D days at both locations.
(2) $y_m$ variations: - The semi-thickness follows the general trend with lowest values around 06 hr. and maximum values around midday. It seems too that semi-thickness at Kodaikanal is greater than at Huancayo. This tendency is clear in July 1957, and November 1957, 1958, but not so in July 1958.

Variations in $y_m$ between Q and D conditions are uncertain. In November 1957 clearly at both stations, $y_m$ in sympathy with $h_{\text{max}} F_2$ is less on D days than on Q days, except for a sudden rise around 12 hours at both places. In July 1958, D values seem greater than Q at Kodaikanal, and less at Huancayo. Nothing specific can be said of July 1957 and November 1958.

(3) $N_T$ and $N_{\text{max}} F_2$ variations - follow the expected trend of minimum values around 06 hr. and maximum values in the daytime. No bite-out effect is observed in $N_T$. In July 1957 and July 1958, D values of both $N_T$ and $N_{\text{max}}$ are greater than Q values, at both stations in conformity with the accepted behaviour of disturbance effects on equatorial $F_2$. A longitudinal difference is that the midday bite-out in $N_{\text{max}} F_2$ seen at Kodaikanal is not seen at Huancayo (Rastogi and Sanatani 1963). In November 1957 it is interesting to see that at both Kodaikanal and Huancayo,
D values of \( N_{\text{max}} F_2 \) and \( N_T \) are less than \( Q \) values. This is an unusual feature for equatorial stations, and it may be recapitulated that this decrease of \( N_{\text{max}} F_2 \) during disturbed conditions also occurred at Huancayo in January 1961, and at Thumba in January 1967. One is left wondering what agent it is that occasionally in December solstitial months, destroys equatorial ionisation during disturbed conditions. In November 1958, at Kodaikanal, D values of \( N_{\text{max}} F_2 \) and \( N_T \) exceed \( Q \) values as expected; at Huancayo, however, D values continue to be less. The midday bite-out in \( N_{\text{max}} F_2 \) is absent at Huancayo in November too; at Kodaikanal it is less in November than in July.

(b) Comparison of electron density distributions at constant heights.

Electron density distributions at constant heights are compared in Fig. 4.18 (Pg. 114 (a)) for \( Q \) and D days for the same solstitial months July 1957 and July 1958, and November 1957 and November 1958, at the two longitude zones. Electron densities at both Kodaikanal and Huancayo are larger in November than in July. The midday bite-out feature is totally absent at Huancayo, while at Kodaikanal, it is more pronounced in July, 1957, 1958, less in November 1957, and least in November 1958. Electron densities are larger on D days than on \( Q \) days; this however is not so at equatorial Chimbote (taken instead of Huancayo) in
Fig. 4.18
November 1958, when disturbed day electron densities in the
daytime are less than on quiet days. In November 1958, there
is no bite-out at Kodaikanal in the midday hours, and the
variations greatly resemble those of Chimbote in the
American zone.

4.9 Conclusions

These studies of Quiet and Disturbed electron
density distributions at true heights for different
seasons and sunspot epochs for equatorial stations, bring
out the following points.

(1) In general there is a tendency for both $N_{max}$ and
$N_T$ to increase during disturbed conditions as compared to
quiet, particularly in low sunspot years. Since both the
parameters increase simultaneously, the peak in $F_2$
ionisation is not a consequence of mere height-changes,
but represents a real absolute increase in the total
number of electrons during disturbances. Such an increase
can be caused by the following possibilities
(1) a decrease in the loss rate of ionisation
(2) an input of ionisation from elsewhere, other latitudes by
thermospheric winds, or from the magnetosphere by
precipitation. Recent satellite studies have proclaimed the
presence of soft particle ionisation at equatorial latitudes
(Heikkila 1971; Hilton et al., 1964). Mariani (1964) feels that corpuscular radiation plays an important role in the formation of the $F_2$ geomagnetic anomaly.

(3) a decrease in the amount of ionisation transported out from equatorial regions to the anomaly crest region. Either the diffusion coefficients associated with the transport of plasma change, or the amount of ionisation made available for easy diffusion at greater heights changes. The latter would be governed by the equatorial $E \times B$ lifting force, and this could be reduced by a decrease in $E$ during disturbed conditions. This is treated in detail in Ch. 6.

Occasionally, particularly in the December solstitial months of high sunspot years, both $N_{max} F_2$ and $N_T$ decrease in the daytime during disturbed conditions as compared to quiet. This is seen at Thumba in January 1967, Huancayo in January 1961, Kodaikanal and Huancayo in November 1957, and at Huancayo again in November 1958. The decrease of $f_0 F_2$ during disturbed conditions as compared to quiet was shown to occur at Huancayo during the December solstitial months of every year from 1957 to 1961 (Rastogi and Rajaram 1965). Since both $N_T$ and $N_{max} F_2$ change, there is an actual loss in the total amount of ionisation. At such times, $h_{max} F_2$ varies sympathetically, with smaller daytime heights during disturbances; this suggests the presence of some force.
driving ionisation down into regions of greater loss. Why it should occur only in December solstitial months is not clear. \( y_m F_2 \) does not show a decrease during disturbed conditions at such times.

Bhargava and Gopala Rao (1959) have classified \( F_2 \) region ionospheric storms at Kodaikanal into the positive and negative categories; they find positive storms generally commence in the evening hours. A study of \( F_2 \) layer ionisation at Kodaikanal during Quiet and Disturbed days was made by Venugopal (1959).

(3) Changes in \( h_{\text{max}} F_2 \) and \( y_m \)

\( h_{\text{max}} F_2 \) during disturbed conditions is greater than during quiet conditions for normal conditions when \( N_{\text{max}} F_2 \) also increases in the daytime on \( D \) days. The change is not uniform over the different hours of the day or over the different seasons, and can vary from 10 km. to 50 km. In general \( h_{\text{max}} F_2 \) variations are sympathetic with \( N_{\text{max}} F_2 \), increasing when the latter increases, and decreasing when it decreases.

\( y_m F_2 \) does not always exhibit this sympathetic variation with \( h_{\text{max}} F_2 \) and \( N_{\text{max}} F_2 \). Its behaviour is quite complicated and requires more study.
Regarding longitudinal differences, equatorial $h_{\text{max}}^F_2$ is larger in the Indian zone than in the American zone in the high sunspot years; this is fairly true of $y_m$ too. The post-sunset rise in $h_{\text{max}}^F_2$ is less on D days than on Q days in both zones, and on Q days, is more pronounced in the Indian zone than in the American zone. These features are clearly connected with the different geomagnetic field values at the two locations.