IONOSPHERIC F2-LAYER DURING MAGNETIC STORMS - I
CHAPTER II

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CHAPTER II

GEOMAGNETIC STORMS AND THE IONOSPHERIC F2-LAYER NEAR THE EQUATOR AND NEAR THE LATITUDE OF DAYTIME PEAK ELECTRON DENSITY

1. INTRODUCTION

It is now well recognised that the earth's ionosphere is greatly affected by the solar phenomena such as sunspot activity, solar flares and corpuscular streams. Geomagnetic activity is also very much connected with such solar phenomena. As early as 1932-33, the British Polar Expedition (APPLETON et al, 1937) discovered that the polar ionosphere was disturbed by geomagnetic storms during which radio black-outs and auroral Es-echoes were observed which are now ascribed to the precipitation of charged particles in the earth's upper atmosphere. Later it came to be known that the equatorial ionosphere too was disturbed during geomagnetic storms. Of the various layers in the ionosphere, the F2-layer is most affected at all latitudes whereas the lower layers viz. F1 and E layers are not much affected in low and middle latitudes. Temporary increase of electron density near the F1-peak at low latitudes was found by KING (1963) who correlated it with low-lying prestorm F-region.

The first report on the storm-effects in the F2-layer at the equatorial station, Huancayo (12°S, 75.2°W; I = 2.6°N)
came in 1940 when BERKNER and SEATON (1940a) showed that the maximum electron density in the F2-layer generally increased with magnetic activity of character figure up to 2 (Fig. 2.1).

Fig. 2.1 Variation of critical frequency of the F2-layer with magnetic activity. (after Berkner & Seaton, 1940).

They (1940b), however, reported a case in which the F2-layer rose to great heights and almost disappeared within about 30 minutes after the onset at 1041 hr (75°W) of the main phase of a great magnetic storm on 24 March 1940. The ionogram traces showing these changes are reproduced in Fig. 2.2. FERREL (1951)
reported that it was possible to communicate at frequencies as high as 50 MHz following magnetic storm via the equatorial F2-layer from North to South America.

Fig. 2.2 The ionogram traces showing the changes in the F2-layer at Huancayo following a very severe magnetic storm of 24, March 1940, SC time 1349 hr GMT. (after Berkner & Seaton, 1940).

Systematic studies on the storm-effects began in the fifties of the 20th century. APPLETON and PIGGOTT (1952) found
from a statistical study that in almost all cases Huancayo recorded a daytime increase in the critical frequency of the F2-layer (foF2) and this decreased at higher latitudes, the depression being more during high sunspot years. KOTADIA (1962) showed from superposed-epoch analysis of the foF2 data of Indian stations that the changeover from equatorial increase to high-latitude decrease of foF2 around midday occurred at about magnetic dip 20° (Fig. 2.3). The reversal in the lunar semidiurnal variation of foF2 also happens to be at the above dip angle (KOTADIA, 1959, 1962; RASTOGI, 1961). Not only the electron density, but the total columnar electron content up to the height of maximum electron density both in the bottomside and the topside is also enhanced on magnetically disturbed days (KING et al. 1967; MATSUSHITA, 1963).

In this chapter, changes in the F2-layer critical frequency are compared with the changes in the H-component of the earth's magnetic field for some specific instances of storms and then average disturbance solar diurnal (DS) variations and storm-time (Dst) variations are calculated for two stations, Kodaikanal (10° 14'N, 77° 29'E; I = 3.5°N) and Ahmedabad (23° 01'N, 72° 36'E; I = 34°N) where the F2-layer changes are believed to be linked with the transport of electrons along geomagnetic field lines. The DS and Dst studies of ionospheric variations were initiated by MARTYN (1953) on the same lines as followed by magneticians (CHAPMAN, 1927; MOOS, 1910). A slightly different method is adopted in our analysis. Some
Figure 2.3 Variation of midday (10-14 hr) foF2 by superposed epoch method at Delhi, Ahmedabad, Bombay, Madras and Tiruchirapalli, 27 epochs in 1954, based on depression of midday foF2 by more than 10% of monthly median at Ahmedabad (right hand side) and at Delhi (left hand side) on zero day. K index for Alibag is also shown at the top. (after Kotadia, 1962).

Japanese workers (SINNO, 1955; OBAYASHI, 1954) made follow-up studies. "We have chosen these two low-latitude places in the East because of their great importance to the understanding of the mechanisms and theories on the equatorial F2-layer".
2. SOME TYPICAL INSTANCES OF STORM-VARIATIONS

The variations in foF2 are expressed as ratios of the disturbed-day foF2 to the monthly median value (treated as normal) at the respective hour and the variations in the H-field are just the deviations from the monthly mean. Deviations of hpF2 at Ahmedabad and of h'F at Kodaikanal are also shown (Kodaikanal tables do not give hpF2). Standard meridian time for these stations is 75°E.M.T. hours.

2.1 Storm on 26-3-59

The magnetic storm on 26 March 1959 commenced at 1342 hr. It was a severe storm producing a maximum variation of the H-field of 520 Y. The ionospheric F2-layer changes at Ahmedabad (AHD) and Kodaikanal (KDK) and those of the H-field at Kodaikanal and Alibag are given in Fig.2.4. It is seen that the changes in foF2 and in hpF2 or h'F are generally in opposite directions with some exceptions, e.g. the morning rise of foF2 at KDK on 28-3-59 is not accompanied by fall in height. The changes in height are rather irregular, these being perhaps greatly offset by the transport of ionization. Simultaneous increase of foF2 and the height of the layer would mean that the loss-rate of electrons is decreased and/or there is a real addition of new ionization in the upper F2-layer. The instance given here is an example of positive F2-storm at Kodaikanal and negative at Ahmedabad on the same day as defined in
Fig. 2.4 Changes in $h'F2$ and $foF2$ at Ahmedabad (AHD) and $h'F$ and $foF2$ at Kodaikanal (KDK) during a severe magnetic storm which commenced at 1342 hr on 26-3-59. H-field variations at Alibag and Kodaikanal are also shown. This is a case of positive $F2$-storm at KDK and negative at AHD on the same day.

Section 4. One cannot say that the increase at KDK is entirely due to the decrease at AHD by way of transport process, when changes of $foF2$ at the two places are in opposite direction particularly during the daytime and sometimes even during the night. Other factors such as loss-rate of electrons and temperature effects add to the complexities of the disturbance.
effects. In this particular instance, the temporary decrease of foF2 at KDK at the onset of the main phase is not to be found, perhaps because of observations at hourly intervals. However, the changes in height are nearly in accordance with the changes in the H-field that are superposed on the storm-time variation.

2.2 Storm on 6-10-60

A severe magnetic storm commenced at 0736 hr on 6 October 1960 and the daily range in the H-field recorded at KDK was 458 T. Inspite of its being severe, the F2-storm turned out to be a positive one at KDK as well as at AHD, though the daytime positive changes at Ahmedabad were not very marked (Fig.2.5). Initial drop of foF2 was recorded at both the places with the onset of the main phase of the magnetic storm. As before, changes in foF2 are generally in opposite direction to those of hpF2, and the latter more or less follow the fluctuations of the disturbance H-field. A large increase of electron density was found in the early morning hours of the day following the day of SC, but it dropped considerably on the second night during the recovery phase,

2.3 Storm on 11-6-59

This was a storm of moderate intensity producing a daily range of the H-field equal to 191 T. It commenced at
Fig. 2.5 Changes in hpF2 and foF2 at Ahmedabad and h'F and foF2 at Kodaikanal during a severe magnetic storm which commenced at 0736 hr on 6-10-60. H-field variations at Alibag and Kodaikanal are also shown. A case of simultaneous positive F2-storm at KDK and AHD.

1406 hr on 11 June 1959. This was an instance when the generally observed disturbance effect in foF2 was reversed, i.e. there was increase of foF2 at AHD and decrease at KDK on the second day of the storm (Fig. 2.6). Regarding the changes in heights, they were as stated in previous two cases. The occurrences of positive F2-storms at AHD and negative F2-storms at KDK during the same magnetic storms were hardly 10 per cent of the total.
Fig. 2.6 Changes in $h'F_2$ and $foF_2$ at Ahmedabad and $h'F$ and $foF_2$ at Kodaikanal during a moderate magnetic storm which commenced at 0606 hr on 11-6-59. $H$-field variations at Alibag and Kodaikanal is also shown. This is a case of negative $F2$-storm at KDK and positive at AHD on the same day.

2.4 Storm on 28-11-58

A magnetic storm of moderate activity commenced at 0608 hr on 28 November 1958, producing a daily range of the $H$-field of 179°. This was classified as negative $F2$ storm both at the equator and at the latitude of daytime peak $foF2$ (Fig. 2.7). However, the nighttime variations of $foF2$ at the two places were of opposite sign. In spite of the large decrease
Fig. 2.7 Changes in hpF2 and foF2 at Ahmedabad and h'F and foF2 at Kodaikanal during a moderate magnetic storm which commenced at 0608 hr on 28-11-58. H-field variations at Alibag and Kodaikanal are also shown. A case of simultaneous negative F2-storm at KDK and AHD.

in foF2 at Ahmedabad in the night, it showed an increase near the sunrise time on the second day of the storm. Such simultaneous occurrence of negative F2-storms was very rare.

3. VARIATION OF foF2 DURING STORMS OF DIFFERENT SC TIMES

MARTYN (1953) suggested that there was a profound diurnal control on the disturbance variation of foF2 and that
the local time of commencement of the magnetic storm significantly modified the trend of variation. Four groups are formed here of the storms with SC times falling in the four quarters of the day, viz. 00-05 hr, 06-11 hr, 12-17 hr and 18-23 hr and the ratios of disturbed-day foF2 to its monthly median value at the proper hour are plotted against the standard meridian time (75°E.M.T.). The curve starts approximately three hours before the time around which the SC's are most frequent. Such a plot gives an idea of Dst variation as well as the diurnal control of the disturbance.

3.1 Frequency of occurrence of SC times of the magnetic storms

A histogram is prepared of the number of geomagnetic storms commencing at different times of the day. The number of storms, however, are shown against ± ½ hr interval of the integral hour that is nearest to the actual SC time. Fig.2.8 shows the distribution of storms with sudden commencement time as recorded at the Kodaikanal Astrophysical Observatory. It is found that there is very nearly an even distribution of SC's, with some indication that there is less probability of commencement at 03-04 hr and 14-15 hr. The storms are divided into three categories according to their intensity, viz. moderate (daily range in H is 150 to 250 Г), moderately severe (daily range in H is 251 to 400 Г) and severe (daily range in H is above 400 Г). It appears from the histogram that the
Fig. 2.8 Occurrences of magnetic storms with different SC times at Kodaikanal (75° E.M.T.) during the years 1957-63.

... commencement of severe storm is more frequent in the morning hours. In general, intense storms commence more frequently in the daylight hours.

3.2 Storm-Variations of foF2 near the equator

Fig. 2.9 gives the average relative variations of foF2 for each time-group of the storms at Kodaikanal. The number of SC's occurring in each group is practically the same.
Fig. 2.9 Storm-variations of foF2 at Kodaikanal showing their diurnal control by the local time of sudden commencement of the magnetic storm. Shown at the bottom is the mean approximate DS variation of foF2 on the day following that of the SC (1957-63).

It is to be noted that foF2 falls down initially within about 2 hours after the SC whatever may be the SC time, but this fall is most pronounced in cases of storms which commence in the night, for example, in 00-05 hr and 18-23 hr quarters. There is, however, no indication of any increase of foF2 coinciding with the SC overshoot of the magnetic field. Except for a few hours in the night, the general effect of the magnetic storms commencing at any time of the day is to
enhance the electron density in the F2-layer with respect to the normal (or monthly median) at the equator. The nighttime decrease of NmF2 is more marked in cases of storms commencing in the forenoon interval. THOMAS (1968) has recently reported on some instances, particularly SC's in the morning hours, that the sharp decrease of foF2 within 2 to 3 hours of the SC time occurs at all latitudes at the time of the onset of the main phase of the storm. This decrease, of course, is short-lived at the equatorial station. The curve at the bottom centre part of Fig. 2.9 gives the DS variation of foF2 for 123 SC type magnetic storms. This has been computed after rearrangement of the relative changes according to diurnal time starting with the 00 hour of the day following the SC. In Martyn's original analysis, the 24-hr day was completed starting with the integral hour nearest to the SC time. Since the initial phase of the storm involves large irregular changes, the method followed in our analysis gives DS variation after the storm activity has become more or less free from large fluctuations. It may be noted that foF2 is depressed around midnight and early morning hours and rises to a peak value near sunrise time. Another daytime enhancement of foF2 starts after 0900 hr and it remains high until about
the next midnight. Of course, the values at the following midnight may not be same as those at the preceding midnight, as here only the SC type storms are considered.

3.3 Storm-variation of $f_{o}F_{2}$ at Ahmedabad

On the same lines as in Sec.3.2, the changes in $f_{o}F_{2}$ for the four groups at Ahmedabad are shown in Fig.2.10. In

![Graph showing storm-variation of $f_{o}F_{2}$ at Ahmedabad](image)

Fig.2.10 Storm-variations of $f_{o}F_{2}$ at Ahmedabad showing their diurnal control by the local time of sudden commencement of the magnetic storm. Shown at the bottom is the mean approximate DS variation of $f_{o}F_{2}$ on the day following that of the SC (1957-63).
In the first 3 or 4 hours after the SC, there is a fall in foF2, which is connected with the onset of the main phase. Later, the diurnal control produces a peak near sunrise and a nighttime depression of foF2 in all the groups of the storms as is found near the equator, but the daytime decrease at Ahmedabad is in contrast to the increase at the equator. Particularly, the daytime or nighttime decrease in foF2 at Ahmedabad is most marked, foF2 falling by as low as 15% on the average, during the storms commencing in the interval 12-17 hr. The decrease of 50% or more in foF2 has been found in some typical magnetic storms. The morning peak of foF2 comes out prominently in the last groups. The average depression during the storms commencing in the first and last quarters of the day does not exceed 7% at the most. There is a tendency of increase in foF2 on the second day of the storm in the last group as at Kodaikanal. The curve at the bottom gives the average DS variation on foF2 for 112 storms which shows a maximum at 0600 hr and a minimum at 2100 hr.

4. POSITIVE AND NEGATIVE F2-STORMS

The storms during which there is a daytime (1000-1800hr) enhancement of foF2 on the second day of the magnetic storm are termed as positive F2-storms and those during which there is a daytime decrease of foF2 are termed as negative F2-storms. Both types of storms occur at the equator and at the latitude of maximum daytime foF2 (i.e. near the well-known Appleton peak).
4.1 **Statistics of the positive and negative F2-storms**

Tables 1-5 give the number of positive and negative F2 storms classified under different SC-time groups and under different seasons for Kodaikanal and Ahmedabad. The number of storms coming under moderate (m), moderately severe (ms), and severe (s) intensities are also stated in the table.

**Table 1**

Distribution of positive and negative F2-storms for SC times in different quarters of the day at Kodaikanal.

<table>
<thead>
<tr>
<th>SC Time Group hr.</th>
<th>POSITIVE</th>
<th>Total</th>
<th>NEGATIVE</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer Equinoxes</td>
<td>Winter Pos.</td>
<td>Summer Equinoxes</td>
<td>Winter Neg.</td>
</tr>
<tr>
<td>00-05</td>
<td>6</td>
<td>12</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>06-11</td>
<td>11</td>
<td>12</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>12-17</td>
<td>7</td>
<td>12</td>
<td>8</td>
<td>27</td>
</tr>
<tr>
<td>18-23</td>
<td>8</td>
<td>9</td>
<td>8</td>
<td>25</td>
</tr>
</tbody>
</table>

Total m = 12, m = 17, m = 10, m = 39, m = 4, m = 1, m = 2, m = 7
ms = 15, ms = 17, ms = 13, ms = 45, ms = 4, ms = 3, ms = 1, ms = 8
s = 5, s = 11, s = 2, s = 18, s = 1, s = 2, s = 3, s = 6
32 45 25 102 9 6 6 21

It is seen from Table 1 that there does not seem to be any significant dependance on season or SC time of a
magnetic storm in the occurrences of a particular type of the F2-storm. It, however, appears that the proportion of negative to positive storms is larger in summer while that of positive to negative storms is larger in equinoxes. The figures given in the table show that majority of the severe storms even produce increase of foF2 at the equator. Thus about 82 % of a total of 123 storms were positive F2-storms at the equator, but their being positive or negative does not bear any definite relation to the time of commencement, season and the intensity of the magnetic storm. Some of the severe magnetic storms which were accompanied by positive F2-storms were even preceded by energetic proton events responsible for Polar Cap Absorption or PCA's (LEINBACH and REID, 1960).

4.2 Statistics of positive and negative F2-storms at Ahmedabad

Table 2 shows that there were larger number of negative F2-storms than the positive in each SC time quarter of the day at Ahmedabad. The largest number of negative storms occurred in SC time interval 12-17 hr against the lowest number of positive F2-storms in the same time interval. Here also it is not possible to say that a particular type of the storm occurs more frequently in any one season or for any one SC time interval. However, one may say that positive storms are less frequent in winter at Ahmedabad.
Table 2

Distribution of positive and negative F2-storms for SC times in different quarters of the day at Ahmedabad.

<table>
<thead>
<tr>
<th>SC Time Group hr.</th>
<th>POSITIVE</th>
<th></th>
<th></th>
<th>NEGATIVE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sum</td>
<td>Equ</td>
<td>Win</td>
<td>Total Pos.</td>
<td>Sum</td>
</tr>
<tr>
<td>00-05</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>06-11</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>12-17</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>18-23</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>10</td>
<td>6</td>
</tr>
</tbody>
</table>

| Total             | m = 4    | m = 6    | m = 2    | m = 12   | m = 11   | m = 11   | m = 11   | m = 33   |
|                   | ms = 6   | ms = 7   | ms = 5   | ms = 18  | ms = 8   | ms = 11  | ms = 10  | ms = 29  |
|                   | s = 2    | s = 4    | s = 1    | s = 7    | s = 3    | s = 6    | s = 4    | s = 13   |
|                   | 12       | 17       | 8        | 37       | 22       | 28       | 25       | 75       |

4.3 Overall comparison of the types of F2-storms at Ahmedabad and Kodaikanal

Table 3a

Overall Survey of the F2-storms at AHD and KDK

<table>
<thead>
<tr>
<th></th>
<th>Positive Ahmedabad</th>
<th>Kodaikanal</th>
<th>Negative Ahmedabad</th>
<th>Kodaikanal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>12</td>
<td>32</td>
<td>22</td>
<td>9</td>
</tr>
<tr>
<td>Equinox</td>
<td>17</td>
<td>45</td>
<td>28</td>
<td>6</td>
</tr>
<tr>
<td>Winter</td>
<td>8</td>
<td>25</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>37</td>
<td>102</td>
<td>75</td>
<td>21</td>
</tr>
</tbody>
</table>
Table 3a gives an overall comparison of the type of the F2-storms at Ahmedabad and Kodaikanal. 67% of a total of 112 storms at Ahmedabad turned out to be negative F2-storms against 82% positive at Kodaikanal. This overall picture given in the above tables does not say how many storms were of similar type or opposite type occurring simultaneously at the two places, e.g. all the 17 positive storms at Ahmedabad in equinoxes might not be among the 45 positive storms at Kodaikanal. In fact, there is more probability of simultaneous occurrence of negative F2-storm at Ahmedabad and positive at Kodaikanal.

Table 3b

Distribution of Positive & Negative F2-storms with SC time

<table>
<thead>
<tr>
<th>Place</th>
<th>00-05 hr</th>
<th>06-11 hr</th>
<th>12-17 hr</th>
<th>18-23 hr</th>
<th>Total No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahmedabad</td>
<td>10</td>
<td>14</td>
<td>11</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>112</td>
</tr>
<tr>
<td>Kodaikanal</td>
<td>22</td>
<td>3</td>
<td>28</td>
<td>8</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>123</td>
</tr>
</tbody>
</table>

Table 3b gives the comparison of the two types of the storms for different groups of SC time. Not much can be said about the dependance of the type of the F2-storm on the SC time, although an onset of main phase in the forenoon may give negative F2-storms on the first day.
4.4 Distribution of similar and dissimilar F2-storms occurring on the same days

Another table is prepared to give the percentage distribution in different seasons of similar and dissimilar type of the F2-storms during the same magnetically disturbed days. The first letter represents the type of the storm at Ahmedabad and the second letter at Kodaikanal, P standing for positive and N for negative F2-storm. It is seen from Table 4

Table 4

<table>
<thead>
<tr>
<th>Type of F2-storm AHD-KDK</th>
<th>Seasons</th>
<th></th>
<th></th>
<th>Annual average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Equinoxes</td>
<td>Winter</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>24 %</td>
<td>27 %</td>
<td>20 %</td>
<td>24 %</td>
</tr>
<tr>
<td>NN</td>
<td>6 %</td>
<td>2 %</td>
<td>13 %</td>
<td>6 %</td>
</tr>
<tr>
<td>PN</td>
<td>11 %</td>
<td>11 %</td>
<td>7 %</td>
<td>10 %</td>
</tr>
<tr>
<td>NP</td>
<td>59 %</td>
<td>60 %</td>
<td>60 %</td>
<td>60 %</td>
</tr>
</tbody>
</table>

| Total No. | 34 | 45 | 30 | 109 |

that 60 % out of a total of 70 % dissimilar storms were negative at Ahmedabad occurring on the same days of positive F2-storms at Kodaikanal. The next lower figure of about 25 % is that of occurrence of positive F2-storms at both the places.
Negative or positive F2-storms occurrences at Ahmedabad accompanying negative F2-storms at Kodaikanal are rare (hardly 10%). The chance of simultaneous negative types is almost nil in equinoxes, but there does not seem to be any significant seasonal influence on the simultaneity of similar or dissimilar type of the F2 storms at these two low-latitude stations in the eastern zone.

Table 5

Types of F2-storms at AHD & KDK for different SC time intervals

<table>
<thead>
<tr>
<th>AHD-KDK</th>
<th>Occurrences during different time intervals of SC</th>
<th>Total average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>00-05</td>
<td>06-11</td>
</tr>
<tr>
<td>PP</td>
<td>35 %</td>
<td>28 %</td>
</tr>
<tr>
<td>NN</td>
<td>4 %</td>
<td>7 %</td>
</tr>
<tr>
<td>PN</td>
<td>9 %</td>
<td>11 %</td>
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Total No. of storms

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Table 5 shows the occurrences of simultaneously similar and dissimilar types of the F2-storms at Ahmedabad and Kodaikanal for SC times in different quarters. It may be noted that occurrence of opposite type of the F2-storms NP
(negative at Ahmedabad and positive at Kodaikanal) on the same disturbed days is most frequent for the magnetic storms commencing in the interval 12-17 hr. The next lower figure of 35% is that of simultaneously occurring positive storms from a total of 23 storms with the 3C time in 00-05 hr interval. As already stated before, the simultaneous occurrence of negative F2-storms at the two places is negligible.

5. NORMAL AND DISTURBANCE DIURNAL VARIATION OF foF2

Monthly median hourly values of foF2 are treated as normal day values.

The method of finding disturbance diurnal variation is already stated in Section 3.

5.1 Normal diurnal variation of foF2 at KDK and AHD

Fig. 2.11 gives the diurnal variation of foF2 at AHD and KDK in March, June and December of high and low sunspot years 1957 and 1963. One can notice that the midday bite-out of foF2 at KDK is followed by a daytime maximum of foF2 at Ahmedabad after about 2 hours. The evening peak of foF2 at the equator is more pronounced than the morning peak in low sunspot activity while the 0900 hr peak is more pronounced in high sunspot activity. In December 1957, the evening peak has almost disappeared. At Ahmedabad, the solar diurnal control of foF2 is masked by other processes, especially in high
Fig. 2.11 Normal diurnal variation of (monthly median) $f_0F_2$ at Kodaikanal and Ahmedabad for three different months representatives of three different seasons for 1957, a year of high sunspot activity and 1963 a year of low sunspot activity.

sunspot year when there are frequent occurrences of magnetic disturbances and large currents flowing in the E-region because of increased ionization. In the continuity equation for the electron density,

$$\frac{dN}{dt} = q - \beta N - \text{div}(Nv)$$

the last term accounting for the electron drift (vertical and horizontal) at different heights becomes more effective in
the control of the diurnal variation of F2-electron density in low-equatorial latitudes in sunspot maximum period. HIRONO and MAEDA (1954) worked out the drift theory and explained the equatorial bite-out and ascribed the differences in the morning and the evening peaks of foF2 in high and low sunspot years to the phase-shift in the drift velocities. MOFFETT and HANSON (1965) took into account the diffusion of electrons along the geomagnetic field lines and also the neutral wind for satisfactorily explaining the anomalous variations of NmF2 in the equatorial zone. However, the theories still require to be perfected in order to account for some irregular changes and the changes that are found during magnetic storms.

5.2 DS variation of foF2 at Kodaikanal

MARTYN (1953), MATSUSHITA (1959) and MAEDA and SATO (1959) had shown that there was a marked difference in the DS and Dst variations of foF2 in summer and winter at midlatitudes. RASTOGI and RAJARAM (1965) later reported that the daytime foF2 remains below normal even at the equatorial station in American zone, particularly in the winter of high solar activity period. In Fig.2.12 is shown the DS variation of foF2 at Kodaikanal for summer (J-solstices), equinoxes and winter (D-solstices). It will be seen that the variation in summer has large range (of about 29%) as compared to 17% in winter and equinoxes. The early morning depression is maximum in summer while the increase near sunrise is highest.
in winter. This increase is conspicuously absent in summer, but there are two prominent maxima at about 1100 and 2200 hr. The 2200 hr peak is suppressed in winter and the daytime maximum occurs at about 1200 hr. Thus there appears to be a gradual shift towards earlier hours in the maxima and minima from summer to winter.
5.3 Seasonal influence on DS variation of \( f_0F_2 \) at Ahmedabad

The DS variation of \( f_0F_2 \) at Ahmedabad is shown in the same Fig. 2.12 for ease of comparison with that at Kodaikanal for the same storms. In summer, the early morning minimum occurs a little later and is smaller than at KDK, and near the sunrise there is no sign of increase of \( f_0F_2 \) at Ahmedabad also. The sunrise increase of \( f_0F_2 \) becomes very much peaky in winter as at the equator. Although the depression of \( f_0F_2 \) is sustained for most of the time in summer, the extent of depression is larger in winter though not for the same duration as in summer. In all the seasons, the daytime depression commences at about 0900 hr which is also the time at which the daytime increase of \( f_0F_2 \) begins at Kodaikanal on disturbed days. It is interesting to note that the minimum around noon at Ahmedabad occurs somewhat later than the midday maximum at KDK. A delay of about 2 hours is also observed in the normal diurnal maximum of \( f_0F_2 \) at AHD behind the bite-out minimum at KDK (Fig. 2.11). Thus the anomalous bite-out effect at the equator which begins to develop at about 0900 hr on normal days is reduced on magnetically disturbed days. It seems that the filling up of the equatorial trough of F2-ionization in equinoxes may not be as much as that in other seasons since the midday decrease at Ahmedabad in equinoxes is not as pronounced as in summer and winter. Further, there is a post-sunset minimum of \( f_0F_2 \) at Ahmedabad corresponding to the increase at Kodaikanal, though the latter is slightly delayed.
This post-sunset delay process is in reverse order to that of midday delay in changes of foF2 between the two stations, a result which may have some bearing on the wind system proposed by KOHL and KING (1967) and KOHL et al (1969).

5.4 DS variation of foF2 for positive and negative F2-storms at Kodaikanal

It was shown in Table 1 that negative F2-storms accounted for only 18% of the total at the equatorial station i.e. 21 out of a total of 123 storms. In order to see if the variation in the H-field was different for the two types of F2-storms, the DS variation of the H-field is shown with that of foF2 for the same storms. A nearly flat averaged-out Dst component contained in the variation of the H-field shifts the horizontal axis downwards by a certain negative field value and the DS component gives variations with respect to this shifted axis.

For the few negative storms, the DS variation of the H-field and foF2 at Kodaikanal (Fig.2.13a) have nearly similar trend except for the delay in the daytime minimum of foF2. These curves are not so smooth as those for the positive storms, obviously because the number of days involved in the latter case is much larger. One interesting feature is the large nighttime or early morning depression of foF2 during negative F2-storms. So the larger number of more effective
negative storms in summer than in other seasons is probably
the reason for the observed DS variation of foF2 in summer
(Fig. 2.12). The clarity of the premidnight peak in summer is
due to greater depression of foF2 occurring at about 1900-2000 hr
in negative storms. The absence of the increase of foF2 near
sunrise is also explained by the great influence of negative
storms. The direct implication of the delayed daytime decrease
of foF2 is that the equatorial trough is no doubt further
deepened on a few negative storm occasions, but this happens
in the late afternoon.
Coming to the positive storms, which happen to be in large number near the equator, the DS variation of foF2 differs very much from that of the H-field, though some similarity is to be found during the interval 00-08 hr. While the variation of the H-field has a dominant diurnal component, that of foF2 is made complex by superposition of other harmonics or irregular variations. BHARGAVA and GOPAL RAO (1959) have attempted a harmonic analysis of the DS variation of foF2 and h'F2 at Kodaikanal for some 30 positive and negative F2-storms and found comparable fundamental and third harmonic components.

The variation of foF2 for positive F2-storms is much like that found in winter and equinoxes, which can be understood because of larger proportion of positive to negative F2-storms in these seasons. The variation also explains the large increase of foF2 near sunrise in winter. The DS variation of the H-field is, however, practically of the same nature for either type of the storms, except for a delay of 1 to 2 hours in the morning rise of H in case of negative F2-storms.

5.5 DS variation of foF2 and the H-field for positive and negative F2 storms at Ahmedabad

In Fig. 13b are shown the DS variations of foF2 at Ahmedabad and the H-field at Alibag. Comparison is done with the Alibag magnetic data since Alibag magnetic observatory happens to be the nearest one to Ahmedabad, about 500 km
south practically along the same meridian, well outside the equatorial zone. The situation at Ahmedabad regarding the type of the F2-storms is almost reversed to that near the equator. At Ahmedabad, the number of negative F2-storms is twice the number of positive F2-storms in a total of 112 storms (Table 3a). See the contrast: The morning increase of foF2 is very clear for negative F2-storms at Ahmedabad as against so for positive F2-storms at Kodaikanal. Similarly, the post-midnight decrease is more pronounced during positive storms at Ahmedabad in contrast to such decrease occurring during negative F2-storms at Kodaikanal. However, at both the places the DS variation of the H-field is very much similar, range of average variation being smaller at Alibag by about 12 gammas than at Kodaikanal. At both the stations, there is a phase delay in the variation of the H-field from that of foF2 for negative F2-storms.

After the morning increase during negative storms, foF2 crosses to the depression at about 0900 hr and reaches to a maximum decrease of about 14 % at 2100 hr, with a steady decrease of 10 % around 1500 hr as compared to a steady increase of 10 % near the equator at about noon for positive storms. The increase of foF2 during positive storms at Ahmedabad is comparatively smaller than depression during negative storms. On the whole, one can say that the similarity of DS variation in the early morning hours and reversal during daytime at these two critical stations are the major features, positive F2-storms at Kodaikanal generally corresponding to negative
F2-storms at Ahmedabad; nevertheless, there may be a few occasions when both the stations have simultaneously the same type of the daytime effects in the F2-layer. The DS variation of the H-field is more or less like that of foF2 for negative F2-storms only.

6. Dst VARIATION OF foF2

The storm-time or Dst variation is obtained by arranging the disturbed-day deviations of the observed parameters according to the storm-time, the integral hour nearest to the time of sudden commencement of the magnetic storm being reckoned as the zero hour. This, in a way, gives a universal time component of the disturbance variation. Tabulations were done starting with three hours before the SC time and ending at 52 hours after it. Fig.2.14 gives the Dst variation of foF2 at Kodaikanal and Ahmedabad and this is compared with the Dst variation of the H-field of the earth. Some smoothing is done of the variation of foF2 by taking 5-hr running average. It is to be noted that the Dst variation of the H-field at both the places and even all over the globe is of the same nature, its amplitude being different at different latitudes. The initial SC amplitude of the H-field is larger at the equator, the main phase starts with a sharper fall, and the minimum is reached within 10 hours of the SC time. At a higher latitude like that of Alibag (I = 25°N), the initial SC amplitude is slightly less, the main phase
sets in with a less rapid rate of fall than at the equator, and the minimum reaches at about 15 hours after the SC time. The recovery of the magnetic storm takes about 3 days. This kind of storm-time variation of the H-field is found both for positive or negative F2-storm. The maximum average decrease of the H-field for 119 storms is found to be about 70 gammas at KDK and about 60 gammas at Alibag. In contrast to this, the storm-time variation of foF2 at Kodaikanal runs in opposite direction to that at Ahmedabad i.e. increase at the former and decrease at the latter, except for the initial 2 or 3 hours after the SC and the onset of the main phase when there is a decrease of foF2 at both these places. The maximum mean positive change in foF2 at the equator is about 8% occurring on the second day of the storm after about 25 hours.
while at Ahmedabad the maximum mean decrease of foF2 is about 7% occurring on the first day of the storm after about 15 hours from the SC time.

7. CONCLUSIONS

From the foregoing paragraphs it is concluded that

1. The maximum electron density NmF2 is generally enhanced relative to the monthly median value in the daytime near the equator (Kodaikanal) on magnetically disturbed days barring a few cases otherwise. In contrast, it generally decreases at a latitude of the well-known Appleton peak in foF2 e.g. at Ahmedabad.

2. About 82% were positive F2-storms near the equator out of a total of 123 storms which occurred during the years 1957-63; at Ahmedabad, on the other hand, negative F2-storms accounted for about 67% in the same years. The occurrence of either type does not seem to have any definite dependence on the SC time or the season.

3. Of the above two types of the F2-storms, nearly 60% accounted for positive storms at Kodaikanal occurring on the same days when Ahmedabad had negative F2-storms. About 20-25% accounted for simultaneous occurrence of positive F2-storms at these places, while simultaneous negative F2-storms seldom occur.
4. The mean disturbance solar diurnal (DS) variation of foF2 shows a sharp rise near sunrise time and below-normal values after midnight at Kodaikanal as well as at Ahmedabad. After 0900 hr, the variation at the two places is in opposite direction i.e. increase at Kodaikanal and decrease at Ahmedabad.

5. The increase of foF2 near sunrise is conspicuously absent in summer and is most pronounced in winter. From the DS variation of foF2 for positive and negative storms separately, it is shown that the sunrise peakiness in foF2 is a feature of positive F2-storms at the equator but of negative F2-storms at Ahmedabad. The proportion of such storms and their individual effectiveness in any one season may be therefore responsible for the characteristic seasonal differences in the DS variation.

6. The DS variation of foF2 is more or less like that of the H-component of the earth's magnetic field only in case of negative F2-storms in the low-equatorial latitude zone considered here.

7. The storm-time (Dst) variation of foF2 at Kodaikanal is opposite to that at Ahmedabad except near the time of the onset of the main phase of the storm when foF2 decreases at both the places. In contrast, the Dst variation of the H-field is similar for either type of the F2-storm at the two places.
8. DISCUSSION

The general result that the daytime F$_2$-ionization at the equator is increased and such increase is accompanied by a decrease at about 35° magnetic dip implies that the equatorial midday bite-out in the normal diurnal (MAEDA et al 1942; APPLETON, 1946) variation of f$_{oF2}$ and the equatorial trough in the latitudinal distribution of f$_{oF2}$ are reduced in their depth or filled up and at the same time the Appleton peaks of f$_{oF2}$ are suppressed on magnetically disturbed days. The total columnar electron content up to the hmF2 level in the topside and the bottomside on disturbed days also shows such filling up of the equatorial trough as illustrated in Fig.2.15 (MATSUSHITA, 1963; KING et al 1967). This result would probably mean that the upward $\mathbf{E} \times \mathbf{B}$ drift of electrons near the equator and their subsequent diffusion along the geomagnetic field lines which normally occurs (MARTYN, 1954; MITRA, 1946; MAEDA, 1963; KING et al 1964; HANSON and MOFFETT, 1966; RISHBETH, 1967; ABUR-ROBB, 1969) are reduced on magnetically disturbed days. The reduction of upward drift may result from the reduction in the electric field associated with the eastward current in the dynamo E-region (BRAMLEY and PEART, 1965; DUNFORD, 1969, 1970). According to the equatorial electrojet model proposed by SUGIURA and CAIN (1966), the E-W electric field is given by

$$E_y = -8.8 \times 10^{-7} \text{ Ve volts/metre}$$
where they assumed $\frac{\sigma_2}{\sigma_1}$ equal to about 30 at the height of maximum electron flow. $\sigma_1$ and $\sigma_2$ are respectively the Pedersen and Hall conductivities and $V_e$ is E-W electron drift velocity in meters per sec. It has been also shown that $f_{oE\delta}$

![Graph](image)

**Fig. 2.15** Integrated electron content between 420 km and the satellite on a disturbed day (15-9-63) and a quiet day (10-9-69). The satellite pass was over Singapore at about 12-30 L.M.T. on the disturbed day. Note the absence of anomalous behaviour of the topside ionosphere on the disturbed day. (after King et al. 1967)

of the q-type sporadic-E layer is directly related to the equatorial electrojet current (Cohen and Bowles, 1963;
KOTADIA, 1964) and it decreases on disturbed days with decrease in the earth's H-field, a part of this decrease in the H-field being probably due to the decrease in the eastward electrojet current. Simultaneously, hpF2 is also lowered and NmF2 increased (KOTADIA and PATEL, 1970). Further, there is a good agreement in the phases of lunar semidiurnal variations of foEs, hpF2 and the H-field, but that of foF2 is almost in phase-opposition at the equator (BROWN, 1956; DUNCAN, 1956; WRIGHT and SKINNER, 1959; JOSHI and KOTADIA, 1969; KOTADIA, 1962; TRIVEDI and RASTOGI, 1969). All these results indicate that the upward vertical drift occurring under normal conditions and causing the equatorial bite-out and trough is reduced or inhibited to some extent under magnetically disturbed conditions, probably due to decrease in the eastward electric field by imposition of the westward field associated with the DS-current in the E-region of the ionosphere. A direct experimental evidence has been reported by BALSLEY and WOODMAN (1969) showing good correlation of vertical drift in the F2-layer with horizontal drift in the E-layer, the downward F2-layer drift corresponding to eastward drift of electrons (i.e. westward current) in the E-region, and vice versa. From the ground-based ionospheric and magnetic data and Alouette I satellite topside sounder observations, DUNFORD (1967) found that the day-to-day changes in the magnitude of the equatorial F2-anomaly are well correlated with the strength of the currents flowing in the equatorial E-region. SKINNER and WRIGHT (1955, 1957) found at
Ibadan that the F2-layer generally descends on magnetically disturbed days, which means downward drift or decrease in the normal upward drift of the electrons associated with some westward electric field or reduction in eastward electric field in the E-region. BRAMLEY and YOUNG (1968) have shown that a very small downward drift (about 5 metres/sec) is sufficient to destroy the equatorial anomaly in foF2. With the disappearance of this anomaly, the peak in foF2 at a place like Ahmedabad will automatically vanish. However, on a few occasions, foF2 distribution may become quite flat over the whole low latitude equatorial zone when positive F2-storms are recorded simultaneously at all the places in this zone. In the nighttime, the electrojet or the E-region current is weak, Esq is absent and the electron drift and diffusion in the F2-layer do not play any significant role and therefore the effects at Kodaikanal and Ahmedabad are very nearly similar in the night and until 0900 hr. Also during this time, the Ds variation of foF2 and the H-field agree very well. The continuance of daytime increase of foF2 to late hours in summer and earlier hours in winter can also be explained by the seasonal extension of the daylight DS-current in the E-layer which provides the electromotive power for changes in the F2-layer.

The facts that the Dst-variation of foF2 at the two places are not similar but that of the H-field is geosymmetrical make one logically conclude that the two phenomena do not have
a common source of origin. The geosymmetrical component of the H-field disturbance is believed to be caused by a current system at large distances from the earth while the dissimilar variations in the ionospheric F2-layer can be thought of as originating from the current systems and movements of ionization within the ionosphere. Particularly, this is very much true for the observed changes of foF2 in the anomalous equatorial zone bounded by the Appleton peaks of foF2. The upward or downward movement of electrons also results in the change of their loss-rate.

The similarity in the changes of Nm and nT represents not a mere redistribution of the electrons, but a real change (decrease or increase) in the total ionization. The theories developed so far only partially explain the F2-layer phenomena and that too restricted to some zonal areas. Further, positive F2-storms or negative F2-storms occurring simultaneously at KDK and AHD cannot be explained by drift and transport mechanisms alone. The widespread decrease of foF2 at the time of onset of the main phase of the magnetic storm poses the question whether this short-lived effect is a real loss of ionization or it results from the bloating up of the layer and if so, how is it related to the setting up of the ring current far above. Maybe that the large sudden rate of decrease in the magnetic field induces a forward emf which may cause a temporary upheaval in the F2-layer and a decrease of electron density at the time of onset of the main phase of the magnetic storm.
REFERENCES

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