which the mean free path varies is small as compared with the mean free path itself. For the very low densities outside the plasmasphere this condition may no longer be justified thus requiring a more rigorous definition of $\lambda$, as well as a higher order expansion for the heat flux.

Acknowledgment

The authors are indebted to Dr. S.J. Bauer for helpful comments. This work was performed while two of us (EGF and KKM) held NAS-NRC Research Associateships at Goddard Space Flight Center.

Manuscrit reçu le 6 Novembre 1972

REFERENCES


RESUME. — La variation avec le temps de l'image de F0F2 indique que dans des orages individuels, des variations atteignent 50% peuvent se produire couramment durant des heures du maximum de l'orage mais également plus tôt et/ou plus tard. Sur des moyennes de plusieurs orages, il existe une bonne corrélation avec le début de la phase principale du phénomène mais avec le SSC. Pour les latitudes fortes et moyennes, les effets ionosphériques Dst sont une nette diminution. Pour les latitudes basses, l'effet est un accroissement mais qui n'est clair que pour les heures de jour, les valeurs de nuit montrant une décroissance ou un comportement erratique. Pour les orages intenses, l'accroissement est de 7 à 10 % et il est précédé d'une décroissance d'environ 3 à 5 % pendant ou avant le début de la phase principale. Les décalages électromagnétiques ne semblent jouer aucun rôle significatif dans ces effets Dst. En revanche, il semble exister des effets dus aux vents solaires et/ou aux précipitations de la plasmasphère ; mais les orages individuels montrent à l'occasion des effets variables à l'intérieur de distances de quelques centaines de kilomètres qui montrent une influence considérable des conditions locales géographiques ou géomagnétiques. On observe des effets nets de SD (temps local) qui sont des renforcements de FoF2 associés avec un affaiblissement de l'électrojet qui indique des effets de décalages électromagnétiques.

ABSTRACT. — The storm-time variation of foF2 indicates that in individual storms changes as large as ±50% can occur usually during peak storm hours but often earlier and/or later. For averages of several storms, there is good correlation with the Main Phase Onset (MPO) (rather than with SSC). For high and middle latitudes, ionospheric $D_s$ effects are unambiguous decreases. For low latitudes, the effect is an increase but conspicuous for day-time values only, the night values showing a decrease or an erratic behavior. For severe storms, the increase is ±10% and is preceded by a decrease of about 20% at or before MPO. For these $D_s$ effects, the electromagnetic drifts do not seem to play any significant role. Instant, effects due to neutral winds and/or precipitation from the plasmasphere are possibly indicated; but individual storms show occasionally disorderly effects even within a few hundred miles indicating considerable influence of local geographic and/or geomagnetic conditions. Conspicuous SD (local time) effects are seen and show enhancements of foF2 associated with a weakening of the electrojet indicating electromagnetic drift effects.

by R.P. KANE

Physical Research Laboratory, Ahmedabad, India.
I - Introduction

The storm-time variation of ionospheric parameters has been studied by several workers. Appleton and Laird (1930) found a foF2 decrease during storms for high latitudes while Berkner et al. (1939) and Berkner and Seaton (1940) reported an increase in foF2 for storms. For Huanuco at equator, Skinner and Wright (1955) found that foF2 decreased during the first 10 hours of a storm and then increased to values above average. Matsushita (1959) studied Dp (foF2) at observatories spread over a wide range of latitudes and reported a decrease in foF2 for high latitudes and an increase in low latitudes. Rajaram and Rastogi (1969, 1971) have studied the storm-time behaviour of foF2 for the Asian as well as the American zones for storm-times from 4 hours to 72 hours and showed an increase in foF2 in the equatorial region.

However, examination of the diagrams presented by these authors gives an impression that whereas for high latitudes the storm effect on foF2 is a distinct decrease, the increase reported at equatorial latitudes is somewhat obscure. Thus in Matsushita's results (1959) for the ±10° latitude belt, the values seem to decrease in the first 6 hours during severe storms and then increase later but still attain almost average values several times in the next 66 hours. For weak storms, the first decrease is small and occurs within ± 2 hours of the zero storm hour. In the results of Rajaram and Rastogi (1969, 1971) also, the values in the 4 prestorm hours are not abnormal but mostly above average and for later storm hours, the values fluctuate widely from above average to below average, differently for different storms. Thus, no clear-cut relationship with storm time is discernible for the equatorial region.

There can be several reasons for these obscure relationships. Firstly, all these authors use the hour of storm sudden commencement (S.S.C) as the zero storm hour. From the point of view of the interplanetary plasma interaction with the magnetosphere, the S.S.C. corresponds to the first impact of an interplanetary shock and marks the beginning of the initial phase of a geomagnetic storm which may last from one to several hours and is then followed by the main phase. Thus, the first few hours of a storm-time starting from S.S.C may or may not represent any part of the main phase which is attributed to a ring current developing about 4 earth radii. Physically, it would be more meaningful to set the time-markers so that foF2 changes could be studied separately for the initial phase and the main phase as also for the succeeding recovery phase of a geomagnetic storm. Thomas and Venables (1966) carried out such an analysis by setting the Main Phase Onset (MPO) hour as the zero hour and showed that the ratio of the foF2 values two hours after and two hours prior to the MPO was nearly near about unity or below unity depending upon whether the MPO occurred during day-time or night-time, thus indicating a considerable local time dependence of the storm effect. Their analysis was, however, restricted to mid-latitudes.

Secondly, there is also the problem of classifying geomagnetic storms. From the Geophysical Data appearing regularly in the Journal of Geophysical Research and Solar-Geophysical data, it is noticed frequently that not all observatories are unanimous in their classification of a particular storm as moderate, rather severe or severe or even whether it is of the S.S.C. type or otherwise. In this communication we propose to carry out such a study on (what we consider) a more critical and objective basis.

II - Experimental data and analysis

The first problem is to indentify and classify a geomagnetic storm. For this purpose we use the Dp values given by Segura and Poro (1971). These represent the equivalent equatorial storm-time disturbance values of the ionospheric field and are obtained by combining the hourly H data at three mid-latitude stations in longitudes roughly 120° apart viz. Honolulu, San Juan and Hermosillo (or Kailua), after multiplying these by sec f where f is their geomagnetic latitudes. Under normally quiet conditions, Dp values are almost zero; but during storms the values become positive (several gamma) during the initial phase and later become negative (several tens of gamma) during the main phase. Because of the longitudinal distribution of the stations mentioned above, the local time effects (daily variation) are eliminated.

From the plots and tables of hourly Dp values for the 11-year period 1957-77, we located intervals when storms occurred. The procedure for locating the hour of Main Phase Onset (MPO) is illustrated in Figure 1 for the storm occurring on 18 April, 1965. The Dp values were consistently above zero for the previous day viz. 17 April 1965. The mean value was 21 gamma and is shown by the horizontal dashed line. The main phase had its maximum (negative Dp) at about 1000 U.T. on 18 April and tracing this phase backwards from 1000 U.T. the drop below the dashed line seems to have started at 0300 U.T. Hence the previous hour viz. 0200 U.T. on 18 April was considered as MPO for this event.

The magnitude of the main phase was considered as the drop from the dashed line to the maximum negative value i.e. (21 + 185) = 206 gamma and the duration of the main phase as (1000-0200) = 8 hrs. Storms were classified as weak, moderate, strong or severe according to whether the main phase magnitude was in the ranges 50-65 gamma, 66-100 gamma, 101-199 gamma or 200 and more gamma respectively. Table 1 lists the dates and other characteristics of the storm shown.

Since the local time of commencement may be important (Appleton and Piggott, 1952; Thomas and Venables, 1966), the storms are listed according to the U.T. hour at which their Main Phase Onsets occurred on the given date. We believe that the onset time has an accuracy of about ± 1 hour.

Thus, a total of 214 storms are considered out of which 53 are strong and 19 are very strong (severe). As expected, a majority of these occurred during the years of high solar activity and the distribution in U.T. hours is fairly well spread except for the severe storms which are more bunched around 1200 U.T. Since there are only a few (19) of these, we shall first study the behaviour of foF2 for these events individually. We shall consider periods of 72 hours at a time wherein the middle 24 hours will...
I - Introduction

The storm-time variation of ionospheric parameters has been studied by several workers. Appleton and Ingram (1935) reported a foF2 decrease during storms for high latitudes while Berkner et al. (1939) and Berkner and Seaton (1940) reported an foF2 increase during storms for Honolulu at equator. Skinner and Whitten (1925) found for Bushland that foF2 decreased during the first 10 hours of a storm and later increased to values above average. Matsushita (1959) studied Dst (foF2) at observatories spread over a wide range of latitudes and reported a decrease in foF2 for high latitudes and an increase in low latitudes. Rajaram and Rastogi (1969, 1971) have studied the storm-time behavior of foF2 for the Asian as well as the American zones for storm-times from -4 hours to +72 hours and show an increase in foF2 in the equatorial region.

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![Image of Dst vs Time](image)

The Dst (Saguna and Poros, 1971) plot for the geomagnetic storm of 17-19 April 1965. MPO = Main Phase Onset.

From the plots and tables of hourly Dst values for the 11 year period 1957-67, we located intervals when storms occurred. The procedure for locating the hour of Main Phase Onset (MPO) is illustrated in figure 1 for the storm occurring on 15 April, 1965. The Dst values were consistently above zero for the previous day viz. 17 April 1965. The mean value was 21 gamma and is shown by the horizontal dashed line. The main phase had its maximum (negative Dst) at about 1000 U.T. on 18 April and tracking this phase backwards from 1000 U.T., the drop below the dashed line seems to have started at 0500 U.T. Hence the previous hour viz. 0200 U.T. on 18 April was considered as MPO for this event.

The magnitude of the main phase was considered as the drop from the dashed line to the maximum negative value i.e. (21 + 185) = 206 gamma and the duration of the main phase as (1900 - 2500) = 8 hrs. Storms were classified as weak, moderate, strong or severe according to whether the main phase magnitude was in the ranges 50-65 gamma, 66-100 gamma, 101-159 gamma or 200 and more gamma respectively. Table 1 lists the dates and other characteristics of the various storms. Since the local time of commencement may be important (Appleton and Piggott, 1952; Thomas and Venables, 1966), the storms are listed according to the U.T. hour at which their Main Phase Onsets occurred on the given date. We believe that the onset time has an accuracy of about ±1 hour. Thus, a total of 214 storms are considered out of which 53 are strong and 19 are very strong (severe). As expected, a majority of these occurred during the years of high solar activity and the distribution in U.T. hours is fairly well spread except for the severe storms which are more bunched around 1200 U.T. Since there are only a few (19) of these, we shall first study the behaviour of foF2 for these events individually. We shall consider periods of 72 hours at a time wherein the middle 24 hours will
Table 1

<table>
<thead>
<tr>
<th>Main Phase</th>
<th>Weak 50-65 $\gamma$</th>
<th>Moderate 66-99 $\gamma$</th>
<th>Strong 100-199 $\gamma$</th>
<th>Severe $&gt;200$ $\gamma$</th>
<th>Main Phase</th>
<th>Weak 50-65 $\gamma$</th>
<th>Moderate 66-99 $\gamma$</th>
<th>Strong 100-199 $\gamma$</th>
<th>Severe $&gt;200$ $\gamma$</th>
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<td>01-12-57(15)</td>
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<td>01:12-60(08)</td>
<td>01-12-60(08)</td>
<td>01-12-57(15)</td>
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<td>01-12-57(15)</td>
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<tr>
<td>02</td>
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<td>12:04-06:00(08)</td>
<td>14:00-57(18)</td>
<td>12:04-06:00(08)</td>
<td>13-00-57(18)</td>
<td>12:04-06:00(08)</td>
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<td>12:04-06:00(08)</td>
<td>13-00-57(18)</td>
</tr>
<tr>
<td>03</td>
<td>23-00-57(12)</td>
<td>22:04-06:00(08)</td>
<td>23:00-57(12)</td>
<td>22:04-06:00(08)</td>
<td>23-00-57(12)</td>
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<td>22:04-06:00(08)</td>
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Table 2

<table>
<thead>
<tr>
<th>Main Phase</th>
<th>Weak 50-65 $\gamma$</th>
<th>Moderate 66-99 $\gamma$</th>
<th>Strong 100-199 $\gamma$</th>
<th>Severe $&gt;200$ $\gamma$</th>
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</tr>
<tr>
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<td>01-00-57(18)</td>
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<td>01:00-60(08)</td>
<td>01-00-57(18)</td>
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<tr>
<td>06</td>
<td>01-00-57(18)</td>
<td>09:40-06:00(08)</td>
<td>01:00-60(08)</td>
<td>01-00-57(18)</td>
</tr>
</tbody>
</table>

Figure 3

Storm-time variation of P2 region

Correspond to the U.T. day which contains the Main Phase Event. Among the 19 severe storms, 4 have a MPO at 11 U.T. and 4 at 14 U.T. Thus the L.T. variations (DS) as well as the $D_p$ variations for these events are expected to be similar for any particular location (longitude). The plots of these eight storms are shown in Figure 2 (a) and (b). The full lines show geomagnetic $D_p$ (Suigara and Peros, 1971) and the dashed lines show $f_{oF2}/f_{oF2}S$ i.e. the ratio of actual $f_{oF2}$ to its monthly median value $f_{oF2}$ for Kodaikanal. The vertical dashed line shows the hour of MPO (Main Phase Onset) on the middle day. From the list of S.S.C. given in the Geophysical Data, we searched for S.S.C. that occurred during these 3-day intervals. These are marked as triangles at the appropriate U.T. hours. The bottom curves in Figure 2 (a) and (b) are the averages of the 4 storms in these columns. Figure 3 (a) and (b) show the remaining 11 severe storms with the MPO occurring on the middle day at different U.T. hours as indicated by the vertical dashed lines. Table 2 gives details of the stations for which data are used in the present analysis.

From the morphological studies conducted so far by other workers, notably Thomas and Robbins (1958), Matsushita (1959), Maeda and Sato (1959), Somayaji (1963), Obayashi (1964), Kotosh (1965), Thomas and Venables (1966), Malajusk (1967) and Thomas (1968, 1970), the conclusion regarding the equatorial region $f_{oF2}$ storm variations seems to be that:

a) the largest changes in $f_{oF2}$ occur after the development of the main phase of the geomagnetic storm,

b) usually an enhancement of $f_{oF2}$ is observed (t eq) and depression is rare except during very intense storms.
Table 1

<table>
<thead>
<tr>
<th>Main Phase</th>
<th>Weak</th>
<th>Moderately</th>
<th>Severe</th>
<th>Main Phase</th>
<th>Weak</th>
<th>Moderately</th>
<th>Severe</th>
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</thead>
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<tr>
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<td>66-99 g</td>
<td>100-199 g</td>
<td>200-299 g</td>
<td>50-65 g</td>
<td>66-99 g</td>
<td>100-199 g</td>
</tr>
<tr>
<td>01</td>
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<td>05-08-65-00</td>
<td>05-12-69-15</td>
<td>13-59-64-00</td>
<td>18-04-59-00</td>
<td>14-07-64-00</td>
</tr>
<tr>
<td>04</td>
<td>05-07-57-03</td>
<td>22-05-60-04</td>
<td>05-08-57-06</td>
<td>04-08-60-03</td>
<td>02-08-57-02</td>
<td>02-07-60-12</td>
<td>02-08-57-01</td>
</tr>
<tr>
<td>Total</td>
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<td>02-10-59-11</td>
<td>02-05-57-195</td>
<td>02-10-59-11</td>
<td>02-05-57-195</td>
<td>02-10-59-11</td>
<td>02-05-57-195</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Storms Time Variation of F2 Region</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MPO</strong></td>
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<tr>
<td><strong>MAR. 12</strong></td>
</tr>
<tr>
<td><strong>APR. 16</strong></td>
</tr>
<tr>
<td><strong>MAR. 20</strong></td>
</tr>
</tbody>
</table>

*Note: The table above shows the time variation of F2 region corresponding to the MPO values indicated.*

Corresponding to the U.T. day which contains the Main Phase Onset.

Among the 19 severe storms, 4 have a MPO at 11 U.T. and 4 at 14 U.T. Thus, the L.T. variations (DS) as well as the \( D_{\alpha} \) variations for these are expected to be similar for any particular location (longitude). The plots of these eight storms are shown in figure 2 (a) and (b). The full lines show geomagnetic \( D_{\alpha} \) (Sugiura and Poros, 1971) and the dashed lines show \( foF2/foF2 \) i.e. the ratio of actual \( foF2 \) to its monthly median value \( F2 \) for Kodakanal. The vertical dashed lines show the hour of MPO (Main Phase Onset) on the middle day. From the list of S.S.C. given in the Geophysical Data, we searched for S.S.C. that occurred during these 3-day intervals. These are marked as triangles at the appropriate U.T. hours. The bottom curves in figure 2 (a) and (b) are the averages of the 4 storms in these columns. Figure 2 (a) and (b) show the remaining 11 severe storms with the MPO occurring on the middle day at different U.T. hours as indicated by the vertical dashed lines. Table 2 gives details of the stations for which data are used in the present analysis.

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a) the largest changes in \( foF2 \) occur after the development of the main phase of the geomagnetic storm,

b) usually an enhancement of \( foF2 \) is observed (at equator) and depression is rare except during very intense storms,
Table 2. Details of stations.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Symbol</th>
<th>Geographic</th>
<th>Magnetic</th>
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</thead>
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<tr>
<td></td>
<td>Latitude</td>
<td>Longitude</td>
<td>Dip</td>
</tr>
<tr>
<td>Trivandrum</td>
<td>8°25'5&quot;N</td>
<td>77°00'0&quot;E</td>
<td>0°</td>
</tr>
<tr>
<td>Kerela</td>
<td>10°0'0&quot;N</td>
<td>77°00'0&quot;E</td>
<td>+5°</td>
</tr>
<tr>
<td>Tiruchirapalli</td>
<td>10°50'0&quot;N</td>
<td>78°50'0&quot;E</td>
<td>+5°</td>
</tr>
<tr>
<td>Ahmedabad</td>
<td>23°01'0&quot;N</td>
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</tr>
<tr>
<td>Ibadan</td>
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<td>73°35'0&quot;E</td>
<td>0°</td>
</tr>
<tr>
<td>Freiburg</td>
<td>48°00'0&quot;E</td>
<td>73°35'0&quot;E</td>
<td>+6°</td>
</tr>
<tr>
<td>Sling</td>
<td>51°30'0&quot;E</td>
<td>0°35'0&quot;E</td>
<td>+6°</td>
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<tr>
<td>Huancayo</td>
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<td>75°20'0&quot;W</td>
<td>+2°</td>
</tr>
<tr>
<td>Port Stanley</td>
<td>51°42'0&quot;S</td>
<td>57°48'0&quot;W</td>
<td>-4°</td>
</tr>
<tr>
<td>Areco</td>
<td>18°50'0&quot;S</td>
<td>66°48'0&quot;W</td>
<td>+5°</td>
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<td>Argentine Is.</td>
<td>65°12'0&quot;S</td>
<td>64°18'0&quot;W</td>
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<tr>
<td>Sagamore Hill</td>
<td>32°42'0&quot;N</td>
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<td>Boulder</td>
<td>48°00'0&quot;N</td>
<td>105°18'0&quot;W</td>
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</tr>
<tr>
<td>Singapore</td>
<td>1°18'0&quot;S</td>
<td>105°48'0&quot;E</td>
<td>18°</td>
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<tr>
<td>Bartoronga</td>
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<td>105°48'0&quot;E</td>
<td>-38°</td>
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<tr>
<td>Auckland</td>
<td>37°00'0&quot;S</td>
<td>175°00'0&quot;E</td>
<td>-63</td>
</tr>
</tbody>
</table>

c) there is a strong diurnal variation as well, an onset occurring during four nights causing foF2 depression and
d) these changes do not occur below about 200 km, but above that height changes are similar at all heights.

In figures 2-3, severe storms starting at various U.T. are depicted. We realise that the data for Kodaikanal are not completely satisfactory. There are frequent gaps of the type (non-latitude measurement) and F (spread echoes) in particular, data in the night-time hours (1900-0600 L.T.) are not completely reliable. Nevertheless, the following points become obvious from figures 2 and 3:

a) Large changes of foF2 are not necessarily confined to the main phase and later periods. In several cases, such changes are observed several hours prior to the maximum. Also, such changes are not necessarily confined to the S.S.C. either which are marked by the triangles. It would then seem that storms or severe storms have an influence on other stations, but this is not in agreement with the data as shown in Figure 2. (This may be attributable to the fact that foF2 is based on a single station.)

b) During and after the M.P.O., there are large increases as well as decreases of foF2, sometimes as large as 50% and not necessarily in any particular sequence. (See figure 2, where peppers indicate the probable level of backscatter. These are L.T. effects due to Kodaikanal, L.T. differences are due to 0 hours difference in 2 and as dots superposed on the dashed curves for Kodaikanal.) Some changes seem to occur simultaneously at the two locations showing a world-wide Dm effect (Thomas 1968, 1970). While some others are either uncorrelated or are anti-correlated and should be DD effects. A distinguishing feature is that many of the extreme values correlate to early morning hours. This is discussed later.

c) Even for storms starting at the same U.T., the changes are not similar indicating substantial differences in Dm, and/or DD effects from storm to storm (see Figure 2a) (or b).

To eliminate the DD effects and express the average Dm, the usual procedure seems to be to superimpose data from all storms with the S.S.C. as the zero hour. This success of the method depends largely upon whether the storm commence-ments are uniformly distributed in the 24 U.T. hours and whether the DD effects at all U.T. hours were similar except for the 15th phase shift for successive U.T. That is a transient phenomenon, the latter assumption cannot obviously be completely correct. Unfortunately, nothing can be done about this, however, a uniform distribution of onset times in all U.T. hours can certainly be checked. It is doubtful whether this is ever done. Even for the very exhaustive analysis of the 346 geomagnetic storms with sudden commencement undertaken by Sugura and Chapman (1966), the S.S.C. distribution over the Germanwood day had an occurrence frequency ranging from 4 to 16 for weak storms, 9 for 14 for moderate storms and 4 for large storms. In the case of the other workers, the total number of storms is much smaller, 109 for a long sequence (1959) and about 80 for Rajaram and Rastogi (1969, 1971) and the fluctuations could be at least as large. These authors have assumed that the storms would be distributed evenly over the different days of the year. Even if the fluctuations over individual successive U.T. hours are large, the results of these authors could still be nearly correct if the occurrence frequencies in four successive quadrants are almost similar. However, this certainly needs to be checked. In our case, this is not the case, and the total number of 19 is distributed as 3, 6, 7, 3 in the U.T. intervals 1-6, 7-12, 13-18, 19-24. In fact, storms are concentrated in the short U.T. interval 1100-1300 hours. We propose, therefore, to combine the storms (together with the corresponding) storms of S.S.C. to form a new group of storms for the purpose of obtaining the average for the new group of storms. The new group of storms, 12, 16, 17, 18 for the weak storms and 45, 51, 67 and 51 for all storms (214 storms). These are still not perfectly normal and we therefore, to find the average Dm + DS curve for foF2 for each U.T. hour and then combine the results from all U.T. hours to get the average. This approach gets the same weighting. We also calculate the Dm by superposing all storms as has been done by other workers and see if there is any difference between the two results.

For analysis, Kodaikanal hourly foF2 values for the 11 year period were first expressed as ratios of the average Dm (A) and for each U.T. hour. There were many gaps in the data due to instrumental failures. Some of these could be filled by interpolation in the filled values (A) near the location of Trivandrum and Tiruch, using their means wherever possible and individual values otherwise. It was also noticed that the gaps were very frequent during the night and early morning hours. Also the ratios varied in a wide range, from about 0.3 to 2.0. Each hour shows the frequency of changes at various L.T. hours for Kodaikanal for a total of 316 days out of which 79 are the dates for

great storms (strong + very strong) and rest are one day preceding and two days following each storm. As can be seen, the scatter is very large for the early morning and mid-night. Whereas some of the scatter could be due to the uncertainties in the observation errors of the S.S.C., it is not clear why the scatter should be large preferentially in the early morning. We feel that this could be due to the uncertainties in the S.S.C. at 10 and 11 A.M. hours. During low sunspot activity years, foF2 values in morning hours are low, sometimes even undetectable. However, no omission of ratios at L.T. hours for which the monthly median values were less than 3.5 MHz. It was found, however, that this did not ensure removal of abnormal ratios. Hence, all ratios deviating by more than ±25% from the average value of 1.00 i.e. ratios outside the range 0.75 to 1.25 were scrutinised individually and omitted when these occurred singly (i.e. for one stray hour only) and also when any of these abnormal ratios differed significantly (more than 20%) from ratios for preceding and following hours during day-time as well as night-time. Thus, stray individual values of abnormally high or low ratios were eliminated. Nevertheless, many abnormal ratios remained, specially in the night and early morning hours.

From the set of ratios so scrutinised, the storm time average variation for storms starting at various U.T. (1-24) was evaluated for the weak and strong storms in our data. During stormy periods it often happens that several distinct storms occur within a few hours of each other. For example, in Figures 2 (a), the period 3-5 Sept, 1958 is characterised by a strong storm on 3 September 1958 having a M.P.O at 1700 U.T. and a severe storm on 4 Sept. 1958 having a M.P.O at 1400 U.T. In the present analysis both storms are considered and included in the list in Table 1, the general criterion being that a storm may be preceded by another less intense storm but not followed. Thus, weaker storms occurring during the preceeding or during the recovery of strong or severe storms are omitted; but strong storms following weak storms are included. Since weak storms have thus an assured pre-storm period, we will study these three. Figure 3 shows the storm time variation for Kodaikanal foF2 ratios for weak storms in each plot. For example, 06 L.T. values are plotted as dots along the corresponding the top curve for the first column of Figure 3 (a) and is shown by the arrow. In the next curve below it, the M.P.O is at 02 U.T. (07 L.T.) and so on. In the last column of Table 1, M.P.O’s range from 09-16 U.T. (14-21 L.T.) and the third column (Fig. 3c) represents M.P.O’s from 17-24 U.T. (22-07 L.T.). Each column shows the frequency of changes at various L.T. hours for which M.P.O occurred at a particular U.T. hour as given in Table 1. The number of days involved are
Table 2. Details of stations.

<table>
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<tr>
<th>Stations</th>
<th>Symbol</th>
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<th>Magnetic</th>
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<td></td>
<td>Latitude</td>
<td>Longitude</td>
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<td>AUC</td>
<td>17°05'00&quot;</td>
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</tr>
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</table>

(a) there is a strong diurnal variation as well, an onsets occurring during six hours after 00 to 02 L.T. depression and
(b) these changes do not occur below about 200 km. but above that height changes are similar at all times.

In figures 2-3, severe storms at various U.T. are depicted. We realise that the data for Kodakkanal are not completely satisfactory. Therefore, frequent gaps of the type (C) (non-solar meridian) and F (spread echo), in particular, do not occur in the night hours (1900-0600 L.T.) are not completely reliable. Nevertheless, the following
results become obvious from figures 2 and 3:

(a) Large changes of foF2 are not necessarily confined to the main phase and later periods. In several cases, such changes are observed several hours prior to the MPO. Also, such changes are not connected with the S.C.C. either which are marked by the triangles. It would thus seem that storm or no storm, large foF2 changes do occur. This is not surprising since it is known that on quiet days the electron density varies from day-to-day by almost a factor of 2 and such changes are also connected with changes in foF2 (Kane and Friel, 1972a; also Aksou et al., 1969; McDougall, 1969; Fatal and Kottal, 1971; Rostogi and Rajan, 1971). For example, on Jan. 22, 1964 and Jan. 27, 1964 both of which were quiet days (Ap = 4), the H ranges at Kodakkanal were 119 gammas and 64 gammas respectively. The corrspective noon-time foF2 values (average of 1000-1300 L.T.) were 5.5 MHz and 6.9 MHz and with the monthly median value of 6.8 MHz for Jan. 1964, gave ratios 0.81 and 1.02. Thus, changes of 20% or more in foF2 values are easily obtained even from one quiet day to another.

(b) During and after the MPO, there are large increases as well as decreases of foF2, sometimes as large as 50% and not necessarily in any particular sequence. (See figure 2, near curve c). Whether these are L.T. effects (due to DS) is discussed in detail further; but similar plots for Huecayo which is a geographically located almost diametrically opposite to Kodakkanal (L.T. effect of importance about 10 hours) are shown in figures 2 and 3 as dots superposed on the dashed curves for Kodakkanal. Some changes seem to occur simultaneously at the two locations showing a world-wide Dn effect (Thomas, 1968, 1970) while some others are either uncorrelated or anti-correlated and could be DS effects. A disconcerting fact is that many of the extreme values refer to early morning hours. This is discussed later.

(c) Even for storms starting at the same U.T., the foF2 changes are not similar indicating substantial differences in Dn and/or DS effects from storm to storm. (See figure 2 (a) or (b)).

To eliminate the DS effects and extract the average Dn effects the usual procedure seems to be to superimpose data from all storms with the S.C.C. one hour as the zero hour. The success of this method depends largely upon the storm commencement is uniformly distributed in several of these U.T. hours and whether the DS effects at all U.T. hours were similar except for the 15° phase shift for successive storms. Since a storm is a transient phenomenon, the latter assumption cannot obviously be completely correct. Unfortunately, nothing can be done about this; however, a uniform distribution of onset times in all U.T. hours can certainly be checked. It is doubtful whether this is ever done. Even for the very exhaustive analysis for the 346 geoelectromagnetic storms with sudden commencement undertaken by Sugisara and Chapman (1966), the S.C.C. distribution over the Greenwhich day had an occurrence frequency ranging from 4 to 16 for weak storms, 9 to 14 for moderate storms and 4 to 8 for strong storms. In the case of the other workers, the total number of storms is much smaller, 109 for Matsushita (1959) and about 80 for Rajaram and Rastogi (1969, 1971) and the fluctuations could be at least as large. These authors have assumed that the storms would be distributed evenly over the different times of the day. Even if the fluctuations individual over successive U.T. hours are large, the results of these authors could still be nearly correct if the occurrence frequencies in four successive quadrants are almost similar. However, this certainly needs to be checked. In our case, this is not true for the severe storms where the total number of 19 is distributed as 3, 6, 7, 3 in the U.T. intervals 6-12, 12-18, 18-24. In fact, 10 storms are concentrated in the short U.T. interval 1100-1300 hours. We propose, therefore, to combine the strong and severe storms to give a new group of great storms for the purpose of the analysis of foF2. The number distributions in the 16, 12-12, 18 and 19-24 U.T. intervals are then, 17, 20, 21, 17 for the great storms, 12 storms, 16, 22, 13 for the weak storms and 45, 51, 67 and 51 for all 214 storms. These are still not uniformly distributed (therefore, to find the average Dn + DS curve for foF2 for each U.T. hour and then combine the results from all U.T. hours we must get the same weightage. We also calculate the Dn by superposing all storms as has been done by other workers and we find that there is any difference between the two results.

For analysis, Kodakkanal hourly foF2 values for the 11 year period were first expressed as ratios with respect to the corresponding values in the near-by stations Trivandrum and Tiruchi, using their means whenever possible and individual values otherwise. It was also noticed that the gaps were very frequent for the night and early morning hours. Also the ratios varied in a wide range, from about 0.3 to 0.2. Figure 4 shows the frequency of these ratios at various L.T. hours for Kodakkanal for a total of 316 days out of which 79 are the dates for great storms (strong + severe) and rest are one day preceding and two days following every storm day. As can be seen, the scatter is very large for the early morning hours and mid-night. Whereas some of the scatter could be genuine by the condition of the atmosphere at these times, it is not clear why the scatter should be large preferentially in the early morning. We feel this indicates the possibility of spurious longitudes at these times. During low sunspot activity years, foF2 values in morning hours are low, sometimes even undetectable. Here, a clearer indication was the omission ratios at all L.T. hours for which the monthly median values were less than 3.5 MHz. It was found, however, that even this did not ensure removal of abnormal ratios. Hence, all ratios deviating by more than ±25% from the average value of 1.00 i.e. ratios outside the range 0.75 to 1.25 were scrutinized individually and omitted when these occurred singly (i.e. for one stray hour only) and also when any of these abnormal ratios differed significantly (more than 20%) from ratios for preceding and following hours during day-time as well as night-time. Thus, stray individual values of abnormally high or low ratios were eliminated. Nevertheless, many abnormal ratios remained, especially in the night and early morning hours.

From the set of ratios so scrutinized, the storm time average variation for storms starting at various U.T. (1-24) was evaluated for the weak, moderate and great storms. During stormy periods it often happens that several distinct storms occur within a few hours of each other. For example, in figure 2(b), the period 3-5 Sept., 1958 is characterised by a strong storm on 3 Sept. 1958 having a MPO at 1700 U.T. and a severe storm on 4 Sept. 1958 having a MPO at 1400 U.T. In the present analysis both these storms are considered and included in the list in Table 1, the general criterion being that a storm may be preceded by another less intense storm but not followed. Thus, weaker storms occurring during the recovery of strong or severe storms are omitted; but strong storms following weak storms are included. Since weak storms have thus an assured quiet pre-storm period, we will study these first. Figure 5 shows the storm-time variation for Kodak- kanal foF2 ratios for weak storms. In each plot, 96 hours (1-24 L.T. vertical axis) for each storm is plotted amongst which the second day contains the MPO which is at 01 U.T. (or 06 L.T. for Kodakka- nal) (Fig. 5i) and is shown by the arrow. In the next curve below it, the MPO is at 02 U.T. (07 L.T.) and so on. In the lower right-hand corner of each MPO range from 09-16 U.T. (14-21 L.T.) and the third column (Fig. 5c) gives the MPO ratios from 17-24 U.T. (22-05 L.T. each). Each curve shows the frequency of these ratios at various L.T. hours for Kodakkanal for a total of 316 days out of which 79 are the dates for which MPO occurred at a particular U.T. hour as given in Table 1. The number of days involved are
marked near each curve and, as can be seen, there is only one single day for some curves. A remarkable point is obvious from almost all the curves viz. the fluctuations in the f0f2 ratios are very large in the pre-storm period (values before the arrows) as well as post-MPO period. In particular, these fluctuations are large during the night and early morning hours (about 2200 L.T. to 0500 L.T.) irrespective of the MPO position. We do not know whether other workers in this field have encountered this difficulty and if so, how exactly they have solved it. We have already mentioned above that ratios at the night and early morning hours look suspect to us and hence, we propose to proceed with the analysis by using these values as they are as also by omitting completely values for 2200-0500 L.T.

If values shown in figure 5 are superposed so that values at the arrows form the zero storm hour, one would obtain Dm (f0f2) for weak storms. Figure 6 shows Dm (f0f2) for Kodaikanal for weak (Fig. 6 a), moderate (Fig. 6 b) and great (Fig. 6 c) storms, at 6-hourly values i.e. averages of two successive hourly values. In each case, the top four full curves give the average Dm for storms having MPOs in various U.T. ranges viz. 01-06, 07-12, 13-18 and 19-24 U.T. which correspond to 06-11, 12-17, 18-23 and 00-05 L.T. for Kodaikanal. The fifth curve is the superposition of these four curves and gives the final Dm (f0f2) which is expected to be devoid of Ds effects. Since the superposition is according to L.T., it is expected that the abnormal ratios occurring at night and early morning hours (L.T. dependent effects) would get cancelled. However, to check the same, we deleted the ratios at these hours (2200-0500 L.T.) and the resultant Dm curves shown by superposed dots represent day-time values only. Following may be noted:

a) The ratios show large fluctuations before as well as after the MPO and values below 1.0 are quite common. However, if values for night and early morning hours are removed, ratios below 1.0 become less frequent.

b) Some influence of local time on Dm is seen. Thus, for the first two curves corresponding to storms occurring in day time, there is an f0f2 increase at and after MPO. For the next two curves,
marked near each curve, and as can be seen, there is only one single day for some curves.

A remarkable point is obvious from almost all the curves viz., the fluctuations in the \( f_{o} F_2 \) ratios are very large in the pre-storm period (values before the arrows) as well as post-MPO period. In particular, these fluctuations are large during the night and early morning hours (about 2200 L.T. to 0500 L.T.) irrespective of the MPO position. We do not know whether other workers in this field have encountered this difficulty and if so, how exactly they have solved it. We have already mentioned above that ratios at the night and early morning hours look suspect to us and hence, we propose to proceed with the analysis by using these values as they are also by omitting completely values for 2200-0500 L.T.

If values shown in figure 5 are superposed so that values at the arrows form the zero storm hour, one would obtain \( D_{st} (f_{o} F_2) \) for weak storms. Figure 6 shows \( D_{st} (f_{o} F_2) \) for Kodaiakan for weak (Fig. 6a), moderate (Fig. 6b) and great (Fig. 6c) storms, as bi-hourly values i.e., averages of two successive hourly values. In each case, the top four full curves give the average \( D_{st} \) for storms having MPOs in various U.T. ranges viz., 01-06, 07-12, 13-18 and 19-24 U.T. which correspond to 06-11, 12-17, 18-23 and 00-05 L.T. for Kodaiakan. The fifth curve is the superposition of these four curves and gives the final \( D_{st} (f_{o} F_2) \) which is expected to be devoid of DI effects. Since the superposition is according to U.T., it is expected that the abnormal ratios occurring at night and early morning hours (L.T. dependent effects) would get cancelled. However, to check the same, we deleted the ratios at these hours (2200-0500 L.T.) and the resultant \( D_{st} \) curves shown by superscribed dots represent daytime values only. Following may be noted:

a) The ratios show large fluctuations before as well as after the MPO and values below 1.0 are quite common. However, if values for night and early morning hours are removed, ratios below 1.0 become less frequent.

b) Some influence of local time on \( D_{st} \) is seen. Thus, for the first two curves corresponding to storms occurring in day time, there is an \( f_{o} F_2 \) increase at and after MPO. For the next two curves,
a decrease is observed, similar to that reported by Thomas and Venable's (1966) for midlatitudes. However, the changes after MPO are so large that the change at MPO looks minor.

c) In the final D$_{ts}$, there seems to be a noise level of about ±2% in the pre-MPO period. The post-MPO effect is a 5-10% increase, which seems to start soon after the MPO for weak and moderate storms but a few hours later for great storms. This delay effect may be due to the presence of storms in the region which are due to low ratios during night and early morning hours. If these are omitted and only dots are considered, the ratio increases significantly at night at the MPO and lasts for more than 24 hours.

Thus, in this method of studying D$_{ts}$ from ratios, the inclusion or exclusion of night-time and early morning values seems to make a substantial difference. Basically, the ratio method is preferred because it is based on quiet day effects which may be season-dependent too. It suffers from the defect that for hours of low fog, even small changes in fog will give large percentage changes. Alternatively one could use (a) the original fog ratio values or (b) the difference for fog ratio change (fog ratio change / original fog ratio). If every U.T. is equally weighted, the quiet day effect will be cancelled but the seasonal effect will remain in (a) even though not in (b). We found out D$_{ts}$ (fog ratio change) by using both these parameters. Figure 7 shows the final D$_{ts}$ obtained. As before, columns (a), (b), (c) refer to weak, moderate and great storms. The top two curves in each column represent the original fog ratio without giving weightage (NW) to U.T. i.e., storms are superposed neglecting the fact that some U.T. may be more or less suppressed than others. In principle, the method of giving equal weightage to all U.T. is obviously better. However, if only one or two stations are available for some U.T., this was used to get the average data for the study (as seen in Fig. 5) and its data for some reason erroneous, the error will creep in the analysis in a larger proportion.

Figure 7 shows the original fog ratio in the first column and the difference between the original fog ratio and the one after giving weightage (fog ratio change) in the second column. The new two curves are for the ratio (fog ratio change / original fog ratio), the weighted one (fog ratio change) being the same as the bottom curve of Figure 6. Matsuishiita (1959) gave the storm effect for N$_{w}$ / F$_{2}$ from which we derived fog ratio change by dividing by a factor of 2 and the resulting curves are plotted for comparisions at the bottom of the 1st and 2nd columns of figure 7 and are marked as M. The zero storm hour for these corresponded to S.S.C. and even though S.S.C. generally precede MPO by a few hours, we have arranged his zero hour to coincide with our MPO. Similar results for ICC/IGC storms obtained by Rajaram and Rastogi (1965) for Kodaikanal have been plotted at the bottom of the middle column (moderate storms) and are marked as RR.

Since figure 7 gives a presentation of the same data analyzed in different ways it gives us a good opportunity for intercomparison. On each of the six full line curves of each column, there are superposed dots depicting the day time data i.e., data after omitting values for the night and early morning hours 2200-0500 L.T. The vertical line indicates zero storm hour (MPO). Following may be noted from figure 7:

i) The weighted (W) curves do not differ very much from the corresponding unweighted (NW) curves. This means that zero through there are fluctuations in the occurrence frequency of storm MPOs at different individual U.T. as shown in Table 1, the distribution in successive 6 hourly quadrants is uniform and enough and is not necessary to give uniform weightage to all U.T.s in xar analysis.

ii) The dots show a substantially different variation from the full curves. In particular, full lines tend to touch the average line more often after the MPO while dots tend to remain above it. This would thus seem that inclusion of data at night and early morning hours (2200-0500 L.T.) has a tendency to dilute the storm effects. The frequent excursions of the dots to average value 1.0 and sometimes even lower can be explained in the results of Matsushita (M) and Rajaram and Rastogi (RR), which could also be due to the inclusion of abnormal ratio values at night and early morning hours.

iii) Amongst the 3 methods viz. using fog ratio, the difference (fog ratio change) and the ratio (fog ratio change / original fog ratio), the use of fog ratio does not seem desirable as the averages show large fluctuations. The other two methods viz. using the difference and the ratios show to seem similar results. Concentrating on these, the storm-time effect could be described as follows:

a) In weak storms, the pre-MPO period is characterised by a noise level of about ±2% around the average level. Soon after MPO (within an hour or two) there is a 5-10% increase by about 5% and remains high for about 24 hours, attaining average value thereafter. The increase is more conspicuous in the day-time value (dots) and inclusion of night-time values tends to dilute it.

b) In moderate storms, the effect is similar to weak storms except that the post-MPO increase is about 7-10% and there is a small 1-2% decrease at near MPO. As before, night values dilute the storm effects.

c) In great storms, there is a tendency for fog to decrease below average by 1-2% in the pre-MPO period, reach a noticeable minimum (2-3%) at MPO and afterwards show a substantial increase (7-10%) lasting for 24-48 hours.

d) For the plots of Matsushita (M) and Rajaram and Rastogi (RR) we adjusted their zero storm hour to coincide with our MPO. Their curves are in many ways similar to our full curves. This is understandable because even though MPOs are preceded by SSCs sometimes by several hours, in most of the cases the lag hardly exceeds two hours. Sugura and Chappell (1960) mention that the average lag is about 3 hours for weak storms and about 1 1/2 hours for moderate and severe storms in the equatorial region. The erratic ups and downs in the curves of M and RR even in the post-MPO period occasionally even touching the average line may be due to erratic behaviour of night-time values (as it is seen in our full curves too) or due to variable time intervals between SSC and MPO, or both.

In conclusion, the storm-time D$_{ts}$ (fog ratio change) at Kodaikanal seems to be an overall increase of about 5-10% in the 24-48 hour period immediately following the MPO of a geomagnetic storm with severe storms showing in addition a small decrease of about 2-3% during the few hours prior to and at the MPO. The effects are very conspicuous for day-time hours whereas night-time values tend to obscure the same.

It would be interesting to compare with results obtained at other latitudes and longitudes. A similar analysis was carried out for Bhaban, Huanzayo, Airhodab and Slough. Figure 8 shows the D$_{ts}$ (fog ratio change) at these places for (a) weak, (b) moderate and (c) great storms. W means all U.T. equally weighted and NW means not weighted. Full curves are obtained by using all L.T. hours and dots by using day-time values (0600-2100 L.T.) only. Bottom curves show results obtained by Matsuishiita (1959) marked as M and Rajaram and Rastogi (1969) marked as RR.
a decrease is observed, similar to that reported by Thomas and Venables (1966) for midlatitudes. However, the pre-MPO conditions after MPO are so large that the change at MPO is less significant.

c) In the final D_{90}, there seems to be a noise level of about ±2% in the pre-MPO period. The post-MPO decreases of 5-10% indicate a trend which seems to start soon after the MPO for weak and moderate storms but a few hours later for great storms. This delayed effect is probably due to storms being too close to give low ratios during night and early morning hours. If these are omitted and only dots are considered, the ratio increases in height at the MPO and lasts for more than 24 hours.

Thus, in this method of studying D_{90} from ratios, the inclusion or exclusion of night-time and early morning values seems to make a substantial difference. Basically, the ratio method is preferred because it corrects for quiet day effects which may be season-dependent too. It suffers from the defect that for hours of low foF2, even small changes in foF2 give large percentage changes. Alternatively one could use (a) the original foF2 values or (b) the difference (foF2-foF2) if every U.T. is equally weighted, the quiet day effect will be cancelled but the seasonal effect will remain in (a) though perhaps not in (b). We found out D_{90} (foF2) by using both these parameters. Figure 7 shows the final D_{90} so obtained. As before, columns (a), (b), (c) refer to weak, moderate and great storms. The top full curve in each represents original foF2 without giving weightage (NW) to U.T. i.e. storms are superposed neglecting the fact that some U.T. may be more or less equally represented than others. In principle, the method of giving equal weightage to all U.T is obviously better. However, if only a single scale is available for some U.T. (as was seen in Fig. 5) and its data are for some reason erroneous, the error will creep in the analysis in a larger proportion than in the simple method of using no weightage. The graph two curves are for the difference (foF2-foF2) with U.T. properly weighted (W) and unweighted (NW). The bottom full curves are for the ratio (foF2/foF2), the weighted one (W) being the same as the bottom curve of Figure 6. Matsushita (1959) gave the storm effect for N_{F2} from which we derived foF2 by dividing by a factor of 2 and the resulting curves are plotted for compari

tion at the bottom of the 1st and 3rd columns of figure 7 and are marked as M. The zero storm hour for these corresponded to S.S.C. and even though S.S.C. generally precede MPO by a few hours, we have arranged his zero hour to coincide with our MPO. Similar results for IGY-IGC storms obtained by Rajaram and Rastogi (1969) for Kodai

nial have been plotted at the bottom of the midddle column (moderate storms) and are marked as RR. Since figure 7 gives a presentation of the same data analyzed in different ways it gives us a good opportunity for comparison. On each of the first six full line curves of each column, there are superposed dots depicting the day time data i.e. data after omitting values for the night and early morning hours 2200-0500 L.T. The vertical line indicates zero storm hour (MPO). Following may be noted from figure 7:

i) The weighted (W) curves do not differ very much from the unweighted (NW) curves. This means that even though there are fluctuations in the occurrence frequency of storm MPOs at different individual U.T. as shown in Table 1, the distribution of successive 6 hourly quadrants is uniform enough and it is not necessary to give uniform weightage to all U.T.s in our analysis.

ii) The dots show a substantially different variation from the full curves. In particular, full lines tend to touch the average line more often after the MPO while dots tend to remain above it. It would thus seem that inclusion of data at night and early morning hours (2200-0500 L.T.) has a tendency to dilute the storm effects. The frequent excursions of the ratios to attain the average value 1.0 and sometimes even lower in the case of the results of Matsushita (M) and Rajaram and Rastogi (RR) could also be due to the inclusion of abnormal ratios values at night and early morning hours.

iii) Amongst the 3 methods viz. using foF2, the difference (foF2-foF2) and the ratio (foF2/foF2), the use of foF2 does not seem desirable as the averages show large fluctuations. The other two methods viz. using the difference and the ratios seem to show similar results. Concentrating on these, the storm-time effect could be described as follows:

a) For weak storms, the pre-MPO period is charac
terised by a noise-level of about ±2% around the average level. Soon after MPO (within an hour or two), the average increases by about 5% and remains high for about 24 hours, attaining average values thereafter. The increase is more conspicuous in the day-time values (dots) and inclusion of night-time values tends to dilute it.

b) For moderate storms, the effect is similar to weak storms except that the post-MPO increase is about 7-10% and there is a small 1-2% increase at or near MPO. As before, night values dilute the storm effects.

c) For great storms, there is a tendency for foF2 to decrease below average by 1-2% in the pre-MPO period, reach a noticeable minimum (2-3%) at MPO and later show a substantial increase (7-10%) for lasting 24-48 hours.

d) For the plots of Matsushita (M) and Rajaram and Rastogi (RR) we adjusted their zero storm hour to coincide with our MPO. Their curves are in many ways similar to our full curves. This is understandable because even though MPOs are preceded by SSCs sometimes by several hours, in most cases the lag hardly exceeds two hours. Sugita and Chumou (1960) mention that the average lag is about 3 hours for weak storms and about 1 1/2 hours for moderate and severe storms in the equatorial region. The erratic ups and downs in the curves of M and RR even in the post-MPO period occasionally even touching the average line may be due to erratic behaviour of night-time values (as is seen in our full curves too) or due to variable time intervals between S.S.C. and MPO, or both.

In conclusion, the average storm-time D_{90} (foF2) at Kodai

nial seems to be an overall increase of about 5-10% in the 24-48 hour period immediately following the MPO of a geomagnetic storm with severe storms showing in addition a small decrease of about 2-3% during the few hours prior to and at the MPO. The effects are very conspicuous for day-time hours whereas night-time values tend to obscure the same.

It would be interesting to compare with results obtained at other latitudes and longitudes. A similar analysis was carried out for Ibadan, Huancoyo, Ahmadabad and Slough. Figure 8 shows the D_{90} (foF2) at these places for (a) weak, (b) moderate and (c) great storms. The top curve in each column shows the average geomagnetic D_{90} (Sugita and Peros, 1971). The next five full curves show the difference (foF2-foF2) for the five stations. Scales are similar except for Slough which shows larger effects and hence the scale is changed by a factor of 2. The next curve (marked as EQU) is representative of the equatorial region and is obtained by superposing Kodai

nial, Ibadan and Huancoyo. The next 5 curves represent the ratio (foF2/foF2) at the five stations. For each curve the superposed dots show results for day-time hours only, obtained after conditioning them for the night hours (2200-0500 L.T.). The following may be noted:

i) In every case, the average storm-effect seems to start within an hour or two of the MPO. Thus, foF2 changes during storms seem to be connected with the same factor as the phase of a geomagnetic storm viz. the ring current. For high latitudes the effect is a decrease and the relation with MPO is very conspicuous, so much so that
may be noticed, however, that for Huancayo the day and night values seem to behave alike and for great storms, the initial rise after MPO is not sustained and both day and night values dip down to average values up to about +12 storm hours and then rise again as at other stations. Thus the behavior at Huancayo for the first few storm hours is different from that at Kodai kanal and Bandan. Abnormal behaviour at Huancayo has been reported earlier by Rajaram and Rastogi (1968).

iv) Comparison of our curves with similar results reported in the literature indicates that relationship with MPO is more conspicuous than that for SSC, at all latitudes. There seems to be a difference in behaviour of weak and strong storms. For weak storms, the pre-MPO period is average at equator and above average for high latitudes. For strong storms, the pre-MPO period is below average at equator and average at high latitudes. Thus behaviour at equator and high latitudes are not just simply reciprocal in the pre-MPO period, while in the post-MPO period there is conspicuous reciprocity.

Let us study now the local time dependence. If the curves in figure 5 are superposed hour to hour (L.T.), the $D_s$ effect will be smeared out and only $S_D$ i.e. additional daily L.T. disturbance will remain. Figure 9 shows $S_D$ so obtained for all the stations. Full curves represent $S_D$ for the ratio ($f_{oF2}$/$f_{oF2}$). The superposed dots represent $S_D$ for the difference ($f_{oF2}$/$f_{oF2}$) in MHz. Four continuous days are depicted in which storm MPOs are supposed to have occurred on the 2nd day. Following can be seen:

i) There are some abnormally large depressions during mid-night and early morning hours at Kodai kanal and Bandan, specially in the ratios (full

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Fig. 6

- $D_s$ ($f_{oF2}/f_{oF2}$) and $D_s$ ($f_{oF2}/f_{oF2}$) for Kodai kanal, Bandan, Huancayo, Ahmedabad and Slough for (a) weak (b) moderate and (c) great storms. The top curves give the average geomagnetic $D_s$, while the bottom curves give $D_s$ of $S_D$ and drift velocity $v$ (see text). Full curves are for all L.T. hours. Dots for day hours only and crosses for night hours only (for Kodai kanal, $f_{oF2}/f_{oF2}$ only).

- $f_{oF2}$ and geomagnetic $D_s$ variations look indistinguishable. For a mid-latitude station like Ahmedabad too the effect is similar though reduced in magnitude and somewhat obscure for weak storms.

- For both middle and high latitudes, day and night values show similar results.

- For the equatorial region, the effect is a definite increase after the MPO but is more conspicuous for day time values (see curves marked EQU).

In figure 8, we have shown for Kodai kanal ($f_{oF2}/f_{oF2}$) ratios the behaviour of night-time values as superposed curves. As can be seen, the behaviour is very erratic and often values below average (1.0) are reached even after MPO. This would mean either that the night values are unreliable or the storm-effect for the equatorial night-time F2 region is different than that for the day-time F2 region. It

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Fig. 8

- $S_D$ at Kodaikanal, Bandan, Huancayo, Ahmedabad and Slough for the ratio ($f_{oF2}/f_{oF2}$) (full curve) and the difference ($f_{oF2}/f_{oF2}$) (dots). Four successive L.T. days are shown in which MPOs occurred in the 2nd day at various L.T. The bottom curves show Kodaikanal $S_D$, $s_D$, and $S_D$. i.e. deviation from the $S_D$ pattern of the 1st day.
may be noticed, however, that for Huancayo the day and night values seem to behave alike and for great storms, the initial rise after MPO is not sustained and both day and night values dip down to average values up to about +12 storm hours and then rise again as at other stations. Thus the behaviour at Huancayo for the first few storm hours is different from that at Kodaikanal and Ibadan. Abnormal behaviour at Huancayo has been reported earlier by Rajaram and Rastogi (1968).

4) Comparison of our curves with similar results reported in the literature indicates that relationship between MPO and F2 is more conspicuous than that for SSC at all latitudes.

5) There seems to be a difference in behaviour of weak and strong storms. For weak storms, the pre-MPO period is average at equator and above average for high latitudes. For strong storms, the pre-MPO period is below average at equator and average at high latitudes. Thus behaviour at equator and high latitudes are not just simply reciprocal in the pre-MPO period, while in the post-MPO period there is conspicuous reciprocity.

Let us study now the local time dependence. If the curves in figure 5 are superposed hour to hour (L.T.), the $D_p$ effect will be smeared out and only $SD$ i.e. additional daily L.T. disturbance will remain. Figure 9 shows $SD$ so obtained for all the stations. Full curves represent $SD$ for the ratio $(f(02)/f(02))$. The superposed dots represent $SD$ for the difference $(f(02)/f(02))$ in MHz. Four continuous days are depicted in which storm MPOs are supposed to have occurred on the 2nd day. Following can be seen:

i) There are some abnormally large depressions during mid-night and early morning hours at Kodaikanal and Ibadan, specially in the ratios (full

$D_p(f(02)/f(02))$ and $D_{sh}(f(02)/f(02))$ for Kodaikanal, Ibadan, Huancayo, Ahmadabad and Strouh for (a) weak (b) moderate and (c) great storms. The top curves give the average geomagnetic $D_p$ while the bottom curves give $D_p$ at $S_{sh}$ and diff. velocity $V$ (see text). Full curves are for all L.T. Hours, dots for day hours only and crosses for night hours only (for Kodaikanal $f(02)/f(02)$ only).

$f(02)$ and geomagnetic $D_p$ variations look undistinguishable. For a mid-latitude station like Ahmadabad the effect is similar though reduced in magnitude and somewhat obscure for weak storms.

ii) For both middle and high latitudes, day and night values show similar results.

iii) For the equatorial region, the effect is a definite increase after the MPO but is more conspicuous for day time values (see curves marked EQU).

In figure 8, we have shown for Kodaikanal $(f(02)/f(02))$ ratio the behaviour of night-time values as superposed crosses. As can be seen, the behaviour is very erratic and often values below average (10) are reached even after MPO. This would mean either that the night values are unreliable or the storm effect for the equatorial night-time $F2$ region is different than that for the day-time $F2$ region.
III - Discussion

There are thus two clear cut aspects of the storm-time variation of foF2. First is the $D_m$ (foF2) shown in figure 8 and the second is the $SD$ (foF2) shown in figure 9. Several attempts have been made in the past to explain these features. Basically the continuity equation for the F-region is

$$\frac{dN}{dt} = Q - L + div(NV)$$

and thus changes in the electron density $N$ could be due to changes in production $Q$, loss $L$, and transport div (NZ). During disturbed conditions all these factors can change. For the equatorial region main sources of change are generally considered to be: electrodynamic drifts and neutral winds (Maeda and Sato, 1959; Rajpar, et al., 1971). The electrodynamic drift occurs during the main phase of a storm, a partial ring current is expected to be produced in the night side of the magnetosphere (Piddington, 1967), electrons drifting towards east and protons towards west giving a net polarised electrostatic field opposite in direction to the normal $\zeta$. Thus, during storms both the electrojet current as also the upward electrodynamic drift near the equator are expected to be reduced. There is some evidence that during quiet periods, the large day-to-day changes in the equatorial electrojet strength as given by the range $\Delta H = H_{eq} - H_{m0}$ is almost completely due to the horizontal component $H$ of geomagnetic field at equator are very intimately connected with foF2 changes, specially the noon-time bits-out (Kane, 1972 a; Aksouf et al., 1969; McDougall, 1969). However, for a disturbed period such analysis becomes meaningless because the range $\Delta H$ as defined above does not represent daily variation range as $H$ values are distorted due to magnetospheric effects. Even the difference in ranges $\Delta H_1 - \Delta H_2$ used by Rajpar and Rashid (1971) represent an equatorial station (Trivandrum) and $A$ represents a low latitude station (Allagab) outside the electrojet influence does not serve as a measure of the equatorial electrojet strength because both $\Delta H_1$ and $\Delta H_2$ are numerical quantities influenced by $D_m$ effects. If the average daily vertical drifts are same for two stations and daily and quiet days are evaluated and their difference obtained hour to hour (L.T.), the SD so obtained is free of $D_m$ effects; but there is no guarantee that SD is of purely ionospheric origins. In fact, as shown by Kane (1972 b), $SD$ is composed of a morning maximum which is partly ionospheric and partly magnetospheric and an evening minimum which is mostly magnetospheric. Thus, the observation of Rastogi and Rajpar (1971) that the daily variation of foF2 on disturbed days is analogous to that on a weak electrojet day does not necessarily guarantee that the electrojet is weak on geomagnetically disturbed days. Recently we have been advocating (Kane 1973) that a reasonably good measure of equatorial electrojet strength could be obtained if the $H$ values at Trivandrum (T) and Allagab (A) in roughly similar longitude are subtracted from each other hour to hour (L.T.) and the range $\Delta H$ obtained from the 24 hourly values of this difference. In short, we proposed using $\Delta H_{T-A}$ instead of $\Delta H_{T}$ to derive $SD$. Further, we add a constant factor $S_q(A)$ which is the average quiet day daily variation at Allagab (A). Thus $SD(T) = S_q(A)$ i.e. the electrojet strength at Trivandrum on any day at any local hour ($h$) will be given by:

$$SD(T) = S_q(A)$$

We evaluated $S_q$ for Kodakanal for all the storm days using the $S_q(A)$ method. It is also important to note that $S_q = \infty$ where $N$ is the electron density in the electrojet and $S_q = 0$ when the $N$ values are proportional to the electric field. Thus, to obtain a measure of the electric field only, it is necessary to divide the daily variation of $N$ by the daily variation of $N$. Due to the presence of sporadic $D_m$ at the equator almost all the time during day, it is virtually impossible to measure equatorial foF2 which would give $N$. Nevertheless, MacDougall (1969) has given a "general form of variation of $E$ region electron density" which can be used to obtain the daily variation of $N$ which can be assumed to be constant. The above method is only valid if $S_q(A)$ is independent of the day-to-day changes in the variation of $N$. Hence $S_q(A)$ is not influenced by the presence of $D_m$ effects. In this way we have obtained the daily variation of foF2 at Trivandrum and thus derived $SD$ which is not influenced by the presence of $D_m$ effects.

Since $S_q$ is essentially a daily variation ("L".effect), it is obvious that it can be computed only with foF2 data for that day and not with foF2 data for the previous day. The $SD$ for the previous day is obtained by subtracting a constant $S_q(A)$ from the present day values of foF2. Thus, the $SD$ for the previous day is obtained by the formula $SD(T) = S_q(A)$.

We may conclude, therefore, that the distortion of foF2 and electrojet strength at equator originate from the same dynamical process on all days, quiet as well as disturbed. The same, however, cannot be said of the $D_m$ effects as these are very conspicuous in foF2 but not in $SD$. We feel that the $D_m$ effects are connected with the dissipation of the ion ring current particles in the magnetosphere. Hence this exactly what we have foF2, and what $SD$ is not. Hence $SD$ is a very useful tool for the study of the magnetosphere. However, this exactly why we have foF2 in the equatorial region; and depells it in the higher latitudes is not quite clear. If one invokes the presence of extra neutral winds flowing from higher latitudes towards equator (Kajjaram et al., 1971) during storms, the observed results could be explained; but the wind direction will have to be local-time independent (i.e. always from high latitudes towards equator), as the foF2 effects are observed at all hours of the day (night) to give a consistent $D_m$ effect. Such a wind system has not yet been observed or inferred. A third possibility is that the winds are from the protonosphere though it is not clear why this should be confined to the equatorial region.

We must admit straightforwardly that an analysis of the type we have described so far it is essentially incomplete unless the height changes of the $F_2$ layer are also simultaneously taken into account. In fact, the difference of behaviour in daytime and nighttime may well be due to differences in height changes. Data of $K_F2$ were available were not used as the true height changes can be significantly different (and smaller) from the virtual height changes which are strongly influenced by group retardation effects. Computed true height N-h profiles were not available to us. It must be realised, however, that even true height information does not give a complete picture as the bottom side ionosphere in one only a part of the overall ionospheric region and there are reasons to believe that storm-time changes are a somewhat more complicated than the obtained in the bottom side (Titheridge and Andrews 1967; Warren 1969). As such, a comprehensive picture of the dynamical processes cannot be obtained only if N-h profiles are available at all latitudes and longitudes and at altitude levels before, during, and after a geomagnetic storm. Unfortunately, beacon satellite data are usually available only for one or two passes per day; these data are usually not supplemented by data from the incoherent backscatter radar technique as also by data from geostationary meteor satellite. Recently, the World Data Center A, Upper Atmosphere Geophysics has been collecting wonderful data from several sources containing data from the few selected geomagnetic storms. Their Report UAG-12 gives contributions from co-author institutions for the major geomagnetic storms of 8 March 1970. In figure 10 we have reproduced some of the data for middle and low latitudes from this report obtained from some other data from outside. The top curve shows the $D_m$ (Sugita and Poros, 1971) for the period 6-10 March 1970. On 8 March, there was a total solar eclipse (marked as ECL) at about 1800-2000 U.T. On 8 March, there was an SSC at 1418 U.T. and an $M$ at about 1800 U.T., the main phase lasting for 6 hours. This was followed by an $F$ recovery which was almost complete by 1700 U.T. on 9th March. The storm, though a large one, had thus a very brief main phase and recovery phase.
curves). If genuine, these would indicate that foF2 decreases appreciably during these hours at all latitudes during storms. We have a feeling, however, that at least some of these are unreliable. Such changes can introduce weal distortions on the graph.

ii) The day time values show average values for the 1st (pre-storm) day followed by a steady in- crease for the 2nd and 3rd (post-storm) days, especially the 3rd (post-MPO) day at equator and low latitudes and at high latitudes. Thus, factors at equator and high latitudes are very similar to each other but only those at the equator are enhanced at about noon following the MPO. 

III - Discussion

There are thus two clear cut aspects of the storm-time variation of foF2. First is the Dv (foF2) shown in figure 8 and the second is the SD (foF2) shown in figure 9. Several attempts have been made in the past to explain these features. Basically the constancy equation for the F-region is

\[ \frac{dN}{dL} = -Q - L - \text{div}(NV) \]

and thus changes in the electron density N could be due to changes in production Q, loss L, and transport div(NV). During disturbed conditions all these factors can change. For the equatorial region main sources of change are generally assumed to be the electrodynamic drifts and neutral winds (Maeda and Sato, 1959; Rajaram et al., 1971). The electrodynamic effect occurs during the phase of a storm, a partial ring current is expected to be produced in the night side of the magnetosphere (Piddington, 1967), electrons drifting toward the earth and protons towards west giving a net polarized electrostatic field opposing in direction to the normal D component. Thus, during storms both the electron current as also the upward electrodynamic drift near the equator are expected to be reduced. There is some evidence that during quiet periods, the large day-to-day changes in the equatorial electron density is probably due to the horizontal component H of geomagnetic field at the equator. The horizontal component of geomagnetic field at the equator are very intimately connected with foF2 changes, especially the noon-beneath-out (Kane, 1972a; Akanou et al., 1969; McDougal, 1969). However, for a disturbed period such an analysis becomes meaningless because the range \( \Delta H \) defined above does not represent daily variation range as H values are distorted due to geomagnetic effects. Even the difference in ranges \( \Delta H_{\text{equ}} \Delta H_{\text{post-MPO}} \) used by Rastogi and Ramachandar in figure 8 represents an equatorial station (Trivandrum) and A respectively presents a low latitude station (Alibaug) outside the equatorial ionization region. The equatorial electrojet strength because both \( \Delta H_{\text{equ}} \) and \( \Delta H_{\text{post-MPO}} \) are numerical quantities influenced by many daily effects. If the average daily vertical drift \( v_{\text{d}} \), day and quiet day values are evaluated and their differ- ence obtained hour to hour (L.T.), the SD so obtained may be a free of \( \Delta H_{\text{equ}} \) effects; but there is no guarantee that SD is of purely ionospheric origin. In fact, as shown by Kane (1972b), SD is in many cases large which is partly ionospheric and partly magnetospheric and an evening minimum which is mostly magnetospheric. Thus, the observation of Rastogi and Rajaram (1971) that the daily variation of foF2 on disturbed days is analogous to that on a weak electrojet day does not necessarily guarantee that the electrons are weak on geomagnetically disturbed days. Recently we have been advocating (Kane 1973) that a reasonably good measure of equatorial electrojet strength could be obtained if the H values at Trivandrum (T) and Alibaug (A) in roughly similar longitudes but subtracted from each other hour to hour (L.T.) and the range SD obtained from the 24 hourly values of this difference. In short, we proposed using \( \Delta H_{\text{equ}} - \Delta H_{\text{post-MPO}} \) instead of \( \Delta H_{\text{equ}} \). Further, we add a constant factor \( K_{T/A} \) which is the average quiet day daily variation at Alibaug (A). Thus \( \Delta H_{\text{equ}} - \Delta H_{\text{post-MPO}} + K_{T/A} \) i.e. the electrojet strength at Trivandrum on any day at any local hour (L.T.) will be given by:

\[ \text{SD}(T/A) = \text{H}(T) - \text{H}(A) + K_{T/A} \]

We evaluated \( \text{SD}(T/A) \) for Kodaikanal (L.T.) for all the storm-time values and find that the variations are proportional to the electric field. Thus, to obtain a measure of the electric field only, it is necessary to divide the diurnal variation of \( \Delta H_{\text{equ}} \) by the corresponding shift of the horizontal component H of geomagnetic field at the equator almost all the time during day, it is virtu- ally impossible to measure equation \( \text{SD}(T/A) \) which would give N. Nevertheless, McDougall (1969) has given a "general form of variation of E region electron density" which can be used to obtain the daily variation of \( \Delta N_{\text{equ}} \) and \( \Delta N_{\text{post-MPO}} \) on any day on the assumption that day-to-day changes of \( \Delta N_{\text{equ}} \) and \( \Delta N_{\text{post-MPO}} \) are caused by changes in the general form of \( E \) and not of \( N \).

Since \( \text{SD}(T/A) \) is essentially a daily variation (L.T.) effect, it is obvious that it can be compared only with SD (foF2) (L.T.) and not with Dv (foF2) and not with Dv (foF2) of figure 8. Nevertheless, there could be a reasonable doubt that there is no real Dv effect in foF2 and what we see in figure 9 is some sort of a residual lingering effect of SD not cancelling away properly. If so, SD, processed the same way should show a non-zero storm effect. The bottom curves in figure 9 show the plots of Sd3 and \( \nu = \text{SD}(T/A) \) at Kodaikanal. To obtain the latter (\( \nu \)) we expressed the daily 24 hourly L.T. values of Sd3 as deviations from the mean of (0045) L.T. of every day. Also, since this deviation is small for certain days, we have omitted values of \( \nu \) when Sd3 were within ±10 gamma. However, on many occasions Sd3 is observed to be negative, indicat- ing counter-electrojets (Gounin and Mayaud 1967, 1969). Such events have been retained if these occurred in the L.T. 6-9 L.T. Full curves represent averages for all hours and dots represent averages for only daytime hours. As can be seen, there is no appreciable \( D_{\text{eq}} \) effect in either Sd3 or drift velocity \( \nu \) except for great storms when drift velocities seem to be reduced to very low values near about zero storm hour. Here again the effect is less conspicuous when only daytime values (dots) are considered. We conclude, therefore, that as far as the \( D_{\text{eq}} \) effect in foF2 is concerned, it is not related in any significant way to the electrojet strength and its associated dynamics and hence most probably not connected with electromagnetic drifts.

Regarding the SD effect in foF2, the average Sd3 at Kodaikanal (L.T.) are shown at the bottom of figure 9. Though the overall daily variation pattern is similar for all the four days, there are some small differences in the amplitudes and drifts for each of the four storms. This is brought out in the bottom curves of figure 9 which are obtained by subtracting the daily variation curves of the 1st day from the other. As can be seen, Sd3 is below average on the 3rd day i.e. the day immediately following the MPO day. (The corres- ponding drift velocity \( \nu \) curves are not shown as these are obtained as \( \Delta N_{\text{equ}} \) and hence show results similar to Sd3). On days of great storms, the reduction in Sd3 is about 25 gamma. Compared to the average value of 100 gamma, this indicates about 25 % reduction in electron density on such days on the average, particularly near noon hours. The Kodaikanal foF2 daily variation curves in figure 9 show about 23-30 % lift-off of foF2 at noon specially at noon hours. Thus, the SD effects in foF2 and equatorial electrojet strength seem to be intimately connected in the same way as their quiet-day variations.

We may conclude, therefore, that the diurnal variations in foF2 and electrojet strength at equator originate from the same dynamical process on all days, quiet as well as disturbed. The same, however, cannot be said of the \( D_{\text{eq}} \) effects as these are very conspicuous in foF2 but not in Sd3. We feel that the \( D_{\text{eq}} \) effects are not connected with the dissipation of the ring current particles in the magnetosphere. How exactly this will enhance foF2 in the equatorial region - and depletes it in the higher

lattitudes is not quite clear. If one invokes the presence of extra neutral winds flowing from higher latitudes towards equator (Rajaram et al., 1971) during storms, this effect could be interpreted to be explained; but the wind direction will have to be local-time independent (i.e. always from high lati- tudes towards equator throughout day as well as night) to give a consistent \( D_{\text{eq}} \) effect. Such a wind system has not yet been observed or inferred. A third possibility is that limitations on the protonosphere though it is not clear why this should be confined to the equatorial region.

We must admit straightforwardly that an analysis of the type we have described so far is essentially incomplete unless the height changes of the F2 layer are also simultaneously taken into account. In fact, the difference of behaviour in daytime and nighttime may well be due to differences in height changes. Data of H2F were available but were not used as the true height changes can be significantly different (and smaller) from the virtual height changes which are strongly influenced by group retardation effects. Computed true height N4 profiles were not available to us. It may be realised, however, that even true height information does not give a complete picture as the bottom side iono- sphere in only a part of the overall ionospheric region and there are reasons to believe that storm- time changes in height above than in the bottom side (Titheridge and Andrews 1967; Warren 1969). As such, a comprehensive picture of the dynamical processes obtained only if N4 profiles as well as temperature-height profiles are available at several latitudes and longi- tudes and at all times both during and after a geomagnetic storm. Unfortunately, beacon satellite data are usually available for only one or two passes per day. As a first approximation, data must be interpolated by data from the incoherent back- scatter radar technique as also by data from geosta- tionary satellites. Recently, the World Data Center A, Upper Atmosphere Geophysics has been doing wonderful job by computing from various sources data pertaining to a few selected geomagnetic storms. Their Report UAG-12 gives contributions from observations for the major geomagnetic storms of 8 March 1970. In figure 10 we have reproduced scene of the data for middle and low latitudes from this report as also from some other data from outside. The top curve shows the \( D_{\text{eq}} \) (Sugiura and Peros, 1971) for the period 6-10 March 1970. On 7 March, there was solar eclipse (marked as ECL) at about 1800-2000 U.T. On 8 March, there was an SSC at 1418 U.T. and an MPO at about 1800 U.T., the main phase lasting for 6 hours. On 9 March, there was a recovery which was almost completed by 1700 U.T. on 9th March. The storm, though a large one, had thus a very brief main phase and recovery phase.
Also, its profile was considerably different at different latitudes and longitudes, indicating substantial geomagnetic DS effects. The next full curve shows the total electron content (TEC) as deduced at Sagamore Hill by measuring the Faraday rotation of VHF signals from the geostationary satellite ATS-1. The superposed dashed curve gives ATEC i.e. deviation of the actual TEC from the median hourly TEC values for the first 12 days of March 1970 and shows a substantial increase in TEC during the initial phase of the storm (1400-1800 U.T.) followed by a spectacular decrease in the next 3 hours. Similar values of ATEC are shown for Boulder, Colorado as also for Areceibo further south towards the equator. Surprisingly, whereas Areceibo shows an increase similar to Sagamore Hill in the initial phase (1400-1800 U.T.), Boulder shows instead a decrease, though for all these, the event has occurred during day time. In the main phase, Boulder shows a decrease similar to Sagamore Hill while Areceibo shows a continuous increase, hence it is counter-intuitive, if these results are correct, it would imply that TEC changes can be drastically different even at places separated by only a few hundred miles. Changes in foF2 at Wallops Island are also shown and seem to be not completely similar to those at Sagamore Hill indicating that the bottom side behaviour is not the same as the total content behaviour. The next few curves show (foF2-foF2) i.e. differences of actual hourly foF2 from the corresponding hourly monthly median values for March 1970 for various stations viz. Port Stanley and Argentine Islands in the American zone, Freiburg and Slough in the European zone and Auckland, Singapore and Rarotonga in the Australian zones. Data sheets for several other stations were also available but unfortunately we were not able to get the corresponding data for 8 March were missing therein. Data for the inter-Indian zone are not shown firstly because the latitudes are such that the data do not cover very good and secondly because the post-MPO period corresponded to night hours for the Indian longitudes. Following may be noted:

i) There is a considerable longitude difference in the foF2 behaviour. Thus, for the American and European zones, values drop below average even on 7 March 1970 i.e. almost a day earlier than the actual storm day. In contrast, values in the Australian zone drop below average on the storm day at or about SSC which happens to be in the early morning. (Vertical lines on curves show local midnights)

ii) There are considerable fluctuations in foF2 values even on quiet days (March 6 and 7).

iii) Fluctuations at Singapore show an initial rise after SSC followed by conspicuous drop in the next 2 hours. However, all this occurred in the night and early morning hours and hence may not be completely reliable.

iv) Other curves in figure 10 show changes in the slab thickness (ratio of TEC to NmF2) as also changes in the height of maximum ionization Hmax at Wallops Island, Boulder and Jicamarca (Peru) as also the vertical drift velocity observed at Jicamarca. All these show abnormal changes on 8 March mostly at or after the SSC, during the main phase.

It seems, therefore, that the storm effect on the F2 region is a large scale churning out of the region resulting in large movements both in latitude, longitude and altitude.

IV - Summary and Conclusions:

The results of the present analysis may be summarised as follows:

1) The storm effect of F2 region is a very complicated phenomenon. In individual severe storms large positive and/or negative changes (as large as 50%) occur mainly during the peak storms hours but often before and/or after.

2) If averages of several storms are studied, a close connection with the main phase Onset (MPO) of the geomagnetic storm is observed. For high latitudes the Dm (foF2) effect is a conspicuous decrease. For low (including equatorial) latitudes the effect is a clear 5-10% increase but for daytime values only. Inclusion of nighttime values has a tendency to dilute the effect. Also, for great storms, the increase is 7-10% and is preceded by a 2-3% decrease at or before the MPO.

3) The storm effect in the American zone (Huanuco) seems to be somewhat different viz. for great storms the foF2 values decrease even sooner after MPO but drop again to average values for several hours and then rise again. This drop occurs for day time as well as nighttime values.

The behavior of high and low latitudes is exactly reversed to the other in the post-MPO period only. In the pre-MPO period, values are average at equator and above average at high latitudes for weak storms and below average at equator and average at high latitudes for strong storms.

The strength of the equatorial electrojet and its associated drift velocity do not show any significant Dm (foF2) effect. Thus, Dm (foF2) is not due to electromagnetic drifts. Peculiar neutral winds and/or precipitation from the protosphere could be possible causes.

3) The local time average SD effect at equator is a conspicuous 5-10% noon-time foF2 increase on the day following the storm day. This is associated with about 25% reduction in the equatorial electrojet strength and is thus an electromagnetic drift effect. At high latitudes the SD effects do not look like a L.T. effect at all but like a general depression below average all hours on the post-MPO day and even thereafter (Dm(DL) effect).

4) Comprehensive data for the great storm of 8 March 1970 when an SSC occurred at 1400 U.T., the MPO at about 1600 U.T. and the Main Phase End (MPE) at about 2400 U.T., show that substantial changes occurred in ionospheric parameters like foF2, Hmax(F2), total electron content, electron and ion temperatures etc. but these were not similar even at nearby locations nor were these always closely connected with the SSC or MPO. Thus, the effect of a geomagnetic storm on the ionosphere seems to be an indirect one in which changes in the magnetosphere seem to affect different geographical (ionospheric regions differently and sometimes even erratically.

Average storm-effects for the total electron content have been reported earlier by Hibberd and Ross (1967) who show that for high latitudes the TEC rises above average during the initial phase and then drops below average for several days. Titheridge and Andrews (1967) report similar results. Evans (1970) also reports that during storms electron content increases in the afternoon with a corresponding increase in height and attributes it to electric fields associated with the ring current. Papagianis et al (1971) report similar dusk increases associated with geomagnetic field increases and attribute these to a possible contraction and draining off of the plasmasphere. Bauer and Kishinorthy (1968) have also suggested that the source of extra ionisation could be compression of the dayside magnetosphere. On the other hand, Nelson and Coger (1971) report for a lower latitude (Areceibo) that evening enhancements occur accompanied with an decrease in height of the F2 layer as a decrease (negative bay) in geomagnetic H. They discuss several possible mechanisms such as energetic particle influx, diffusion from protosphere, north-south and eastward transport and conclude that none of these are satisfactory. The fact remains, however, that violent changes in ionospheric parameters are seen during storms (though no two storms seem to show a similar pattern) which indicates that these must be connected with the leaking of interplanetary matter and energy inside the magnetosphere through different modes and paths. There is considerable interest to see which of the interplanetary plasma parameters are responsible for creating thermal and electromagnetic environments which seem to affect the ionospheric regions differently at different latitudes and longitudes and what exactly is the leakage path. For such a study much more copious and continuous data than shown in figure 10 would be needed. It is hoped that such an analysis would be possible in future.

Acknowledgment:

Thanks are due to the various research groups which have contributed data used in the present analysis. Thanks are due to the Department of Atomic Energy, Government of India for financial support and to Mr. M.V. Bhaskar, Mrs. S. Bokare and Mr. R.V. Shal for computational assistance.

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The initial phase of the storm (1400-1800 U.T.) followed by a spectacular decrease in the next 3 hours. Similar values of TEC were shown for Boulder, Colorado as for Areceibo further south towards equator. Surprisingly, whereas Areceibo shows an increase similar to Sagamore Hill in the initial phase (1400-1800 U.T.), Boulder shows instead a decrease, though for all these, the event has occurred during day time. In the initial phase, Boulder showed a decrease similar to Sagamore Hill while Areceibo shows a continued increase. If these results are correct, it would imply that TEC changes can be drastically different even at places separated by only a few hundred miles. Changes in foF2 at Wallops Island are also shown and seem to be not completely similar to those at Sagamore Hill indicating that the bottom side behaviour is not the same as the total content behaviour. The next few curves show (foF2-foF2) i.e. differences of actual hourly foF2 from the corresponding monthly median values for March 1970 for various stations viz. Fort Stanley and Argentine Islands in the American zone, Freeburg and Slough in the European zone and Auckland, Singapore and Rarotonga in the Australian zones. Data sheets for several other stations were also available but unfortunately data for 8 March was missing therein. Data for the bottom side are not shown firstly because the data for this period were not very good and secondly because the post-MPO period corresponded to the winter season for the Indian longitudes. Following may be noted:

1) There is a considerable longitude difference in the foF2 behaviour. Thus, for the American and European zones, values drop below average ever on 7 March 1970 i.e. almost a day earlier than the actual storm occurs. In contrast, values in the Australian zone drop below average on the storm day at about SSC which happens to be in the early morning. (Vertical lines on curves show local midnights)

2) There are considerable fluctuations in foF2 values even on quiet days (March 6-7) and

3) Fluctuations on foF2 show an initial rise after SSC followed by conspicuous drop in the next 2 hours. However, all this occurred in the night and early morning hours and hence may not be completely reliable.

4) Other curves in figure 10 show changes in the slant thickness (ratio of TEC to ionoheight) as also changes in the height of ionopause. At Wallops Island, Boulder and Jacarandia (Peru) as also the vertical drift velocity observed at Jacarandia. All the above show abnormal behaviour and show that substantial changes occur in ionospheric parameters like foF2, NoN (F2), total electron content, electron and ion temperatures etc. but these were not similar even at nearby locations nor were there always closely connected with the SSC or MPO. Thus, the effect of a geomagnetic storm on the ionosphere seems to be an indirect one in which changes in the magnetosphere seem to affect different geographical ionospheric regions differently and sometimes even erratically.

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Effect of neutral winds on ionospheric F-region at a pair of conjugate stations in low latitude

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RESUME. — Les différences dans le comportement de la région ionosphérique F dans un couple de stations conjugées (Ranotonga et Maui) à basse latitude ont été étudiées par une évaluation des vents de l'atmosphère neutre et des données électroniques pour la période d'équinoxe. Pendant la plus grande partie de la journée, le vent électrostatique à Ranotonga est plus faible que celui à Maui, et lors de la nuit, le vent est inversé. Une variation similaire de hmF2 est également observée pour la plupart des équinoxes. On peut expliquer qualitativement ces différences par le vent électrostatique lors de la région F si y a une exception cependant pour : 1) les années de forte activité solaire lorsque hmF2 à Ranotonga est plus fort qu'à Maui même pendant le jour. 2) les années de faible activité solaire quand hmF2 à Maui est plus fort qu'à Ranotonga. Ces variations de hmF2 observées entre les stations conjugées sont attribuées à des glissements de phase dans les déviations verticales induites par les vents neutres dans ces deux stations.

ABSTRACT. — Differences in the behaviour of the ionospheric F-region at a pair of conjugate stations (Ranotonga and Maui) at low-latitude have been investigated by evaluating neutral wind and electron density for the equinoctial period. During most of the day the electron density at Ranotonga is less than at Maui, while during night time the situation is reversed. A similar variation in hmF2 is also observed for most of the equinoxes. These differences can be explained qualitatively when neutral wind effects in the F-region are taken into consideration, except for : 1) high solar years when hmF2 at Ranotonga is greater than that at Maui, even during daytime; 2) for low solar years when hmF2 at Maui is greater than that at Ranotonga, for a few hours in the early part of the night. The observed phase shift between the diurnal variation of hmF2 at Ranotonga and Maui, particularly during night time, can be attributed to the phase shift in vertical drifts induced by neutral winds at these two stations.

I. — Introduction

It is well known that the global thermospheric neutral wind patterns produced by pressure gradients contribute significantly to the dynamics of the F-region (King and Kohl, 1965; Geider, 1966; Rubie, 1967, 1972). In the present work the observed differences in the behaviour of the F-region at a pair of conjugate stations have been investigated.