CHAPTER VI

ELECTROJET EFFECTS ON THE EQUATORIAL AND LOW-LATITUDE F-REGION DURING MAGNETICALLY QUIET AND DISTURBED DAYS.

6.1 Introduction

The equatorial or geomagnetic anomaly of the F-region whose detailed behaviour during quiet conditions has been dealt with in Ch. 2, and during disturbed conditions in Ch. 5, is one of the most intriguing features of the ionosphere. The presence of a trough at the equator, and a crest at ± 30° dip in the latitudinal variation of $f_o F_2$ was first pointed out by Appleton (1946) and since then, a good amount of work has been done on it. Explanations of the feature have taken several forms. Mitra (1946) explained it as the gravitational diffusion to the two hemispheres of ionisation locally produced at great heights over the equator; Martyn (1949) invoked the vertical $E \times B$ drift over the equator to be the factor which supplied ionisation at such great heights rather than solar U.V. radiation. Electron density distributions at different heights and latitudes were obtained by solving the continuity equation for the F-region (Moffett and Hanson (1965) Bramley and Pearse (1965), Abur-Robb (1969). Baxter and Kendall (1968) included time-dependent electrodynamic terms, but Norton and Van Zandt (1964) were able to obtain electron density distributions similar to those over Huancayo without such a term, assuming only
temperature-dependent photoionisation and recombination rates. King and Kohl (1965) suggested that ion-drag by neutral winds contributes to the formation of the anomaly. Rastogi (1959) supported the idea of the $\mathbf{E} \times \mathbf{B}$ drift being responsible for the equatorial $F_2$ anomaly.

In this chapter, an attempt is made to examine the influence which equatorial electric fields have on the $F_2$ region ionisation observed at crest and trough stations. An index of these equatorial electric fields is

1. $\Delta H$ the daily range in $H$ at an equatorial station or
2. the difference in $\Delta H$ between stations within and without the electrojet region (Nair et al., 1970)

Reasoning shows that this should be really valid for magnetically quiet conditions; during disturbed conditions, ring current effects are liable to be present, and the range in $H$ would no longer be an index of ionospheric currents alone. It is however shown that during magnetically disturbed conditions and following geomagnetic storms, electron density distributions at the anomaly crest and trough are such as to suggest a weakening of equatorial electric fields. Rastogi et al. (1971) have shown that $F$-region horizontal drifts at Thumba show a steady decrease with increasing $K_p$ value. The study here is carried out for the Indian zone, the equatorial station being Kodaikanal (dip 3.6°N) and the crest station being Ahmedabad (dip 33°N).
The ionograms of the two stations were available and it was possible to work out the required electron density distributions.

Studies showing the relationship between electric fields and F-region electron densities have been made for the American zone by Dunford (1967; 1970), Duncan (1960) and McDouggall (1969). Bramley and Young (1968) showed that a very small downward drift of 5n/sec. is sufficient to destroy the equatorial anomaly in $f_0F_2$. Direct evidence of correlation between E-region horizontal drifts and F-region vertical drifts has been obtained from incoherent backscatter technique by Balsley and Woodman (1969). Kotadia and Patel (1970) showed that equatorial $E_s$ generally decreases during magnetic disturbances.

6.2. Relationship between equatorial electrojet and low-latitude $F_2$-ionisation — high sunspot.

Some aspects of these features have been dealt with in the Paper which follows (Rastogi and Rajaram 1971). The relationship between the electrojet and the F-region electron densities at the crest (Ahmedabad) and trough (Kodaikanal) stations during both magnetically quiet and disturbed conditions has been shown for high sunspot conditions, the data being mainly that of IGY-IGC (though a few examples
of low sunspot are given).

( Paper 8 follows overleaf )

6.3 Quiet-day $f_0 F_2$ variations at anomaly crest and trough for Strong and Weak electrojet

We now choose a low sunspot year, 1964, and show that it exhibits the same type of relationship between the electrojet and F-region ionisation at the anomaly trough and crest.
Electrojet Effects on the Equatorial F-Region during Magnetically Quiet & Disturbed Days

R G RASTOGI & (Mrs) GIRIJA RAJARAM
Physical Research Laboratory, Ahmedabad

The critical frequency of the \( F_2 \)-region at stations close to the crest and trough of the equatorial anomaly in the Asian zone have been studied in relation to the equatorial electrojet strength. It is shown that the midday bite-out in \( f_{cF_2} \) at an equatorial station and the afternoon peak of \( f_{cF_2} \) at a mid-latitude station are greatly enhanced on days of strong electrojet; on some weak electrojet days the noon bite-out of \( f_{cF_2} \) at Kodaikanal is completely absent. Regarding the daily variations, \( f_{cF_2} \) at Kodaikanal is shown to decrease, and \( f_{cF_2} \) at Ahmedabad to increase steadily with the increase of equatorial electrojet estimated by the difference in daily range of \( H \) between Trivandrum and Alibag. Electron density profiles computed for Kodaikanal indicate that the 'fountain' effect is operative normally at heights above 180 km and is greatly reduced or absent on a weak electrojet day or on magnetically disturbed days. The diffusion of electrons along the geomagnetic lines of force from the equatorial regions starts at higher altitudes in the morning, and gradually extends to the lower regions by midday; in the afternoon hours, the deficit of electrons during strong electrojet days or magnetically quiet days vanishes first at lower heights. It is concluded that the behaviour of the \( F_2 \)-region at equatorial stations during magnetically disturbed days is equivalent to that on weak electrojet days. Thus, the equatorial electrojet current decreases in strength during magnetically disturbed days; it is suggested that this decrease is due to weakening of the equatorial east-west electrostatic field during magnetic disturbances.

The equatorial anomaly in the \( F_2 \)-region, in which the latitudinal variation of daytime electron density shows maxima (crests) at regions around 30° dip north and south with a minimum (trough) directly over the magnetic equator, has been one of the most speculated features of the ionosphere since its discovery by Appleton. The first explanation of this feature was by Mitra who suggested that ionization locally produced at great heights over the equator diffuses under the effect of gravity to the two hemispheres along the earth's magnetic field lines causing the enhancement of ionization in the vicinity of the anomaly crests. It was pointed out that the local ultraviolet production of electrons at such great heights over the equator would be insufficient to explain the observed increase of electron density at the crests. Martyn showed that the electron density distribution with height at any station could be greatly affected by vertical transport of ionization. At equatorial regions, this vertical drift was suggested as arising as a consequence of eastward electric field \( E \) crossing the northward magnetic field \( B \). It was further suggested that the ionization so lifted upward near the equator could diffuse horizontally towards north and south along the magnetic lines of force as suggested by Mitra.

Studying the diurnal development of the equatorial anomaly as well as the daily variation of \( f_{cF_2} \) at closely spaced equatorial stations, Rastogi showed that the two anomalies of \( f_{cF_2} \) at an equatorial station are due to the vertical drift of ionization over the magnetic equator after sunrise, followed by the pole-ward movement of ionization along the lines of force. Similar suggestions were advanced by Duncan, while comparing \( f_{cF_2} \) at an equatorial station, Chimbote, with that of a tropical station, Panama.

**Electron Density Calculations**

On the basis of the above suggestion, quantitative calculations of electron density with height and latitude were made by Moffett and Hanson and Breamley and Page. King and Kohl invoke an additional effect of the ion drag by neutral winds to be a contributive factor in the formation of the anomaly. Detailed calculations using time-dependent electrodynamic terms have been computed by Baxter and Kendall. Balsley and Woodman have obtained a direct correlation between E-region horizontal drifts and F-region vertical drifts using incoherent backscatter technique at Jicamarca. Rastogi has shown evidence of such vertical movement in the equatorial ionosphere in the vertical upward moving 'kinks' observed in ionograms obtained at Thumba and Kodaikanal. It is thus evident that the equatorial \( F_2 \)-region is closely associated with the equatorial electrojet current. The relationship between the equatorial anomaly and the equatorial electrojet has been studied by Dunford and McDougal.

In this paper, we have studied electron density distribution in the equatorial anomaly during magnetically calm days with strong and weak electrojet intensities, as well as during magnetically quiet (Q) and disturbed (D) days. The daily range of the horizontal component \( H \).
at Kodaikanal has been taken to represent the strength of the equatorial electrojet current. Also studied is the effect of the equatorial electrojet current intensities on the daily variation of $f_0F_2$ at stations situated on the crest and trough of the anomaly in the Indian zone. Rastogi\(^{18}\) has shown that the crest of the equatorial anomaly in the Asian zone occurs very close to the latitude of Ahmedabad or Okinawa, while Kodaikanal is situated close to the trough. It has been shown that $f_0F_2$ at Kodaikanal has two maxima occurring around 08 and 16 hrs, irrespective of the epoch of solar activity (Rastogi and Sanatani\(^{19}\)). At stations near the crest, one observes a single maximum of $f_0F_2$ around 15 hrs in the low sunspot years, but the high values of $f_0F_2$ continue even after sunset during years of high solar activity.

The daily variations of $f_0F_2$ at the trough and crest were compared on three days in the same month when $H$ varied appreciably but the magnetic character figures did not indicate any disturbance. Under such conditions the diurnal range of $H$ may be taken as an index of the electrojet current strength. A day of large $H$ range is a day of strong electrojet current, while one of small $H$ range is a day of weak electrojet. An example of such a set showing daily variation of $H$ at Kodaikanal, and $f_0F_2$ variations at Kodaikanal and Okinawa, for the month of January 1958 is depicted in Fig. 1.

On the day of strong electrojet, the daily variation of $f_0F_2$ at Kodaikanal shows the lowest midday value of $f_0F_2$ with the greatest amount of noon bite-out. On the weak electrojet day, the daily variation of $f_0F_2$ does not show any bite-out and its maximum around noon with very high values, which seems unusual for an equatorial station. On a medium electrojet day, the value of midday $f_0F_2$ lies in between, and a weak bite-out is evident.

Comparing the variations of $f_0F_2$ at Okinawa (crest) for the same days, it is seen that the highest noon values of $f_0F_2$ occur on the strong electrojet day while the lowest occur on the weak electrojet day which is opposite to what happens for midday $f_0F_2$ at Kodaikanal. This clearly shows that the strength of the equatorial electrojet contributes significantly to the equatorial $f_0F_2$ bite-out, and the tropical enhancement of $f_0F_2$ in the afternoon hours.

The effect of the equatorial electrojet on $f_0F_2$ at crest and trough stations was further studied by comparing the daily variation of $f_0F_2$ at Kodaikanal and Ahmedabad during a weak and strong electrojet day for each month of the year 1965, as shown in Fig. 2. In each block, the lower curves refer to Kodaikanal, while the upper ones are for Ahmedabad. The variations on strong electrojet days are shown by full lines while those on weak electrojet are shown by dashed lines. The dates as well as the diurnal range of the horizontal field component $H$ are indicated close to the curves for Ahmedabad. Referring to the curves for Kodaikanal it is clearly seen that in each of the months the midday $f_0F_2$ is more on a weak electrojet day than on the strong electrojet day. Further, the midday bite-out is generally deeper on strong electrojet days, and is less or even absent on weak electrojet days. An exception to this is noticed for the equinoctial month of April when the average electrojet is stronger than in other months. Thus, the electrojet strength on any of the days in April 1965 was above the minimum threshold value required to produce the bite-out of $f_0F_2$. Referring to the $f_0F_2$ variations at Ahmedabad, it is seen that in most of the months, the afternoon value of $f_0F_2$ is larger on the strong than on the weak electrojet days. The month of April was exceptional as the equatorial bite-out was present on almost all days; in the local summer months of June and July, a noon bite-out is observed at tropical latitudes (Rastogi and Sanatani\(^{20}\)).

Nair et al.\(^{21}\) have suggested that the diurnal variation of $H$ at a ground station could be contributed by electrojet current which would be present only at equatorial stations — say Trivandrum in our longitude — as well as due to magnetospheric currents present at equatorial stations. —— Trivandrum as well as Alibag. The difference of the daily ranges at the two stations, i.e. $\Delta H_1 - \Delta H_2$, would, represent more precisely the contribution due to ionospheric currents flowing over the magnetic equator at the E-region heights. Fig. 3 shows the correlation of F-region horizontal drifts at the equatorial station Thumba, as well as for the $f_0F_2$...
Fig. 2 — Comparison of daily variation of $f_0F_2$ at Kodaikanal and Ahmedabad during weak (-----) and strong (— — —) electrojet days for each month of the year 1965.

Fig. 3 — Correlation of F-region horizontal drifts at the Thumba equatorial station as well as of the $f_0F_2$ deviations obtained at an equatorial and crest stations with $\Delta H_T - \Delta H_A$. It is seen that the horizontal F-region drift increases linearly with electrojet range $\Delta H_T - \Delta H_A$ — obviously the vertical drifts in the F-region would also increase with increase in horizontal drift velocity. The values of $f_0F_2$ at Kodaikanal during the midday hours (11-13 hrs) is seen to decrease with increase of electrojet while the $f_0F_2$ values at Ahmedabad for the noon hours (14-16 hrs) show a steady increase with electrojet. It may be noticed that for the same change in $(\Delta H_T - \Delta H_A)$, the change in $f_0F_2$ is larger for Ahmedabad than for Kodaikanal. This could be due to the F$_2$ ionization being spread over a greater vertical height at the equator than at tropical latitudes. The ionization transported away from the equator would be distributed over a comparatively smaller vertical column at the crest regions, giving rise to slightly greater change in $f_0F_2$.

Daily Variations of $f_0F_2$ on Magnetically Quiet and Disturbed Days

To study the effect of magnetic activity on $f_0F_2$ at the equator, daily variations of $f_0F_2$ and $H$ at Kodaikanal were compared on a quiet day ($C_p$ low) and a disturbed day ($C_p$ high) both of the same month. An example of these variations for 3 different months are shown in Fig. 4. As is well known, during a quiet day, the daily variation of $H$ is smooth with a maximum shortly before midday; while on a disturbed day, the mean variation of $H$ is greatly decreased, the variations are irregular, and the daily pattern of midday maximum is also

---

533
obiterated. These features are clearly seen from the diagram. The variation of $f_{0}F_{2}$ on quiet days of these months shows significant bite-out while the curve corresponding to disturbed days do not show any decrease around midday; rather a maximum is evident around or even before noon. This suggests that the daily variation of $f_{0}F_{2}$ at Kodaikanal on magnetically disturbed days is analogous to that on a weak electrojet day.

The effect of a particular magnetic storm on the $f_{0}F_{2}$ variations at equatorial station, Kodaikanal, and crest station, Ahmedabad, is shown in Fig. 5. The lowest curve shows the $H$ variations of the storm at an equatorial station, Trivandrum, commencing from over 24 hr before s.s.c., marked by an arrow — to over 72 hr after the storm. The $f_{0}F_{2}$ variations are shown for the same period. During the days when the storm is in progress — indicated by the depression of the magnetic field $H$ — the $f_{0}F_{2}$ values at Kodaikanal have increased while those at Ahmedabad have decreased as compared to the corresponding values on an undisturbed day. Further the noon bite-out in $f_{0}F_{2}$ at Kodaikanal is absent on the storm days, probably indicating weakening of transport of electrons away from the equator during disturbed conditions.

**Electron Density Distributions**

In order to determine the effect of the equatorial electrojet and magnetic activity on the electron density at different heights of the ionosphere rather than at the $F_{2}$ peak, $N-h$ profiles were calculated from the ionograms for Kodaikanal. This was done for selected weak and strong electrojet days, as well as for averaged 5 international quiet and 5 international disturbed days of a particular month. The topside profile was calculated by fitting a Chapman distribution at the $F_{2}$ peak. These sets of profiles are shown in Fig. 6. To the left are the $N-h$ profiles for two strong and weak electrojet days of January 1958 for the different hours, commencing from 07 to 19 hrs — the lines correspond to the profile for the strong electrojet (S) day and the dashed ones to the weak electrojet (W) day. To the right are the averaged profiles for the 5 quiet (Q) and 5 disturbed (D) days of July 1957 — the full lines represent the quiet days and the dashed lines represent the disturbed days. In both cases, the dotted area represents the deficit of electrons on the full line day (S or Q) as compared to the dashed line day (W or D).

It is noted that even to start with, the electron density was more on a weak than a strong electrojet day, the difference being mainly in the top part.
of the profile. At 09 hrs and more so at 10 hrs the difference in electron density between the two days extends to heights lower than the F$_2$ peak. At midday — 11 and 12 hrs — the electron density is less on S than on W days from heights starting as low as 200 km. With further progress of the day, this difference starts vanishing from low heights till about 15 hrs when the difference remains only above the F$_2$ layer. This suggests that the daily cycle of removal of the electrons from the equatorial F$_2$ to higher latitudes as a consequence of the fountain effect created by the $\mathbf{E} \times \mathbf{B}$ force, starts first at higher heights, and remains longer too at higher height. A more or less similar pattern is seen due to the magnetic activity such that a weak electrojet day corresponds to a magnetically disturbed day, and a strong electrojet day corresponds to a magnetically quiet day.

The daily variation of electron density for fixed heights of the ionosphere at intervals of 20 km from 100 km to the F$_2$-layer peak for the days of strong and weak electrojet are shown in Fig. 7. It is seen that daily variation of electron density is fairly symmetrical at lower heights of the E-region — but as the height increases, the electron density seems to become higher in the morning than in the evening hours. This departure seems to commence from 160 km which is roughly the height of the F$_1$ peak. During the weak electrojet day, the electron density at any height above 200 km has a maximum in the forenoon hours and continually decreases during the latter part of the day. The maximum electron density $N_{mF_2}$ shows a clear maximum close to noon without any indication of bite-out. On a strong electrojet day, there is a rapid decrease of electron density after the morning peak, and it increases after midday for heights above 340 km. There is a significant bite-out of $N_{mF_2}$ around midday.

Electron density profiles can also be shown as the variation of height contours for constant electron density values. Such contours for the strong and weak electrojet days are shown in Fig. 8. It is seen that on a weak electrojet day, the contours have a maximum at about 10 hrs and the height of the F$_2$ peak continually increases from 09 to about 19 hrs as shown by the thick dashed line. Similar profiles of electron density obtained at Huancayo have been explained by Norton and Van Zandt in terms of rapid photo-ionization and recombination with a temperature rapidly increasing in the morning, and constant in the afternoon, without any necessity for the $\mathbf{E} \times \mathbf{B}$ drift. The contours for the strong electrojet day show two maxima, and a very strong peak of $N_{mF_2}$ is seen at 19 hrs. It is interesting to note that the height of the F$_2$ peak remains almost constant during 10-16 hrs when the main bite-out of electron density occurs. This suggests that the electrons are removed from the F$_2$ peak as fast as they are produced or lifted from the lower regions.

Comparing similar contours for quiet and disturbed days shown in Fig. 9, we find disturbed days contours are similar to that of a weak electrojet day. The height of the F$_2$ peak increases steadily from 09 to 19 hrs and there is a major peak of electron density in the evening hours. The contours on a quiet day compare well with those of a strong electrojet day, namely the two loops of maxima in the morning and evening hours, and
the height of the F₂ peak does not increase steadily with time after the start of the bite-out effect.

Conclusion
1. The amount of noon \( f_0F_2 \) bite-out at an equatorial station is proportional to the strength of the equatorial electrojet.
2. The afternoon increase of \( f_0F_2 \) at a crest region and the noon increase in bite-out at an equatorial station are complementary to one another.
3. The daily variation of \( f_0F_2 \) and the electron density profiles on a disturbed day are analogous to that on a weak electrojet day; the daily variation on a quiet day is analogous to that on a strong electrojet day.

It is suggested that the magnetic disturbance effect at the region in the equatorial anomaly trough is a consequence of the decreased 'fountain' effect. This could arise because of decrease of the east-west electrostatic field, and thereby the decrease of the equatorial electrojet during magnetically disturbed conditions.

Acknowledgement
The authors are grateful to Dr M. K. V. Bappu, Dr J. C. Bhattacharya and the staff of the Astrophysical Observatory, Kodanikkanal, for their extended cooperation in making this study possible. Thanks are due to Prof. K. R. Ramamathan for helpful discussions throughout the course of the work.

References
Fig. 6 (a) (Pg. 162(a)) shows the $f_0F_2$ variations at Ahmedabad and Kodaikanal on identical days, one being a day of strong electrojet, and one a day of weak electrojet. Such pairs of days have been chosen for each month of 1964, care being taken to see that only magnetically calm days are considered; the intensity of the electrojet is determined from the range of the $H$ variation at the equator on these days. The range is $H$ is defined as

$$[\text{Mean } H (11, 12, 13 \text{ hr}) - \text{Mean } H (00, 01, 02, 03, 04 \text{ hr})]$$

the hours being taken in $75^\circ$ E.M.T. A day with large range in $H$ is considered as a day with large electrojet current intensity, and a day with small range in $H$ as a day with small electrojet current intensity. The strong electrojet days (S) are shown by full lines, the weak electrojet days (W) by dashed lines, and the dates and the corresponding equatorial range of $H$ in gammas are indicated against each.

It is seen without exception that it is on the strong jet days that Kodaikanal the equatorial station shows the greatest midday bite-out in $f_0F_2$, and on the same days the crest station Ahmedabad exhibits the
WEAK ELECTROJET DAY

STRONG ELECTROJET DAY

HOURS IN 75° E. M. T.

Fig. 6.a

AHMEDABAD (4-16) HR - KODAIKANAL (1-13) HR

1964

Fig. 6.b
largest frequencies, with a peak around 15 hr. In contrast, on the weak jet days Kodaikanal shows less midday bite-out with overall higher values of \( f_0^2 \); correspondingly on the same days, Ahmedabad experiences decreased frequencies. This is seen in each month of 1964, and suggests that on a strong jet day, there is more vertical uplift of ionisation from the equator, and transport (associated with higher heights) to the crest, while on a weak jet day, there is less uplift, and less transport. The same feature was shown for the different months of 1965 in Fig. 2 of the Paper. The only exception here was the month of April which showed uniformly high values of jet strength throughout, and no reduction of midday \( f_0^2 \) bite-out at the equator on any day of that month. The decrease in daytime bite-out with increase in magnetic disturbance was noticed by Bhargava and Subrahmanyan (1962) at Kodaikanal.

6.4 Relation of \( \Delta H_T - \Delta H_A \) with \( f_0^2 \) at anomaly crest and trough.

In Fig. 6 (b) (Pg. 162 (a)) we show the difference between peak \( f_0^2 \) at Ahmedabad (14-16 hr.) and the trough \( f_0^2 \) at Kodaikanal (11-13 hr.) plotted as a function of \( \Delta H_T - \Delta H_A \) (which represents the difference in range of \( H \) between Trivandrum within the electrojet region and Alibag outside the electrojet region). This difference in \( \Delta H \) is taken as an index of the electrojet current.
The difference $\Delta f_o F_2$ is shown separately for quiet days ($C_p < 1.0$) and disturbed Days ($C_p > 1.0$) of 1964.

Both curves show that the difference steadily increases with $\Delta H_T - \Delta H_A$, till at a certain value of $\Delta H_T - \Delta H_A$ (85°) in both cases, the difference starts decreasing. Error bars are shown on both curves; it is seen that the trend is better for $C_p < 1.0$, and that there is some scatter for $C_p > 1.0$. The curves again suggest that large electrojet intensities cause the removal of $F_2$ ionisation from equatorial regions, and it is transported to the crest regions. The decrease in $\Delta f_o F_2$ beyond 85° is interesting. It could be caused by several factors, two of these being:

1) Beyond this value, probably $\Delta H_T - \Delta H_A$ ceases to be an index of electrojet current. $\Delta H_T$ may be caused by polar currents closing through low-latitudes, and ring currents, apart from purely ionospheric currents.
2) For very large values of $\Delta H_T - \Delta H_A$ the equatorial $F_2$ peak may be raised to heights where electron loss rates are considerably reduced, and the reduced loss compensates for the drop in $f_o F_2$ caused by the transport of ionisation to the crest region.

In any case, this feature is an important one, and requires more investigation. The variations for 1964...
of the $\Delta f_0 F_2$ at Ahmedabad (14-16 hr. minus daily mean) and at Kodaikanal (11-13 hr. minus daily mean) with the parameter $\Delta H_T - \Delta H_A$ is shown in Fig. 3 of the Paper; also shown is the variation of Thumba F-region horizontal drifts as a function of the same parameter.

6.5 Quiet-day equatorial electron density distributions for Strong and Weak electrojet.

Of the pairs of days in 1964 with strong and weak electrojets, shown in Fig. 6 (a) (Pg. 162 (a)) those for the months of August and December have been chosen, and their electron density distributions at Kodaikanal worked out from the ionograms.

1) The electron densities at constant heights for these pairs of days are depicted in Fig. 6(c) (Pg. 166(a)) The weak electrojet days are shown to the left and the strong electrojet days to the right. The $N_{max} F_2$ variations are shown by thick lines, and exhibit the largest bite-out on strong jet days. The bite-out effect is seen at lower region heights, and here it starts earlier and ends later; the morning and evening peaks approach closer with increasing height. On weak jet days, the bite-out in $N_{max} F_2$ is not seen at all; some bite-out is seen at the lower heights on such days. The profiles are mostly for the daytime hours. In the pre-down hours, no reflection traces are seen in the ionograms as the electron density
is too small to be recorded by the equipment; spread F conditions set in after sunset. The electron density variations at the various heights are clearly seen. Such profiles for a pair of strong and weak jet days for high sunspot years are plotted with a logarithmic scale for electron density in Fig. 7 of the Paper. It shows similar characteristics, except that the forenoon peak in $N_{\text{max}} F_2$ is larger as is typical of high sunspot years.

(ii) The $N$-$h$ profiles for these two sets of strong and weak jet days are shown in Fig. 6 (d) (Pg. 166 (a)). The first two blocks show the two sets of days from 07 to 12 hr. while the second two blocks show the same sets from 13 to 18 hr. The full lines show the strong electrojet days while the dashed lines are the weak electrojet days. The profiles are shown from a height of 100 km to 550 km with the electron density in electrons/cm$^3$ as the abscissa.

The August set shows an excess of electron density in the topside on weak electrojet days, but a deficit in the lower side, till 09 hr. At 10 hr. the excess during weak electrojet extends to the lower side too, but from 11 hr. onwards, there is considerable excess in the lower side, with a deficit in the topside. The greatest excess is at 14 hr. and 15 hr., after which it gradually decreases and at 18 hr. there is a deficit in both bottomside and topside on weak electrojet days. It is
worth noting that the weak electrojet day profiles are remarkably different from the profiles of the strong electrojet day.

The December set shows a different trend. The ionisation on the weak jet day shows an excess in the bottomside from as early as 08 hr. though there is a large deficit in the topside. With progress of time the bottomside excess increases while the topside deficit decreases till 13 hr. Later on, a gradual increase on weak jet days starts at the topside too, and at 17 hr. and 18 hr. the ionisation in the bottomside decreases. Once again the profile shapes on the strong and weak jet days are quite different.

The pattern of variation on the strong and weak jet days in August and December is different, but the main point to be noted is that in both months, between 10 hr. and 16 hr. when daytime $f_0F_2$ bite-out on the strong jet days is seen, the ionisation in the bottomside is notably larger on the weak jet day than on the strong jet day - that means there is a deficit of ionisation on the strong jet day. The deficit of ionisation could have been caused by the transportation of electrons upward and partly away to the anomaly crest. The dissimilarities in the topside are likely to arise from the different heights.
associated with the different seasons of the August and December months. Such a set of curves comparing electron density profiles on strong and weak electrojet days of January 1958 (a high sunspot year) is shown on the left-hand side of Fig. 6 of the Paper. It is also characterised by an excess of ionisation on the bottomside on a weak electrojet day, though here the ionisation excess extends to the topside too. The cross-over of weak electrojet ionisation and strong electrojet seems to occur at the larger heights, associated with high sunspot. On the right-hand side of the same figure are shown the corresponding profiles of a magnetically Quiet and Disturbed day of a high sunspot year, and the resemblance of the Quiet to the Weak jet day, and the Disturbed to the Strong jet day is readily seen.

(iii) It was thought worthwhile to examine the time-variations of $h_{\text{max}} F_2$, $y_n$, $N_{\text{max}} F_2$ and $N_T$ for these sets of days, and these are shown in Fig. 6(e) (Pg. 166(a)). The $N_{\text{max}} F_2$ variations follow the course of the $f_0 F_2$ variations with clear bite-out on strong jet days and reduced bite-out on weak jet days. The total electron content below the $F_2$ peak ($N_T$) variations however, show little difference between the strong and weak jet days in either month. This may be partially understood by studying the variations of $h_{\text{max}} F_2$ in August. $F_2$ peak heights are
much larger on a strong jet day than on a weak jet day; semi-thickness $y_n$ follows the same variations as $h_{max} F_2$ showing that the whole layer expands and thickens on a strong electrojet day, while no such thing is seen on a weak jet day. Strong jet days seem to be associated with large peak heights and reduced electron densities, while weak jet days are associated with smaller heights and higher densities, so that $N_T$ does not appreciably change between the two days. In December, it may be noted that the bite-out occurs earlier on the strong jet day, and is accompanied simultaneously by greater heights $h_{max} F_2$ and larger semi-thickness $y_n$. On a weak jet day, forenoon heights and semi-thickness are both smaller. In the afternoon hours when the bite-out ceases, the reverse is seen, with greater heights and a larger $N_T$ on weak jet days. The behaviour of these parameters in December is slightly complicated and could do well with further investigation.

6.6 Electrojet effects on $F_2$ critical frequencies associated with geomagnetic storms.

Fig. 4 of the Paper shows the $f_{o}F_2$ variations on some typical International Quiet (Q) and Disturbed (D) days of the IGY-IGC period, together with the corresponding H variations. The Q days all show deep midday bite-out in $f_{o}F_2$ while the D days show hardly any bite-out.
This suggested a resemblance of Q days to strong jet days and D days to weak jet days, and in order to show this better, constant electron density contours for Q and D days were compared with similar contours for strong and weak jet days, both for high sunspot conditions (Fig. 9 of Paper). The resemblance between the two at all heights is seen.

Here we have studied some geomagnetic storms for the year 1964 as to how $f_o F_2$ changes at Ahmedabad (crest) and Kodaikanal (trough) from a day before the storm through 3 days after the storm when conditions are expected to return to normal. Three storms which depict the changes clearly are shown in Fig. 6(f) (Pg. 170(a)). In each block, the lower curve shows the variations of H at Trivandrum (equatorial), with the beginning and end of the storm marked on it and the maximum $A_p$ attained during the course of the storm (this is a measure of the intensity of the storm) indicated too. The variations of $f_o F_2$ on the same days are shown above the H variations, those at Kodaikanal being indicated by a full line, and at Ahmedabad by a dashed line.

(i) Consider the storm of January 1964. On 1st (a control day) Ahmedabad frequencies are high, and some bite-out is seen at Kodaikanal, on 2nd both these features reduce, on 3rd there is no bite-out at
Fig 6.6
Kodaikanal, and the frequency here is higher than at Ahmedabad, which means that the equatorial $F_2$ anomaly has completely vanished. Some bite-out is seen at Ahmedabad on this day - it is an unusual feature and its cause is not known (Rastogi and Sanatani 1968). On the 4th normal conditions regain - the bite-out at Kodaikanal returns and Ahmedabad $f_0F_2$ increases.

(ii) Consider the storm of March 1964. On 3rd Kodaikanal exhibits a marked bite-out in $f_0F_2$ while Ahmedabad frequencies are high. On 4th the bite-out vanishes completely and Kodaikanal frequencies increase while Ahmedabad frequencies show a sharp drop below even Kodaikanal - once again the $F_2$ equatorial anomaly seems to have vanished. On 5th normal conditions are restored with bite-out at Kodaikanal and increased $f_0F_2$ at Ahmedabad. On 6th again Ahmedabad frequencies decrease and Kodaikanal frequencies increase slightly, but this may be associated with a weakening of electrojet by factors other than magnetic disturbances.

(iii) The storm of August 1964 is a weaker one and there is no effect till 5th August. On 3rd, 4th, 5th throughout, the $f_0F_2$ bite-out at Kodaikanal and enhanced frequencies at Ahmedabad are seen. On 6th the bite-out at Kodaikanal vanishes completely and Ahmedabad frequencies drop below
Kodaikanal — once again the equatorial anomaly has completely disappeared. This is also a day of very weak jet as can be seen from the $H$ variation below.

All these $f_o F_2$ variations at crest and trough stations suggest a weakening of equatorial electric fields following a geomagnetic storm; how long after the storm commencement the weakening sets in, evidently varies from storm to storm. This is supported by drift observations at equatorial station Thumba, where the $F$-region horizontal drift is found to reverse from a Westward to an Eastward direction during the main phase of a storm (Misra (1971) Ph.D Thesis).

6.7 Electron density distributions at anomaly crest and trough for a geomagnetic storm

A similar effect of change in $f_o F_2$ at Ahmedabad and Kodaikanal is shown for a large s.c. storm in June 1965 together with the corresponding $H$ variations in Fig. 5 of the paper. It was decided to work out the detailed electron density profiles at both Ahmedabad and Kodaikanal from the ionograms for these storm days — namely 15th, 16th, 17th June — to see how the ionisation pattern changes. The storm commenced at a late hour of the 15th, and so 15th was treated as a control day. The 16th represents the main phase of the storm while the recovery phase has started on the 17th.
(i) **Electron densities at constant heights at Ahmedabad and Kodaikanal**

These variations are shown for 15th, 16th and 17th June 1965 at Kodaikanal (trough) and at Ahmedabad (crest) in Fig. 6 (g) (Pg. 175(a)). On the control day (15th) a deep bite-out in $N_{\text{max}} F_2$ is seen at Kodaikanal, while $N_{\text{max}} F_2$ at Ahmedabad is very large with a peak value of $(200 \times 10^4)$ el/cm$^3$. During the main phase (16th) the amount of bite-out at Kodaikanal is considerably reduced and $N_{\text{max}} F_2$ has increased too; at Ahmedabad on the same day peak $N_{\text{max}} F_2$ has dropped sharply to $(100 \times 10^4)$ el/cm$^3$ and the shape of $N_{\text{max}} F_2$ is unusual with three peaks. When the recovery phase starts (17th), the bite-out almost vanishes at Kodaikanal and $N_{\text{max}} F_2$ increases considerably at Ahmedabad, though peak $N_{\text{max}} F_2$ has risen to $(140 \times 10^4)$ el/cm$^3$, it is still below the normal level. Apparently the greatest effect of the storm at Ahmedabad is during the main phase on the 16th, while at Kodaikanal it is on the 17th during the recovery phase. The reason for this is not clear.

These electron density distributions suggest that with the onset of the geomagnetic storm, the forces which cause daytime $F_2$ bite-out at an equatorial station are reduced; the ionisation which
was being received by the crest station before the storm is reduced too. If we agree that the crest ionisation comes from that lost by the trough, the force which is reduced during storms is the vertical $\mathbf{E} \times \mathbf{B}$ lifting force, which can come about as a consequence of a weakening of $\mathbf{E}$, the electric field over the equator.

(ii) $N$-h profiles at Kodaikanal and Ahmedabad are compared for the 15th (control day) and 17th (storm day) in Fig. 6(h) (Pg. 175 (a)). These profiles are shown for every hour from 07 hr. to 18 hr. for heights ranging from 100 km to 550 km. The ordinate is the true height in Kilometers and the abscissa shows the electron density in electrons/cm$^3$. The control-day profiles are depicted by full lines, and the storm-day profiles by dashed lines.

At the trough (Kodaikanal), the storm-day shows increased electron density at levels below the $F_2$ peak from 09 hr. to 12 hr., though there is a deficit in the topside as compared to the control day. From 13 hr. to 17 hr. the excess ionisation extends to the top too on the storm-day, and is found at all levels, both bottomside and topside. By 18 hr. the excess remains at the topside, but a deficit starts in the bottomside on the storm-day.
At the crest (Ahmedabad) a slight excess in ionisation on the storm-day is seen at levels from 100 km to 250 km from 10 hr. to 16 hr., but at higher levels, near the F\textsubscript{2} peak and above in the topside, there is a great deficit of ionisation. This is in direct contrast to the excess ionisation seen at Kodaikanal on the storm-day. Only at 17 hr. and 18 hr. does the topside deficit start reducing; the deficit at the F\textsubscript{2} peak however remains.

The profiles suggest that at levels near the F\textsubscript{2} peak there is a large excess of ionisation at the equator on the storm-day while the crest stations shows a large deficit on the same day. These N-h profiles in Fig. 6(h) (Pg. 175 (a)) at Kodaikanal show a great resemblance to the N-h profiles at Kodaikanal shown in Fig. 6 (d) (Pg. 166 (a)) the storm-day profile resembling that on the weak electrojet day, and the control day profile resembling the strong electrojet day. This suggests a weakening of the E x B force over the equator during a storm day which results in increased ionisation at the equator and reduced ionisation at the anomaly crest.

(iii) The variations in the parameters $h_{\text{max}}$, $F_{\text{2}}$, $y_{\text{n}}$, $N_{\text{max}}$, $F_{\text{2}}$, and $N_{\text{F}}$ for the control day (15th) and the storm day (17th) at Kodaikanal and Ahmedabad are shown.
Fig. 6.a
Contour map for $\Delta N/N$ and position of plasmapause in $L$-value versus time. (Obayashi 1971)
in Fig. 6 (i) (Pg. 175(a)) and are quite interesting. The most striking features are seen in $N_{\text{max}}$ and $N_T$. On a storm day (dashed lines) the daytime bite-out in $N_{\text{max}} F_2$ seen on the control day (full lines) is greatly reduced at Kodaikanal; Correspondingly $N_T$, the total electron content up to the $F_2$ peak is greatly enhanced on a storm-day. At the crest station Ahmedabad however, the reverse is seen with reduced $N_{\text{max}} F_2$ on the storm-day and greatly reduced $N_T$. It seems reasonable that on the storm-day there is reduced transport of ionisation from the anomaly trough to the crest, since both $N_{\text{max}}$ and $N_T$ increase at the former and decrease at the latter. This could very well be associated with decreased $E \times B$ vertical uplift at the equator, and hence reduced electric fields during storms.

$F_2$ peak heights seem reduced at most hours on the storm day at Ahmedabad. At Kodaikanal the decrease in height is seen only in the forenoon hours, and is associated with increased $N_{\text{max}} F_2$ at those hours; in the afternoon, storm day heights are more than control day heights and $N_{\text{max}}$ and $N_T$ too remain larger. The observed increase in equatorial $N_{\text{max}} F_2$ has thus nothing to do with the different recombination rates associated with variations in the $F_2$ peak level. The variations in $y_m$ at Kodaikanal
are in sympathy with those of $h_{\text{max}} F_2$, with increased forenoon layer thickness and little change in afternoon semi-thickness. The variations in $y_m$ at Ahmedabad do not show any clear trend.

It is interesting to note that Obayashi (1971; private communication) has studied the same storm of June 15th - June 21st for stations located all over the world and situated above $30^\circ \phi_c$ (corrected geomagnetic latitude). $\Delta N/\bar{N}$ at the $F_2$ peak level is studied from both ground-based sounders and topside sounders, and is depicted along with the $L$-value of the plasmapause as inferred from whistler data (Fig 6 (j) (Pg. 175 (a))). It can be seen that the plasmapause moves in from a value of $L = 4.5$ on 15th to a value of $L = 2.3$ on 16th. Enhancement of electron density is seen at locations above $30^\circ \phi_c$ on the 15th and 16th, and a decrease is seen in the later stages of the storm. The variations below $30^\circ \phi_c$ are possibly extrapolated, and show the same. We see however from the results in this Chapter that a decrease in electron density occurs at Ahmedabad ($+14^\circ \phi_c$ geomagnetic latitude) from 16th June itself, though Kodaikanal ($+0^\circ \phi_c$ geomagnetic latitude) at equatorial latitudes does show an enhancement on 15th, 16th and 17th June. This suggests that the observed decrease at Ahmedabad is associated with factors other
than the neutral winds across the plasmasphere by which Obayashi explains the electron density enhancement of 15th and 16th at latitudes above 30° $\phi_c$.

6.8 **Conclusions**

From these studies of $f_o F_2$ and electron density distributions at an anomaly trough and crest station, we deduce the following:

1. Daytime $f_o F_2$ at both anomaly trough and crest station are related to the strength of the equatorial electrojet as inferred from the daily range of $H$. This relationship holds better for magnetically quiet conditions than for disturbed conditions.

2. Weak electrojet days at the equator are associated with smaller $F_2$ peak heights and larger ionisation at the bottomside as compared to strong electrojet days.

3. Following a geomagnetic storm, ionisation at the $F_2$ peak level and above increases at a trough station, while it decreases at a crest station. Following a storm both $N_{max} F_2$ and $N_T$ increase at the trough and decrease at the crest. This is very likely a result of the weakening of equatorial electrostatic fields during storm-conditions, with a consequent reduction in the $E \times B$ uplifting force.