CHAPTER - II
THE MORPHOLOGY OF THE QUIET F-REGION

2.1 Introduction

The F-region of the ionosphere can be defined as the part of the ionosphere lying above 140 km. The lower limit is fairly well-defined, but the upper limit is greatly dependent on latitude, season, and solar cycle epoch. The upper boundary may be taken as the level where the light ions He$^+$ and H$^+$ replace O$^+$ as the dominant ion i.e. at about 600-1000 km. By day the F-region bifurcates into two layers - the $F_1$ and the $F_2$ layers - and by night unites to form a single layer again.

The $F_1$ region can be considered to exist between 140 km and 200 km where the predominant ions are NO$^+$ and O$_2^+$. The electron concentration is typically of the order of $(2.5 \times 10^5)$ electrons/cm$^3$ at noon during sunspot minimum, $(4.0 \times 10^5)$ electrons/cm$^3$ during sunspot maximum, and exhibits large diurnal variations. The $F_1$ region was previously believed to show a simple solar zenith angle dependence, but gradually this was disproved. Rastogi (1958) showed that while this was true of the high latitudes, stations at middle and equatorial latitudes showed equinoctical maxima; also that markedly in high sunspot years, the latitudinal variation of $f_0F_1$ shows a trough about the equator, and is hence subject to some form of geomagnetic control.
The F region exists above 200 km and the composition here is mainly O\(^+\) and to a smaller extent N\(^+\) (Johnson et al., 1958; Istomin 1960; Poloskov 1960). The reason why a second ionisation peak is formed at the F\(_2\) region although the peak production occurs in the F\(_1\) region, is that the recombination rate falls off more rapidly with altitude than does the ionisation rate. Ultimately, downward diffusion of ions becomes faster than either ionisation or recombination, and causes ionisation to decrease above the F\(_2\) peak.

The behaviour of \(h_{\text{max}} F_2\), the height of peak F\(_2\) ionisation is quite complicated. In Fig. 2.1 (Thomas, 1959) is shown the latitude – dependence of \(h_{\text{max}} F_2\) averaged at noon and midnight equinox for two epochs of the solar cycle. In general at high latitudes, \(h_{\text{max}} F_2\) is higher at night than by day, while the reverse is seen at the equator. There is a general trend for \(h_{\text{max}} F_2\) to be greater in summer than in winter, and also to increase with solar activity. The solar cycle and seasonal variations of \(h_{\text{max}} F_2\) for equatorial stations are dealt with in detail in Section 2.7.

The F-region reveals itself in diverse forms and shapes on ionograms obtained from ionosondes. One of these forms shows a diffuse character called spread-F which is attributed to scattering by irregularities of ionisation imbedded in the surrounding region. This feature has marked latitudinal and diurnal variations (Shimazaki 1959). In low-latitudes
Fig. 2.1 Equinoctial variation of $h_{max}F_2$ with geomagnetic latitude for high and low sunspot, day and night (Hanson 1961)

Fig. 2.2 Computed wind vectors at 300km. The bar at bottom left represents a wind vector of 200 m/sec. (Geisler 1967b)
sometimes an additional stratification called the \textit{F}_{1.5} \text{ layer}
appears (Kasuya, 1957; Kotadia, 1963). Often irregularities with quasi-periodicities of 15 min to 1 hour show up on ionograms as \textit{travelling disturbances} (Heisler 1958; Munro 1958). Most observations show these to move downwards in the \textit{F}-region, but recently Rastogi (1970) has observed upward-travelling kinks at Indian equatorial stations, which are in a sense, direct evidence of the vertical \textit{E} \times \text{B} \text{ drift}.

2.2 \textbf{Chemistry of the \textit{F}-region}

The \textit{F}-region like the other ionospheric regions experiences production and loss of ionisation. In addition, it is controlled to a great extent by transport processes arising from various causes, and these are discussed in the next section. Ionisation in the \textit{F}-region is caused by the spectrum of solar radiation lying between 200 \text{ A}^\circ \text{ and 911 A}^\circ, chiefly by the \text{He I} (584 \text{ A}^\circ) \text{ and He II (304 A}^\circ) \text{ lines} (Hinteregger et al., 1960). The photo-electrons are released with relatively high energy which they share with neighbouring electrons. Consequently, electron temperatures can be several hundred degrees higher than the ion temperatures in the daytime (Hanson and Johnson 1960).

For wave-lengths outside this range, the absorption cross-section is too small, and the radiation penetrates to levels below the \textit{F}-region. The \text{He II (304 A}^\circ)
emission has a flux density of about \(6 \times 10^9/\text{cm}^2\text{-sec}\) and varies with solar activity. Atonic oxygen is photoionised thus

\[
0 + h\nu \rightarrow 0^+ + e
\]

The electrons formed recombine directly with atomic ions only at heights above the \(F_2\) peak. Below this, atomic ions first react with neutral molecules to form molecular ions, and these latter recombine with electrons dissociatively.

\[(1)\]

\[
\begin{align*}
0^+ + O_2 & \rightarrow O_2^+ + O \quad (\beta = 2 \times 10^{-11} \text{ cm}^3/\text{sec}) \\
0^+ + N_2 & \rightarrow NO^+ + N \quad (\beta = 1 \times 10^{-12} \text{ cm}^3/\text{sec})
\end{align*}
\]

Dissociative recombination takes place as follows:

\[(2)\]

\[
\begin{align*}
O_2^+ + e & \xrightarrow{2.2 \times 10^{-2} (300) \ T} O^* + O^{**} \quad (\alpha = 2 \times 10^{-8} \text{ cm}^3/\text{sec}) \\
NO^+ + e & \xrightarrow{5 \times 10^{-7} (300) \ T} N^* + O^* \quad (\alpha = 5 \times 10^{-9} \text{ cm}^3/\text{sec})
\end{align*}
\]
The reaction rates for all these are indicated against the equations (Yonezawa and Takahashi, 1960). The excited atoms in returning to their ground-states, emit airglow. The reaction rate of the formation of molecular ions (1) can be expressed as:

\[
\frac{dn}{dt} (0^+) \rightarrow K_1 n(0^+) n(XY)
\]

where \(K_1\) - constant rate coefficient

\(n(XY)\) - density of neutral diatomic molecule

The reaction rate of electron loss (2) can be expressed as

\[
\frac{dN}{dt} = -K_2 N n(XY^+)
\]

where \(K_2\) - constant rate coefficient

\(N\) - electron density

\(n(XY^+)\) - density of positive diatomic ion.

\(K_1 n(XY)\) is effectively the attachment coefficient \(\beta\) and \(K_2\) is effectively the recombination coefficient \(\alpha\).

The net loss rate is \(L(N) = \frac{\beta \alpha N^2}{\beta + \alpha N}\) (Ratcliffe, 1956 a)

From the above relation

If \(\beta \gg \alpha N\) (as in the \(F_1\) region), \(L(N) = \alpha N^2\)

If \(\beta \ll \alpha N\) (as in the \(F_2\) region), \(L(N) = \beta N\)

This change-over from a quadratic loss to a linear loss occurs at a transition level where

\(\alpha N = \beta\)
It lies at about 160-200 km, and happens to coincide with the level at which the production rate \( q \) is largest. Ratcliffe (1956a) showed that these features caused the splitting of the F-region into \( F_1 \) and \( F_2 \) layers.

Other processes in the F-region have been suggested such as \( N_2^+ + O \rightarrow NO^+ + N \) (Norton et al., 1962).

The rate reaction for
\[
N_2^+ + e \rightarrow N^* + N^{**}
\]
is \( \alpha = 2 \times 10^{-6}\, \text{cm}^3/\text{sec} \). This is believed to be too rapid for ionisation to be observed (Richbeth 1962).

Changes in atmospheric temperature are believed to affect these reaction rates considerably (Schneltekopf 1967, Yonezawa, 1963; Matuura 1963; Thomas and Norton, 1966; Paulson, 1964). Moreover, the reaction rates given above are all laboratory measurements at around 300\(^\circ\)K, whereas temperatures in the F-region are over 1000\(^\circ\)K.

2.3 Dynamics of the F-region

The continuity equation for the electron density in the F-region
\[
\frac{\partial n}{\partial t} = Q - L - \text{div} (NV),
\]
contains a transport term \( \text{div} (NV) \) which is believed to be
the main cause of the non-Chapman like behaviour shown by the $F_2$ layer. This term can be expanded into:

$$\text{div} (NV) = \text{div} \left[ N \left( V_{EM} + V_T + V_D \right) \right]$$

$V_{EM}$ - movement caused by electromagnetic forces
$V_T$ - movement caused by temperature changes
$V_D$ - movement by ambipolar or plasma diffusion

This mass transport is particularly important at heights above 300 km where the neutral density is smaller, and the effective collision frequency is $\nu_{ei}$, that between electrons and ions. Chapman (1956) estimated $\nu_{ei}$ as:

$$\nu_{ei} = \left[ 34 + 4.18 \log_{10} \left( T^3/N_e \right) N_e T^{-3/2} \right]$$

and Martyn (1959) gave the value of $\nu_{ei}$ to be 900/sec for the $F_2$ peak.

The $F$-region is electrically neutral, and ions and electrons essentially diffuse together (ambipolar diffusion). Except at the equator where the field inclination is such that horizontal movements cannot be neglected, it is assumed that it is only the vertical movements which are important for the transport term and

$$\text{div} (NV) = \frac{\partial}{\partial h} (NW)$$

where $W$ - vertical velocity of ions and electrons.
These are obtained from the equations of motion for electrons and ions (Dougherty, 1961). In recent years there has been a growing emphasis on the part played by neutral winds in exerting ion-drag, and an equation of motion for neutral air too is required (Kohl and King, 1967). Each of these processes is temperature-dependent, and a heat balance or thermal continuity equation is involved too. Thus the complete dynamics of the F-region is obtained by the solution of a set of several equations, which is a very complicated procedure.

In a greatly simplified way

\[ V_{\text{EM drift}} = \frac{E}{B} \cos \theta \]

\[ V_{\text{ion-drag}} = -\frac{u_B}{B} \sin \theta \]

and

\[ V_{\text{ambipolar diffusion}} = -D_a \sin^2 \theta \left( \frac{1}{N} \frac{\partial N}{\partial z} + \frac{1}{T} \frac{\partial T}{\partial z} \right) \]

Where

- \( D_a \) = ambipolar diffusion coefficient
- \( \theta \) = dip angle
- \( T \) = neutral temperature
- \( H \) = scale height
- \( u \) = neutral gas velocity
- \( B \) = total geomagnetic field
- \( E \) = East-west component of electric-field
2.4 Thermospheric wind effects in the F-region

The effect of thermospheric neutral winds on the F-region is believed to be of enough importance to merit the attention of several workers (Johnson 1964; King-Hele 1964; Hines, 1965). G.A.M. King (1965) suggested that the seasonal anomaly of the F-region was caused by a wind system which transported neutral air from the summer hemisphere to the winter hemisphere. King and Kohl (1965) have shown that neutral air pressure gradients at F-layer heights will produce important atmospheric winds.

The driving force for these worldwide thermospheric wind systems are the horizontal pressure gradients around the diurnal bulge caused by the daily temperature variations. The diurnal bulge is the daytime expansion of the atmosphere and is centred in low latitudes at around 1400 hr local time. The highest temperatures, and therefore the highest atmospheric densities, occur near 1400 L.M.T., and the lowest pressures occur near 0400 L.M.T. The winds thus blow from the daylit hemisphere to the nightside of the earth across the polar regions and the sunrise-sunset lines.

The driving force \( \frac{\nabla \cdot \mathbf{v}}{\rho} \) has to be calculated from atmospheric data, and several authors have used data given by Jacchia (1965) for medium sunspot cycle and equinoctial conditions. The winds are influenced by
1. Coriolis force \[ = 2\rho \left( \mathbf{u} \times \omega \right) \]

2. Viscous force \[ = \rho \mu \left( \frac{\partial^2 \mathbf{u}}{\partial t^2} \right) \]

3. Inertial force \[ = \rho \left[ \frac{\partial^2 \mathbf{u}}{\partial t^2} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right] \]

4. Ion drag experienced by neutral particles given by
\[
\rho \nu_n (\mathbf{u} - \mathbf{u}_i) = \frac{\rho \nu_i N_i}{N_n} (\mathbf{u} - \mathbf{u}_i)
\]

In the above expressions:

- \( p \) - atmospheric pressure
- \( \rho \) - atmospheric density
- \( \omega \) - frequency of earth's rotation
- \( \mathbf{u} \) - atmospheric wind velocity
- \( \mu \) - kinematic coefficient of viscosity
- \( \nu_n \) - collision frequency of neutral particle with all ions
- \( \nu_i \) - collision frequency of ion with all neutrals
- \( \mathbf{u}_i \) - ion velocity
- \( N_i \) - ion concentration
- \( N_n \) - neutral particle concentration

Assuming that electric fields are not involved, and that ions move mainly in the direction of the earth's magnetic field, Kohl and King (1967) obtain the equation of motion for the atmosphere as:
\[
\frac{\partial \mathbf{u}}{\partial t} - \mu \frac{\partial^2 \mathbf{u}}{\partial h^2} = 2(\mathbf{u} \times \omega) + \frac{\nu_i N_i}{N_n} \left[ \mathbf{u} - (\mathbf{u} \cdot \mathbf{t}) \mathbf{t} \right] = -\frac{1}{\rho} \nabla p
\]
where \( \mathbf{t} \) is the unit vector in the magnetic field direction.

As a lower boundary condition, it is assumed that at around 120 km the air is stationary, and all parameters are constant. This assumption isolates the thermospheric motions from any motions at lower heights, and though inaccurate for levels in the vicinity of 120 km it is all right for larger heights. The equation of motion is then solved to obtain the value of \( \mathbf{u} \).

For a height of 300 km Kohl and King (1967) obtain a wind velocity of 40 m/sec for an electron density of \( 10^6/\text{cm}^3 \), and 150 m/sec for an electron density of \( 3 \times 10^5/\text{cm}^3 \). Geisler (1966, 1967 b) obtains typical speeds of order 100 m/sec. This implies that such an air-cell can travel some thousands of kilometers within the course of a day.

The diurnal variation of these wind-vectors at 300 km for different latitudes is shown in Fig. 2.2. (Pg. 29(a)) after Geisler (1967 b).

2.5 \( F_2 \)-region anomalies

The \( F_2 \)-region anomalies are a consequence of the transport effects which determine its behaviour apart from simple production and loss. The \( F_2 \) region does not obey the simple Chapman law; at equatorial and polar latitudes, very
often night-time $F_2$ frequencies are higher than daytime ones. The ionospheric $F$-region shows annual, semi-annual, geomagnetic and seasonal anomalies which have been studied by many workers (Berkner et al., 1936; Appleton 1935; Rishbeth and Setty 1961; Taylor 1966; Bannon and Wood 1964; Yonezawa 1959; Yonezawa and Arima 1959).

(a) The annual variation refers to world-wide $N_mF_2$ being higher in December than in June by about 20%. About 6% of this can be accounted for by the reduced sun-earth distance in December, and the consequent increase in ionising solar flux. The remaining 14% increase is still to be accounted for. The annual variation is seen under conditions of both high and low sunspot.

(b) The semi-annual variation of $N_mF_2$ shows increased values twice a year during the equinoxes (Yonezawa, 1959) in magnitude often as large as the December values. These maxima coincide with the semi-annual variation in neutral air temperature (Jacchia 1963), and are possibly related to them. Semi-annual variations have been observed in $h_{max}F_2$ (Becker, 1966). The semi-annual variation in $N_mF_2$ shows up most at the low latitudes and in the southern hemisphere, as it is masked by the winter anomaly at higher latitudes. It is observed during low sunspot conditions (Yeh and Flaherty 1966; Yuen and Roelofs, 1967).
(c) **The geomagnetic anomaly**

This refers to the observation that noontime $f_o F_2$ does not achieve largest values at the equator but is found at regions of $20^\circ N$ and $20^\circ S$ geomagnetic latitude even in the equinoxes (Appleton 1946). As early as 1942 K. Maeda et al., showed that $f_o F_2$ variation at American and Asian stations tallied better if geomagnitude latitude was used rather than geographic. Rastogi (1959 a, b) showed that the latitudinal distribution of noon $f_o F_2$ showed far less scatter if dip were used rather than dipole latitude. The symmetry is thus found to be about the dip equator rather than about the geographic or geomagnetic equator. The equatorial regions lie in the **anomaly trough** while the regions of maximum electron density are referred to as the **anomaly peaks** or crests. These anomaly crests vary in magnitude and position with time of the day, season, solar cycle epoch, longitude etc., and have been the subject of work by many authors [Rastogi (1966); Rao and Malhothra (1964); L. Thomas (1968); Lyon and Thomas (1963); C.H. Rush et al., (1969)].

The diurnal development of the $F_2$ anomaly for the equinoctial months of low sunspot years (1953-54) was studied in detail by Rastogi (1959). The same for the high sunspot years (IGY-IGC) has been done by Sanatani in his Ph.D thesis (1966).
The main features of the development of the $F_2$ anomaly are summarised in Fig. 2.3 (Pg. 41 (a)). The first two blocks compare the development of the anomaly in the American zone and the East zone during the IGY-IGC years (high sunspot years). The development is shown every six hours for magnetically quiet days, for the three seasons separately. The apparent features are:

1. The anomaly is flattest at 06 hr. and most pronounced at 22 hr. and 00 hr. This itself is unusual, as the cause of the anomaly is believed to be the upward $E \times B$ lifting force over the equator and would be expected to be strongest around midday. When one compares the curve for 12 hr. and 22 hr. it is clear that the anomaly peak frequencies remain unchanged at night, while the trough frequencies have dropped by almost $5\,\text{Mc}$. This is understandable if one assumes a downward $E \times B$ drift at the equator at night, driving charged particles into the regions of greater loss. A time-lag of 10 hr. between the maximum upward $E \times B$ lifting force, and the maximum anomaly development is hardly accountable. This feature is most pronounced in both zones in the E-months when the maximum post-sunset rise (see Section 2.7) in equatorial $h_{\text{max}} F_2$ occurs. In the D-months it is greater in the American zone than in the East zone. It is less in both zones in the J-Months, when the post-sunset rise in $h_{\text{max}} F_2$ at equatorial stations is less. It is quite likely that the enhanced night-time $F_2$ anomaly in high sunspot years is connected with this equatorial post-sunset
Fig. 2.3
2. The winter spur relates to the observation that there is a sudden rise in $f_0F_2$ at a magnetic dip of $70^\circ$ in the winter hemisphere in the daytime. Much work has been done on this by Croom et al., (1960), J.O. Thomas (1962, 1963), and it is believed that such a spur exists only in the daytime and disappears at night. The D-month curves in Fig. 2.3 (Plate 1) however show that in both zones there is a spur at $60^\circ$S (Summer hemisphere) at 22 hr. and 00 hr. The spur seen at $70^\circ$N dip in the daytime seems to have shifted over to $60^\circ$S dip at night. It is possible that this feature has shown up prominently because purely quiet days were used instead of median values; as will be shown later (Chapter 5) the spur is levelled out on Disturbed days. It may be noticed that the daytime spur is more prominent in the East Zone than in the American zone where it saturates out. In the J-months, the spur shows up in the daytime at $70^\circ$S dip (winter hemisphere) in the East zone, but is not visible at all in the American zone. This brings out a marked longitudinal asymmetry in its occurrence. There is a slight suggestion of its being at $70^\circ$N dip at 22 hr. and 00 hr. in the East zone, but the shift is certainly not as prominent as in the D-months. In the East zone, in the E-months too, the spur occurs at 12 hr and 18 hr. at $70^\circ$N dip. If this night-time reversal of the spur is connected with the night-time
reversal of the $F_2$ seasonal anomaly, it is likely that the causes of the two are the same. This point could do well with some investigation.

Other salient differences between the two longitude zones are that in general, certainly so in the B and D months, the northern anomaly peak is higher in the East zone, while the American zone does not exhibit a difference too clearly. The diagrams on the right-hand side of Fig. 2.3 (Pg. 41(a)) compare the development of the anomaly in the East zone between IGY-IGC (high sunspot years) and IGY + 1953-55 (low sunspot years) in a similar way. The prominent differences are -

1) Overall frequencies are much lower in low sunspot years as is to be expected.

2) In the low sunspot years the anomaly trough is deepest at 12 hr. and flattens out in the nighttime hours - this behaviour is opposite to the high sunspot years. In both epochs however, the anomaly is flattest at 06 hr.

3) A slight tendency for a spur continues to be seen in the low sunspot years in the E-months around 70°N dip. It is not seen in the other seasons (Thomas, 1964).

4) In the low sunspot years equatorial trough frequencies do not change as drastically from day to night, as they do in high sunspot years.
(d) **The seasonal anomaly** refers to mid and high-latitude daytime $F_2$ critical frequencies being larger in winter than in summer; the feature vanishes at night. In the northern hemisphere, the winter anomaly and December anomaly add up to give greatly enhanced values of $N_m F_2$. Unlike the annual and semi-annual anomalies in $N_m F_2$, the winter anomaly occurs only in the high sunspot years. The winter spur at 70° dip is a special feature of the seasonal anomaly showing that it is most enhanced at a locus of dip angle $I = 70°$. In the southern hemisphere, $N_m F_2$ seems to depend more on geographic latitude (Sato and Rourke 1964). Rishbeth and Setty (1961) found that just after layer sunrise, $dN/dt$ in the $F_2$ layer is larger in winter than in summer. Increase in electron density seems to start at solar zenith angle $\chi = 97°$ in winter, and at a smaller zenith angle $\chi = 93°$ in summer.

Most of the features of the seasonal anomaly described above can be seen in Fig. 2.4 (Pg. 45 (a)). Here the variation of December and June solstitial $f_0 F_2$ with magnetic dip for the midday hours (averaged 10 hr. to 14 hr.) and the midnight hours (averaged 22hr. to 02 hr.) are shown for magnetically quiet days. The longitudinal differences are brought out by comparing the West zone and the East zone for IGY-IGC. The salient differences are:

1) At midday, the equatorial anomaly is completely masked in the West zone in the D-months although it is
clear in the East zone. The winter spur at 70°N dip shows up better too in the East zone than in the West zone. In most of the southern hemisphere there is little difference between the D-month and J-month $f_{0}F_2$ in the West zone, but in the East zone, June solstice values (winter hemisphere), are distinctly greater than December solstice values. While the cross-over of the two curves occurs at the dip equator in the East zone, there is a vast difference at the dip equator in the West zone.

2) In both East and West zones it is interesting to see that the December spur at 70°N dip in the daytime has shifted over to 60°S dip at night-time; this has been pointed out earlier. This feature is a notable one, and is worth further investigation. It could have something to do with the sunward tilt of the geomagnetic axis with respect to the geographic axis, or the direction-reversal of neutral winds at night.

3) The night-time D-month $f_{0}F_2$ values seem to be more pronounced in the southern hemisphere of the West zone than of the East zone as compared to the J-month $f_{0}F_2$ values. This is so too in the low latitudes of the northern hemisphere in the West zone. In the East zone, there is little difference between D-month and J-month values, at low latitudes, but there is large difference beyond 30°N dip.
The solar cycle features of the seasonal anomaly are brought out by comparing the last zone during the IGY-IGC, and (IQSY + 1953-55) in Fig. 2.4 (Pg. 45 (a))

The prominent features are:

1) During low sunspot years too, D-month values are greater than J-month values in the daytime, the maximum difference being at 40° dip latitude. The winter spur is not seen in either hemisphere, by day or by night.

2) At night, the December anomaly is seen in low sunspot years only in the southern hemisphere; in the northern hemisphere, there is a reversal, with June solstice values being larger. The cross-over of the two curves is at the dip equator by day, and slightly north of it at night.

2.6 World-wide variations of quiet-day $f_0F_2$

The existence of a longitudinal effect in quiet-time $F_2$ behaviour was recognised early by several workers (Ranzi 1939; Bailey 1948; Liang 1947; Appleton 1950). The classification of the world map into the longitude zones East (E), West (W), and Intermediate (I) was done such that in each zone the change of geomagnetic latitude for a given geographic latitude is not too great. Also in the West zone, the magnetic equator is farthest south of the geographic equator while in the East
zone it is farthest north. In the Intermediate zone the two cross each other. Studies revealed that the variations of $f_0F_2$ also depend on the magnetic declination of the place of observation (Eyfrig 1963).

Such a world map showing the E, W, and I zones is shown in Fig. 2.5 (Pg. 45(a)). It is worth mentioning that the two zones chosen for our study correspond well with the W and the E zones. The variations of $f_0F_2$ at the longitude zones E and W for different seasons and different sunspot cycles are shown in Fig. 2.6 (Pg. 47(a)). They are shown in the form of contours of quiet-time $f_0F_2$ against latitude and time.

During the high sunspot years of IGY-IGC the general appearance of the contours in both East and West zones is fairly similar; most differences occur in the regions of the anomaly crests. In the E-months, the contours are truly symmetrical about the dip equator in both zones, with highest frequencies occurring around midday in the regions of the Appleton anomaly crests ($\pm 30^\circ$ dip). In the D-months, the crowding of contour lines in the winter hemisphere is seen with a large density of lines in the daytime hours around $75^\circ$N dip, and around $40^\circ$N dip after 18 hr. A fewer number of contour lines are seen in the summer hemisphere. In the J-months the crowding of lines is more in the southern (winter) hemisphere; minor
Fig. 2.7: Maps of $f_0F_2$ median values (Martyn 1959) 1943–1944, low sunspot
(a) equinox (b) June solstice; 1947, high sunspot (c) equinox (d) June solstice.
differences like maximum frequencies being attained in the forenoon hours in the East zone, and in the afternoon hours in the West zone can be observed.

In the D-months this is reversed, with the East zone experiencing highest frequencies after noon, and the West zone doing so at forenoon.

Notable differences between the high sunspot years (IGY-IGC) and the low sunspot years (IQSY) for the East zone are clearly seen. During IQSY, the marked crowding of contour lines seen in the winter hemisphere of IGY-IGC is not seen. In the E-months, the contour lines are perfectly symmetrical about the dip equator; in the D and J-months too, there is a fair amount of symmetry with a slightly closer spacing of lines in the winter hemisphere.

The various anomalies of the F-region described in the previous sections can be seen from these contour diagrams. It is interesting to compare these contour diagrams with Martyns (1959) contour diagrams of $f_0 F_2$ for the epochs 1943-1944 (sunspot minimum) and 1947 (sunspot maximum) shown in Fig. 2.7 (Pg. 47 (a)).
2.7 Solar cycle and seasonal studies at equatorial station Kodaikanal.

Electron density distributions on magnetically quiet days at Kodaikanal (+ 3.6° dip) have been obtained by reducing ionograms to true height profiles by the Budden's Matrix method (Budden 1954). The diurnal, seasonal, and solar cycle variations of electron density have been studied.

(a) Daily variation of $h_{\text{max}} F_2$, $y_m$, $N_T$, $N_{\text{max}} F_2$

Fig. 2.8 (Pp. 50 (a)) shows the daily variations of the following parameters:-

1. $h_{\text{max}} F_2$ - the true maximum height of the $F_2$-layer
2. $y_m$ - the semi-thickness of the $F$-layer (this is also twice the scale height and is therefore proportional to temperature.)
3. $N_T$ - the total electron content from $h_m F_2$ to the ionospheric base
4. $N_{\text{max}} F_2$ - the maximum electron density at the $F_2$ peak.

The variations are shown for 3 typical seasons - January (winter), April (equinox) and July (summer) for 3 solar cycle epochs - 1958 (high sunspot), 1961 (medium sunspot), and 1964 (low sunspot).
The main feature can be summarised thus:

1) In general, $h_{\text{max}} F_2$ reaches its minimum value at 06 hr. and its maximum value a little later than 18 hr. The clarity of these features decreases with decreasing sunspot as also the absolute height of $F_2$. In the July months, the post-sunset rise is not clear even in 1961. In 1964, $h_{\text{max}} F_2$ follows a flat variation in all seasons. The post-sunset rise in $h_{\text{max}} F_2$ is not clearly understood; it has been attributed to $E \times B$ drift (Martyn 1959). Calvert (1962) believed the $E \times B$ force to arise from electric fields induced by the downward motion of the suddenly cooled-neutral atmosphere across the geomagnetic field lines.

2) The semi-thickness $y_m$ becomes maximum after mid-day, and the minimum values are attained at 06 hr. and 18 hr. This is true for all sunspot years. It is important that in July there is hardly any difference between the different years. In the other months semi-thickness decreases with decreasing sunspot, the change being markedly larger in the hours after the peak in $y_m F_2$ is reached. There is no post-sunset rise in semi-thickness $y_m$. This strong diurnal variation in slab thickness of the layer at the magnetic equator was observed by Ross and Blumle (1962) and interpreted as the $E \times B$ vertical uplift.
3) At 06 hr, both $h_{\text{max}} F_2$ and $y_m$ reach their minimum values which shows the ionosphere is thinnest at that time. At midday, both $h_{\text{max}} F_2$ and $y_m$ increase when the ionosphere is thickest. At sunset time, $h_{\text{max}} F_2$ increases but $y_m$ does not, which shows that at this time, the ionosphere moves up as a whole.

4) The variations of $N_T$ and $N_{\text{max}}$ are similar. Minimum values are attained at 06 hr and maximum values in the daytime. The magnitudes decrease with decreasing sunspot. The midday bite-out is better seen in $N_{\text{max}} F_2$ than in $N_T$. In $N_{\text{max}} F_2$, the fore-noon peak is prominent in 1958, while the post-noon peaks are larger in 1961 and 1964. This feature at Kodaikanal has been studied by Bhargava and Subrahmanyan (1962).

(b) Changes in $h_{\text{max}} F_2$, $y_m$, and $N_{\text{max}} F_2$ from low to high sunspot.

The solar cycle changes in the parameters $h_{\text{max}} F_2$, $y_m$, and $N_{\text{max}} F_2$ from low to high sunspot are shown at Kodaikanal by taking the ratio of $N_{\text{max}}$ (1958) to $N_{\text{max}}$ (1964) and the difference between 1958 and 1964 of $h_{\text{max}} F_2$ and $y_m$. These are shown for the different hours in Fig. 2.9(Pg. 50(a)); the full lines show the changes in January, the dashed lines in April, and the dotted lines in July. The largest changes in $N_{\text{max}}$ occur between 00 and 06 hr, and are most pronounced in April; there is some change after 20 hr too.
$h_{\text{max}} F_2$ does not show much change in the morning hours when $N_{\text{max}} F_2$ changes, but it starts gradually before noon, reaching peak difference at 18 hr. which is the time when the post-sunset rise in height commences in high sunspot years. There is no pronounced difference between the different months. $y_m$ too shows larger changes in the hours after noon in sympathy with the $h_{\text{max}} F_2$ variations, but the curves are flatter especially that for July.

(c) Contours of constant electron density.

Contours of constant electron density are depicted in Fig. 2.10 (Pg. 52(a)) for all heights ranging from 100 km to 700 km. The dotted lines depict the $h_{\text{max}} F_2$ level, and the density distributions at higher levels are obtained by fitting the topside to the $F_2$ peak, assuming a Chapman distribution. The values on the contour lines represent the electron density in $10^5$ electrons/cm$^3$. From this diagram, the seasonal variations as well as the solar cycle variations can be clearly seen. The main features which emerge are:

1) There is a general steep crowding of lines in all months around sunrise and sunset corresponding to the sudden changes in electron density distributions at these times. Such crowding is more below the $h_{\text{max}} F_2$ level than above.
Fig. 2.10

KODAIKANAL - Q DAYS - EQUINOX

APR 1958

APR 1961

APR 1964

LOCAL TIME IN HOURS

KODAIKANAL - Q DAYS - WINTER

JAN 1958

JAN 1961

JAN 1964

LOCAL TIME IN HOURS

KODAIKANAL - Q DAYS - SUMMER

JULY 1958

JULY 1961

JULY 1964

LOCAL TIME IN HOURS

Fig. 2.10
2) Largest electron densities occur in April (equinoxes) less in January (winter) and least in July (Summer). In any season, electron density decreases with decreasing sunspot. The maxima in electron density seen before noon and afternoon correspond to the peaks bordering the midday bite-out. These change with sunspot in the following way:

<table>
<thead>
<tr>
<th>Month</th>
<th>Forenoon peak in el./cm.$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1958</td>
</tr>
<tr>
<td>January</td>
<td>$24 \times 10^5$</td>
</tr>
<tr>
<td>April</td>
<td>$26 \times 10^5$</td>
</tr>
<tr>
<td>July</td>
<td>$17 \times 10^5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Month</th>
<th>Afternoon peak in el./cm.$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1958</td>
</tr>
<tr>
<td>January</td>
<td>$18 \times 10^5$</td>
</tr>
<tr>
<td>April</td>
<td>$20 \times 10^5$</td>
</tr>
<tr>
<td>July</td>
<td>$17 \times 10^5$</td>
</tr>
</tbody>
</table>

3) Post-sunset rise in height is most pronounced in 1958, less in 1961, and negligible in 1964. It is strongest in April, less in January, and least in July.

4) Ionisation almost vanishes just before sunrise (06 hr) in all seasons of 1964; 1961 shows an intermediate behaviour with evidence of this feature only in July. In 1958, however, a good amount of ionisation persists right till larger heights before sunrise.

5) Ionisation at the lowest heights of 100-150 km is least affected by season or solar cycle. This supports the observations of Wright (1962) whose analysis of noon density profiles for Huancayo (dip 2°N) showed that the effect of solar activity is more on the F2 region, with little or no change at the E and F1 regions.

6) The ionisation density at higher heights in the nighttime hours progressively decreases through 1958, 1961 and 1964.

(d) Electron density variations at constant heights

Fig. 2.11 (Pg. 54 (a)) shows the electron density variations at constant heights for Kodaikanal for the same months - for January (winter), April (equinox), and July (summer) of 1958, 1961 and 1964. The heights are indicated against the variation lines, and the electron density values
Fig. 2.11

KODAIKANAL—Q DAYS

JANUARY APRIL JULY

1958

1961

1964

Electron Density in 10^4 El/cm^3

Local Time in Hours
are in $10^4$ el/cm$^3$. The thick line bounding each set of curves is the $N_{\text{max}} F_2$ level. The midday bite-out feature is seen in all the figures and starts only at heights above 200 km. It may be noted that it is the forenoon peak which is pronounced in 1958, while the afternoon peak becomes pronounced in 1961 and 1964. The sharp gradient in electron density at sunrise and sunset is clearly seen. In each year, equinoctial electron densities are largest. With decrease in sunspot, there is a progressive decrease in electron density, and in July 1964 the variation is almost flat. The diagrams suggest that the forenoon and afternoon peaks at all heights lie on a smooth curve which completes somewhere above the $N_{\text{max}} F_2$ level.

2.8 **Longitudinal differences in electron density distributions at equatorial stations**

These studies compare electron density distributions during identical periods at the equatorial stations Huancayo (75°W) and Kodaikanal (75°E). It may be recapitulated that the former is located in a region of low geomagnetic field, and the latter in a region of large geomagnetic field. Comparisons were made for the International Quiet Days of 3 seasons - January, April and July - for the years 1961 (medium sunspot) and 1964 (low-sunspot).
Comparisons of $h_{\text{max}} F_2$, $y_m$, $N_T$, and $N_{\text{MAX}} F_2$ are shown in Fig. 2.12 (Pg. 56(a)) Some striking points are:

1) Longitudinal differences show out more in 1961 than in 1964. In April and July of 1964, there is very little difference, though in January some difference is seen.

2) In January and July of both years, $h_{\text{max}} F_2$ at Huancayo is more than at Kodaikanal. April variations are uncertain; it appears as though in 1961, Kodaikanal heights are more, but nothing can be said of 1964. The post-sunset height rise is shown at both stations in January and April of both years. In July it is not too clear. The height variations in 1964 are flatter.

3) $y_m$ reaches a maximum just before midday, in all seasons in both years. Semi-thickness in April and July is larger than in January, notably in 1964. Minimum $y_m$ occurs around 06 hr. In 1961, in January and April, $y_m$ at Kodaikanal is larger than at Huancayo; in July this trend is seen prominently around midday and less at other hours.

4) In general $N_T$ attain higher values at Kodaikanal than Huancayo in April and July of both years though the July 1964 behaviour is uncertain. In January of both years,
this is reversed, the total electron content over Huancayo being larger than over Kodaikanal. In both zones, \( N_T \) is decreased in 1964 as compared to 1961 in all seasons; maximum values occur in the day-time hours.

5) \( N_{\text{max}} \) \( F_2 \) variations follow \( N_T \) variations as regards comparison between Huancayo and Kodaikanal. The midday bite-out phenomenon is seen more clearly in \( N_{\text{max}} \) \( F_2 \) and in both zones is pronounced in April of both years. In July of both years, Kodaikanal shows a clear bite-out with a higher afternoon peak while no such feature is seen at Huancayo. In January, it is difficult to make comparisons as Huancayo shows bite-out in 1964, and Kodaikanal shows bite-out in 1961. In 1964, \( N_{\text{max}} \) \( F_2 \) is lower than in 1961 in all seasons as can be seen from the scale.

(b) **Comparison of constant electron density contours.**

The height variations of constant electron density contours on Quiet days are shown in Fig. 2.13 (Pg 58 (a)) for two equatorial stations. The comparisons are made season wise for 1964, a low sunspot year. The main features which emerge are:-

1) While Kodaikanal attains highest electron densities in the equinoxes (noon peak value is \( 12 \times 10^5 \) el/cm\(^3\)), Huancayo seems to attain it in local summer, the noon
peak being \((10 \times 10^5) \text{ el/cm}^3\). It may be seen that the general shape of the contours of Kodaikanal equinox and Huancayo summer is rather similar. The presence of the forenoon and afternoon peaks is clearly seen in both, and the differences in these are as follows:

<table>
<thead>
<tr>
<th>Month</th>
<th>Forenoon peak in el/cm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kodaikanal</td>
</tr>
<tr>
<td>January</td>
<td>(-)</td>
</tr>
<tr>
<td>April</td>
<td>(6 \times 10^5)</td>
</tr>
<tr>
<td>July</td>
<td>(4 \times 10^5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Month</th>
<th>Afternoon peak in el./cm(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kodaikanal</td>
</tr>
<tr>
<td>January</td>
<td>(7 \times 10^5)</td>
</tr>
<tr>
<td>April</td>
<td>(12 \times 10^5)</td>
</tr>
<tr>
<td>July</td>
<td>(7 \times 10^5)</td>
</tr>
</tbody>
</table>

2) Though it is the local seasons of the two stations which have been compared, there is a greater resemblance between the July contours at the two stations. Huancayo January contours too certainly resemble Kodaikanal.
CONTOURS OF CONSTANT ELECTRON DENSITY vs DAYS

KODAIKANAL

Fig -2A4

ELECTRON DENSITY IN 10^4 EL/CM^2

LOCAL TIME IN HOURS

FIG - 2A4
January more than Kodaikanal July. Evidently at equatorial stations as is to be expected, seasonal changes play a smaller part in electron density distributions than solar zenith angle changes. Thus January behaviour at the two stations is similar, and differs from the July behaviour. The overall density of the contour lines is far less in July than in January, and the absolute electron densities are certainly less at Kodaikanal.

3) In all seasons, at both stations, the most rapid changes in electron density with height occur at around sunrise and sunset hours (06 hr. and 18 hr.). This seems more true of heights between the $h_{\text{max}} F_2$ level and 200 km where there is the largest crowding together of the contour lines; the effect again appears to become less with increasing height. It is greatest in the equinoctial months possibly because of the overhead position of the sun.

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

Comparisons between the two stations are made for the January, April, and July months of 1961 (medium sunspot) and 1964 (low sunspot) in Fig. 2.14 (Pg 53 (a)). In 1961 the $N_{\text{max}} F_2$ shapes differ greatly between the two stations; there is sometimes a third peak at Huancayo at midday, notably in January and July. The sharp gradients in electron density at sunrise and sunset are seen more in
January and April months than in July. It is also seen that the midday bite-out feature commences at levels above 200 km. At both stations the bite-out is clearest in the equinoctial months.

A study of the solar cycle and seasonal variations in the F-region over Kodaikanal has been made by Ganesh (1965) by using true height electron density profiles obtained by the 10-point method of Schmerling and Ventrice. His studies support the observations made here of

1. Solar activity effects manifesting themselves more at the higher F levels, with little or no change at the E and F₁ levels.

2. Little or no change in \( y_m \) from low to high sunspot in summer (July), but considerable change in winter (January), the larger change occurring in the afternoon hours.

Ganesh has also made a comparison of electron density profiles for winter noon at Kodaikanal and Huancayo. He finds that the peak density in the South American zone is generally smaller than in the Indian zone. This does not quite tally with the results observed in this study.