CHAPTER - III

OBSERVATIONS AND INTERPRETATIONS OF LEDGE FORMATION

III.1 INTRODUCTION

In this chapter the author describes some new features of the ionisation ledge in the equatorial topside ionosphere as revealed by the ISIS-1 and 2 satellite topside sounder data recorded at Ahmedabad. The ionisation ledge manifests itself in the form of a 'V' shaped cusp on the echo traces on the topside ionograms, similar to those observed on the bottomside ionograms corresponding to the 'Fl' ledge.

The ledge is found to be present on more than 200 days between 1100 and 2200 hrs LT during the period 1972-75. The time at which the ledge is usually present is around 1200 hr. However, on rare occasions the ledge is present around 1000 hr LT.

King et al. (1964) and Lockwood and Nelms (1964) observed the ionisation ledge in the topside ionosphere, by means of Alouette-1 satellite, in the Asian zone (105°E) and the American zone (75°W) respectively. These authors showed that the presence of the ledge is revealed through cusp formations on the topside ionograms. Subsequently, Rishbeth et al. (1966), Rush et al. (1969) and Van Zandt et al. (1972) studied this phenomenon. Although the ledge has been investigated for over a decade, there was no
mechanism which could explain its various observational features satisfactorily. Raghavarao and Sivaraman (1974), henceforth referred to as RS1, proposed a new mechanism for the ledge formation by invoking the presence of the neutral anomaly (NA), similar to the equatorial ionisation anomaly (IA). The observational evidence for the neutral anomaly at the F region altitude was provided by Hedin and Mayr (1973) by means of the mass spectrometer on-board OGO-6 satellite. Subsequent work by Raghavarao and Sivaraman (1975), henceforth referred to as 'RS2', showed that the mechanism proposed by them is consistent with many of the observed features of the ledge.

In this chapter the author presents a number of new features of the ionisation ledge. A brief description of the observational features and the interpretations of the ledge by the earlier workers is presented in view of his own observations.

**III.2 OBSERVATIONAL FEATURES OF THE IONISATION LEDGE**

Fig. 3.1(a) shows a topside ionogram obtained from the ISIS-2 satellite pass on March 19, 1974 at 14.54.07 U.T. at 80°9E longitude (local time 2018 hr). The presence of the cusps on the ordinary (O) and extraordinary (X) echo trace is apparent; the cusp tip frequencies being 1.40 and 1.80 MHz respectively. The apparent range (p'), of the X trace is read at 0.05 MHz interval in the frequency range 1.30-3.0 MHz, during which the apparent range changes
Fig. 5.1(a, b)— (a) An ISIS-2 ionogram on March 19, 1974 at 2018 hr LT showing prominent cusp formation and (b) the corresponding computed $N(h)$ profiles. The vertical and the horizontal arrows denote the altitudes corresponding to the cusp tip and the maximum electron concentration in the ledge respectively.
steeply with frequency. In the frequency range 3.0-7.0 MHz, the change in the apparent range of the X echo is small and therefore it is read at 0.5 MHz frequency interval.

The reduction of the p'-f data is done by the "parabolic-in log N" method given by Jackson (1969). The method gives fairly accurate N(h) profiles corresponding to the ionograms showing cusp formation, provided the p'-f data are read at sufficiently close frequency intervals. This method has been adopted by RS1 and RS2 for computing the N(h) profiles from the ionograms showing cusp formations. The computed N(h) profile corresponding to the ionogram in Fig. 3.1(a) is shown in Fig. 3.1(b). The enhancement of electron concentration in the altitude range 970-1220 km is apparent. The dashed portion of the N(h) profile represents the normal profile of ionisation that would have been obtained in the absence of the ledge by assuming the diffusive equilibrium in the topside ionosphere (e.g. Bauer, 1969). This procedure has been adopted on the basis of the work presented in RS1 and RS2. The tip of the vertical arrow denotes the true height corresponding to the frequency of the cusp tip on the X trace. The excess percentage electron concentration in the ledge with respect to the dashed profile is calculated at each 10 km altitude interval. The horizontal arrow denotes the altitude (1110 km) at which the excess ionisation in the ledge is maximum (19%). It may be noted
that the ledge occurs above the ion transition \((O^+ - H^+)\)
alogue, the latter being seen as broad curvature of the \(N(h)\)
profile around 800 km altitude.

Fig. 3.2(a) shows an ionogram obtained from an
ISIS-1 satellite pass on May 8, 1973 at 10.55.31 UT at 65\(^\circ\)E
longitude (1704 hr LT), showing cusp formation on the O and the
X echo traces. The cusps are less prominent than those shown
in Fig. 3.1(a). The \(N(h)\) profile computed from the X echo
trace of Fig. 3.2(a) is shown in Fig. 3.2(b). The maximum
excess electron concentration in the ledge is 13\% at 875 km
altitude. The \(O^+ - H^+\) transition is estimated to be around
750 km altitude from the shape of the \(N(h)\) profile.

Fig. 3.3 shows the \(N(h)\) profile computed from an
ionogram obtained on May 24, 1974 at 10.55.31 UT at 65\(^\circ\)E
longitude (approximate LT 1515 hr) with prominent cusp formation.
The excess electron concentration in the ledge is 42\% at 520 km
altitude. The ledge in this case occurs between the F2
peak (not seen) and the \(O^+ - H^+\) transition altitude, the latter
estimated to be around 700 km.

It may be noted that the ledge shown in Fig. 3.3,
which is nearest to the F2 peak, of the three examples shown
in Figs. 3.1 - 3.3, is the strongest. The higher intensity
of the ledge when it occurs near the \(h_{max}\) F2 altitude is
probably significant, as this behaviour is found to be true
on a number of occasions of the ledge formation around midday
Fig. 5.2(a, b): Same as in Fig. 3.1(a, b) obtained on May 8, 1973 at 1704 hr LT by means of ISIS-1 satellite.
ALTITUDE (KM)

Mg.3° Sa«» N(h) profile obtained from an ISX9-S ionogram with the cusp formation on May 24, 1974 at 1516 hr V S. The details are same as in Fig. 1(b).

Fig. 3.5: - N(h) profile obtained from an ISIS-2 ionogram with the cusp formation on May 24, 1974 at 1515 hr LT. The details are same as in Fig. 1(b).
hours. The N(h) profiles presented in Fig. 3.4 showing ionisation ledges at different local times also reveal this feature (at 10.0 and 10.7 hrs LT) when the ledge occurs nearest to the altitude of the F2 peak.

The field alignment of the ledge was noted by King et al. (1964) as well as Lockwood and Nelms (1964). These authors computed the true heights corresponding to the frequency of cusp tips on successive ionograms obtained during individual satellite passes and found that these altitudes lie on a magnetic field line, henceforth referred to as "cusp-tip field line". These authors found that the cusp-tip field line is coincident with the anomaly field line. The diurnal behaviour of the IA itself is, however, seen to be different in the Asian and the American zones, on the basis of the examples presented by King et al. and Lockwood and Nelms for the same year (1962).

King et al. showed that the IA usually develops around 1000 hr LT. The height of the top of the anomaly field line increases until about 1500 hr and then decreases with local time until the IA collapses around 2200 hr LT. The magnetic field line passing through the cusp-tip altitudes (being coincident with the anomaly field line) also shows the same diurnal behaviour as the anomaly field line. They presented (in Fig. 40 of their paper) the cusp-tip field lines on four occasions at 1545, 1930, 2030 and 2045 hrs LT,
which shows that the altitude of the top of the field line decreases with increasing time.

Lockwood and Nelms (1964) however, observed the diurnal behaviours of the IA and the ledge in the American zone to be different than that in the Asian zone shown by King et al. The diurnal development of IA as well as the ledge, according to Lockwood and Nelms, depends upon the magnetic activity. On quiet days ($K_p \leq 2^+$) the IA formed around 1100 hr and persisted until about 2200 hr LT. The anomaly moved to higher magnetic field lines with increasing local time. The location of the ledge was found to be on the anomaly field line and therefore the altitude variation of the ledge followed the same diurnal behaviour as that of the IA. On disturbed days ($K_p > 2^+$), however, the IA as well as the ledge was not observed until 1730 hr LT. The ledge was located on the anomaly field line and the altitude of the top of the field line increased with local time between 1730 and 2200 hrs. Thus the movement of the ledge to the higher field lines until about 2200 hr LT in the American zone is strikingly different than the behaviour observed by King et al. in the Asian zone.

On the basis of the ledge observations revealing its presence between 1730 and 2200 hrs LT, Lockwood and Nelms suggested that the longitudinal extent of the ledge is about $70^\circ$ centered near 2000 hr LT. The observed increase in the height of the ledge at the equator with increasing time of
day, reveals that the ledge exists along higher field lines at 2200 hr than at 1730 hr LT. On the basis of these features, they suggested: "the ledge defines a surface or shell of ionisation whose north-south locus is a magnetic field line and whose east-west locus is a series of field lines that reach successively higher field lines".

Rishbeth et al. (1966) also investigated the ledge formation in the topside ionosphere by using Alouette-1 ionogram data in the American zone. They found that the ledge occurs in the altitude region dominated by the light ions, He+ and H+.

Van Zandt et al. (1972) observed enhancement in the electron concentration on the N(h) profiles obtained by means of the incoherent scatter radar at the equatorial station, Jicamarca. Fig. 3.4 reproduced from their work shows the diurnal development of the ionisation ledge on a single day in the year 1964. This example is perhaps the only one reported in literature regarding the diurnal development of the ledge on a single day. The ledge is seen to form at 10.0 hr near the $h_{\text{max}}$F2 altitude subsequently moving up with time until 13.1 hr, and then onwards maintains itself at nearly constant altitude until 16.1 hr.
Fig. 3.4 - The thermal development of the ledge for periods of low and high solar activity as obtained from Alouette-1 longrange. The details are given in the text.

(Both reproduced from Van Zandt et al., 1972)
Van Zandt et al. also presented the solar cycle variations of the ledge in the Asian zone on Alouette-1 ionograms. Fig. 3.5 reproduced from their work shows the occurrence frequency of the cusps at different local hours for the years 1964 and 1968 (low and higher sunspot years respectively). The figure gives the copies of the ionogram echo traces at different local hours; 9-14 hrs in the upper half and 15-20 hrs in the lower half part. For each hour, the number of passes with usable ionograms and the number of passes with ledges (the latter written inside the parentheses) are mentioned. In 1964, the ledge is first observed between 10 hr and 11 hr LT and is seen to be present until 2000 hr LT. In 1968 the ledge first forms between 11 hr and 12 hr LT, the occurrence decreases after 1500 hr LT and it disappears after sunset. Van Zandt et al. state that the difference in diurnal behaviour of the ledge does not necessarily indicate that the causative mechanism of the ledge is different in the two epochs. However, they mention that the absence of the ledge after sunset in the high sunspot year 1968 is probably significant.

Raghavarao and Sivaraman (1974, 1975) investigated the phenomenon of ledge formation in the topside ionosphere by means of the ISIS-1 and 2 topside data recorded at Ahmedabad during 1972-73 revealing prominent cusp formation on the ionograms. They calculated the excess percentage electron concentrations in the ledge from the N(h) profiles obtained in a satellite pass and showed that the altitudes of
ledge maxima at different latitudes lie on a magnetic field line, henceforth referred to as the "ledge field line". By definition, the "ledge field line" would be higher than the "cusp-tip field line" by the altitude equal to half the vertical extent of the ledge on the N(h) profile at the magnetic equator.

Fig. 3.6, reproduced from RS1, shows the latitudinal plot of constant electron concentration in the topside ionosphere, from an ISIS-2 pass on Oct. 6, 1972 at 1240 hr (70° EMT). The 'squares' denote the location of the ledge maxima and the magnetic field line passing through these is seen to be the same as the anomaly field line. The open circles denote the true heights corresponding to the frequency of the cusp tips at various latitudes. The apex of the cusp-tip field line is about 90 km lower than the anomaly field line. This observation thus differs from that of King et al. (1964) which showed the cusp tip field line to be coincident with the anomaly field line.

Fig. 3.7, reproduced from RS2, shows the constant electron concentration plot obtained from an ISIS-2 pass on Oct. 7, 1973 at 2040 hr (77° EMT). The equatorial heights of the ledge field line and the cusp-tip field line are 1075 km and 960 km respectively. The presence of the ionisation anomaly is doubtful. If at all it occurs, the crest to trough
OCT. 1973 L.T. 2040 LOWS.

DIP LATITUDE

Fig. 3.7

Fig. 3.8

Fig. 5.6- Lateral variations of the height of the constant electron concentration on Oct. 6, 1972 at 1240 hr at 70°E longitude (after Raghunathan and Sivarssan, 1975).
ratio of electron concentration is very small and magnetic field line with its equatorial height as 585 km would be the anomaly field line. Thus the work of Raghavarao and Sivaraman shows that the ionisation ledge can be present at the premidnight hour, even though the IA becomes very weak. This result differs from that presented by King et al. (1964) and Lockwood and Nelms (1964) which showed the ionisation ledge to be associated with intense IA formation only.

Fig. 3.8 shows the constant height plot on March 19, 1974 at 2015 hr corresponding to the ledge observation shown in Fig. 3.1(a,b). The electron concentration at any altitude is maximum at the magnetic equator thus showing the absence of IA. This result supplements the result of RS2 (shown in Fig. 3.7) in that the ledge could be present in the premidnight hours when the IA completely disappears.

The daily variation of the altitudes of the top of the ledge field line and the corresponding anomaly field line are shown in Fig. 3.9(a) and 3.9(b) respectively, in which a pair of corresponding data points represents the observations on one day. The altitudes of the two field lines are estimated from the same satellite pass in the manner illustrated in Figs.3.6 and 3.7. The error in estimating the altitude of the ledge field line is about ±25 km and is due to the subjectivity in delineating the magnetic field line due to the scatter of the ledge maxima points.
Fig. 3.8 - Latitudinal variation of electron concentration at constant altitudes on March 19, 1974 at 2015 hr LT at 80°E Long.

Fig. 3.9(a,b) - Daily variation of the altitudes of the top of the ledge field line and anomaly field line. The pair of data points in (a) and (b) at any particular LT are obtained from a single satellite pass.
The subjectivity in delineating the altitude of the anomaly field line is about $\pm 25$ km when the anomaly is strong (i.e. the peaks are well defined, e.g. shown in Fig. 3.6). However, in the evening hours, when the anomaly is very weak (e.g. Fig. 3.7) the subjective error in delineating the field line, due to the poorly defined peaks, could be up to $\pm 50$ km. The comparison of the corresponding data points of Fig. 3.9(a) and 3.9(b) reveals that the two field lines are the same until about 1530 hr LT. The pair of data points at 1600 hr LT shows that the ledge field line is higher than the anomaly field line by about 100 km. After 1600 hr, the difference in the equatorial heights of the two field lines increases with time. The top of the ledge field line goes up in altitude between 1700-2100 hrs LT, after the slight dip between 1600 and 1700 hrs. However, the altitude of the anomaly field line decreases rapidly with time due to the decay of the anomaly in the evening hours.

The diurnal variation of the altitude of the ledge field line, shown in Fig. 3.9(a), differs from the result of King et al. (1964) mentioned earlier. However, the daily variation of the altitude of the anomaly field line shown in Fig. 3.9(b) is consistent with the observations of King et al. showing that the anomaly field line altitude increases until about 1500 hr LT and decreases smoothly in the evening hours.
The diurnal variation of the top of the ledge field line shown in Fig. 3.9(a) is consistent with the result of Lockwood and Nelms described earlier.

Fig. 3.9(a,b) reveals a very interesting feature of the ionisation ledges viz., until about 1530 hr LT the ionisation ledge seems to be coupled to the anomaly field line. Around 1600 hr LT, however, the ledge detaches itself from the IA and moves onto higher magnetic field lines with increasing local time. In the evening hours, although, the IA collapses, the ledge remains virtually unaffected.

III.3 SOME NEW FEATURES OF THE IONISATION LEDGE

The author now presents some interesting morphological features of the ionisation ledges observed in the longitude zone 50° - 100°E covered by the ISIS-1 and 2 passes recorded at Ahmedabad.

1) The ledge formation is observed on the satellite passes recorded around midday when the IA is fairly well developed. Fig. 3.10(a,b,c) illustrates this point. The figure shows the latitudinal distribution of electron concentration at constant altitudes on three consecutive days, Oct. 12-14, 1972, obtained from the ISIS-2 satellite data. Fig. 3.10(a) shows that on Oct. 12, the IA is not formed at 1209 hr LT. None of the ionograms for this pass shows cusp formation. On Oct. 13, the constant height plot
Fig. 5.10 (a, b, c): Latitudinal distribution of electron concentration at constant altitudes on Oct. 12-14, 1972 by means of ISIS-2 satellite.
shown in Fig. 3.10(b) reveals the presence of prominently developed anomaly peaks at 1205 hr LT. The ionograms corresponding to this pass show cusp formation; the maximum excess electron concentration in the ledge being about 13%. Fig. 3.10(c) shows that the IA is very weakly developed on Oct. 14 at 1203 hr LT. The ionograms obtained during this pass do not show cusp formation. From these examples it is apparent that the ledge formation necessitates the presence of well developed IA peaks around midday hours. The significance of this feature is discussed in the Sec. III.4 in view of the explanation of the ledge proposed by Raghavarao and Sivaraman (1974).

2) Two consecutive passes of the polar orbiting satellites ISIS-1 and ISIS-2, differing in U.T. by 2 hours, occur at two longitudes about 30° apart and hence the local time of the two passes is nearly the same. It is interesting to compare the occurrence and intensity of the ledge at two longitudes 30° apart at the same local time.

Fig. 3.11 shows two N(h) profiles, marked A and B, obtained from two consecutive passes of ISIS-2 on Oct. 5, 1972. These two passes at 0721 UT at 80°E longitude (pass 07007) and the next pass at 0917 UT at 51°E longitude (pass 07008) are at nearly the same local time, 1245 hr. The two N(h) profiles A and B showing the presence of the ledge are computed from two ionograms at nearly the same dip latitude (7°) at
Fig. 5.11: Two N(h) profiles (marked A and B) showing ledges of ionisation on Oct. 5, 1972 at 1245 hr LT obtained from two consecutive ISIS-2 passes 07007 and 07008 respectively.
07.25.11 and 09.18.32 hrs UT respectively. The maximum excess electron concentrations in the ledge on the profiles A and B are 17% and 13% respectively.

The latitudinal distribution of electron concentration at constant heights for the passes 07007 and 07008 is shown in Fig. 3.12(a,b). The comparison of Fig. 3.12(a) with 3.12(b) shows that the crest to trough ratio of electron concentration at any altitude, revealing the IA strength, is higher at the longitude 80°E (of pass 07007) than that at the corresponding altitude for the longitude 51°E (of pass 07008). The comparison of the ledge strengths at the two longitudes with the corresponding IA strength leads to the conclusion that the strength of the ionisation ledge is proportional to the IA strength around noon hours. It should, however, be mentioned that the linear relationship between the strengths of the ledge and the IA, in view of the result presented in Fig. 3.9(a,b), is true only around midday hours. The more important feature revealed by these observations is that the ionisation ledge as well as the IA are present at two closely longitudes with different intensities at the same local time.

Fig. 3.13 shows two N(h) profiles, marked A and B, at about 3° dip latitude obtained from two consecutive ISIS-2 passes 16901 and 16902 respectively, recorded on Nov. 25, 1974. The passes 16901 and 16902 were recorded at 0645 UT
Fig. 5.12(a, b): Latitudinal distribution of electron concentration at constant altitudes obtained from the passes 07021 and 0917 respectively.
Fig. 3.18: The N(h) profiles (marked A and B) at nearly the same dip latitude obtained from the IRIS-2 passes 16901 and 16902 respectively on Nov. 25, 1974 at about 1300 hr LT.
The local time for both the passes is about 1300 hr. The ionograms corresponding to the pass 16901 show cusp formation whereas none of the ionograms corresponding to the pass 16902 shows cusp formation. The profile 'A' shows the presence of the ionisation ledge, with maximum intensity 13% at 860 km altitude. The profile 'B' derived from a normal ionogram shows a smooth decrease of electron concentration in the topside ionosphere.

Fig. 3.14(a,b) shows the latitudinal distribution of electron concentration at various fixed altitudes obtained from the passes 16901 and 16902 respectively. It is apparent from this figure that the IA is prominently developed at 94°E longitude at 1300 hr LT and is not developed at 65°E longitude at the same local time.

The observations presented in Figs. 3.11 - 3.14 are very interesting in that they bring out two new features of the ionisation ledge as well as the ionisation anomaly.

a) They occur, on occasion, in a narrow longitude zone as revealed by the examples presented in Fig. 3.13 and 3.14. Both are present at 94°E longitude and absent at 65°E longitude,
Fig. 5.1(a,b) - Latitudinal distribution of electron concentration at constant altitudes obtained from the ISIS-2 passes 16901 and 16902 respectively.
b) They occur at the longitudes 80°E and 51°E but with different strengths, as seen from the examples in Figs. 3.11 and 3.12.

It may be noted that the features (a) and (b) have been reported in the counter-electrojet phenomenon in the E region (Gouin and Mayaud, 1967; Kane 1973a; Rastogi 1973a, 1974a). It should also be mentioned that these features of the IA have not been reported in literature so far.

3) It is found that the ledge usually occurs on a sequence of days in succession although there are some exceptions. An evidence for its occurrence on a sequence of days is presented in Fig. 3.15. The figure shows the spatial distribution of excess electron concentration in the ledge on 5 days between Oct. 4-9, 1972 obtained by means of ISIS-2 satellite. On Oct. 8, the ionogram data are not good due to local interference caused by noise. However, cusp formations are seen on the ionograms. The contours represent excess percentage electron concentrations in the ledge over the ambient level, the outermost contour represents 0% excess ionisation and thus delineates the boundary of the ledge. The inner contours represent excess concentrations in increasing steps of 5% on Oct. 4-7 and in steps of 10% on Oct. 9. The dashed lines represent the earth's magnetic field lines. The position of the magnetic equator is approximately at 9° geographic latitude for the longitude zone 60° - 90°E.
It may be noted that the ledge on Oct. 9, 1972 is the lowest in altitude and the highest in intensity, of the sequence of observations shown in Fig. 3.15. The individual N(h) profiles at different latitudes from which the spatial structure on Oct. 9 is obtained, reveal that the ledge occurs below the O⁺ - H⁺ transition altitude. This observation supports the conclusion stated in Sec. 3.2 that the ledge is more intense when it occurs near the F2 layer peak than in the case when it occurs higher up. An explanation for this behaviour of the ledge is given in Sec. III.4 on the basis of the mechanism proposed by RSI.

The spatial structures of the ledge (such as shown in Fig. 3.15) are described in Chapter 4. It is shown that the spatial distribution of the ledge intensity reveals some interesting features of the interaction between the ionised and the neutral atmosphere at the F region altitudes.

III.4 INTERPRETATIONS OF THE IONISATION LEDGE

King et al. (1964) considered the ionisation ledge as a natural manifestation of the presence of the IA on the N(h) distribution in the topside ionosphere. According to these authors, the presence of IA, having enhanced ionisation concentration along the anomaly field line, would reveal a distortion on the N(h) profiles when the column investigated intersects the enhanced arch of ionisation on which the anomaly peaks lie. In particular, at the locations where the
Fig. 5.15: Contours of excess percentage electron concentration in the ledge on Oct. 4-7 and Oct. 9, 1972 as described in the text.
peaks of the IA occur along the anomaly field line, the topside sounder will experience more ionisation than at other locations. Thus, according to the explanation of King et al., the excess ionisation in the ledge at a particular location is just that associated with the relevant anomaly peak.

The explanation offered by King et al. could explain one of the features by which the ledge manifests itself on the ionograms, namely, the cusps usually occur at the lowest frequency over the magnetic equator and at progressively higher frequencies towards either crest of IA. However, the following features of the ionisation ledge cannot be explained on the basis of their explanation.

1) The formation of IA is almost an everyday phenomenon but the ledge is not observed on all the occasions when the anomaly is present.

2) If the explanation of King et al. were correct, there should be no ledge formation at the magnetic equator where the trough of the IA occurs. However, King et al. did observe the ledge at the magnetic equator. Our observations of the spatial distribution of the ledge intensity shown in Fig. 3.15 and a number of spatial structures shown in Chapter 4, reveal that the ledge is always present at the magnetic equator. In fact, on most occasions in the equinoctial period, the ledge at or near the equator is found to be stronger than at the latitudes of the IA crest. For instance, on all the
five occasions during Oct. 72 presented in Fig. 3.15, the ledge maxima occur within \( \pm 10^\circ \) latitude of the magnetic equator, whereas the anomaly crests occur farther away. More specifically, on Oct. 6, 1972 the ledge maxima occur within \( \pm 2^\circ \) geographic latitude (\( \pm 1.5^\circ \) dip lat.) of the magnetic equator (at \( 9^\circ \) geog. lat.) as seen from Fig. 3.15. The dip latitude of the northern crest of the anomaly on the same day is found to occur at about \( 18^\circ \) dip latitude, as apparent from Fig. 3.6.

(3) According to the mechanism of King et al., the magnetic field line passing through the ledge should be the same as the anomaly field line, and also that the ledge should not be observed when the IA is absent. However, the observations presented in Fig. 3.9(a,b) reveal that the ledge field line is distinctly higher than the anomaly field line after 1600 hr LT. Figs. 3.7 and 3.8 reveal that the ledge is present even though the IA is either very weak or absent.

Lockwood and Nelms (1964) studied the ledge formation in the American zone using Alouette-1 ionograms. The location of the ledge was found to be along the anomaly field line. They found that the ledge developed earlier on magnetically quiet days than on disturbed days. A qualitative interpretation of the ledge was suggested by Lockwood and Nelms on the basis of their observations in the following manner.
The upward movement of ionisation caused by the eastward electric field produces an increased concentration (dome) over the magnetic equator. This process starts after sunrise and continues until mid-afternoon. In the afternoon, the upward drift is reduced and the ionisation begins to fall, first along the low and then along successively higher field lines. The redistribution of ionisation along a particular field line causes the contours of fixed electron concentration to appear flat below and dome shaped above the field line (e.g. see Fig. 3.6). The apparent excess ionisation above the field line is observed as the ledge.

The explanation of Lockwood and Nelms can be best summarised in the following sentences reproduced from their paper: "The redistribution of ionisation below the field line leaves an apparent excess of ionisation above, causing the field-aligned ledge observed by the topside sounder. The ledge represents the transition between elevated ionisation at higher heights and redistributed ionisation below."

The explanation of Lockwood and Nelms for the ledge formation is similar to that of King et al. (1964), except that they describe it by the physical process responsible for giving rise to an apparent excess ionisation along the anomaly field line. Hence the same discrepancies, which are pointed out for King et al.'s explanation also arise for the mechanism of Lockwood and Nelms.
Rishbeth et al. (1966) also investigated the phenomenon of the ledge formation from the Alouette-1 satellite data for the American zone. They noted that the ledge occurred in the altitude region dominated by light ions, He$^+$ and H$^+$. They derived the vertical distribution profiles of the ions, O$^+$, He$^+$ and H$^+$, by assuming the diffusive equilibrium in the topside ionosphere. Their results showed that the ledge in the electron concentration profile occurs at the altitude where the ion transition O$^+$ - He$^+$ occurs. On the basis of their results, Rishbeth et al. suggested that the ionisation ledge at the equator is merely a manifestation of the He$^+$ profile.

Recently Bauer and Hartle (1974) showed that the F2 ledge in the ionosphere of Venus occurs at the altitude where the ion transition, O$^+$ - He$^+$, takes place.

Although, the author agrees with the importance of the role of ion transition in causing the ionisation ledge, the suggestion of Rishbeth et al. (1966) that the ledge in the earth's topside ionosphere is due to O$^+$ - He$^+$ transition is not consistent with the following facts and features of the ionisation ledge:

1) It is now known that He$^+$ is a minor constituent at the equator in the altitude range 600-1000 km during daytime, as shown by Farley et al. (1967) by means of Jicamarca backscatter radar. The mass spectrometer measurements (Taylor, 1971) also showed that in the low latitude region He$^+$ is a
minor ion in the afternoon hour. Thus, the ion transition $O^+ - He^+$ considered by Rishbeth et al. is now known to be $O^+ - H^+$ transition. Therefore, we would compare the diurnal variation of the altitude of the ledge with the observed daily variation of the $O^+ - H^+$ transition altitude, in the subsequent discussion.

2) The latitudinal variation of the $O^+ - H^+$ ion transition height, derived by Titheridge (1976) from Alouette-1 electron density profiles, shows that the transition height is practically constant within $\pm 30^\circ$ geomagnetic latitude and increases with increasing latitude on either side. The latitudinal variation of the ledge (e.g. shown in Figs. 3.6 and 3.7) follows a magnetic field line very precisely. Thus the latitudinal variations of the ion transition height and the altitude of the ledge are different, indicating that the two are really uncorrelated.

3) The diurnal variation of the ion transition altitude, as given by Farley et al. (1967) at the equator and Titheridge (1976) for the low latitudes, shows that these heights are lower in the evening and the premidnight hours than during daytime. The diurnal behaviour of the ion transition height at the equator cannot thus explain the local time variation of the altitude of the ionisation ledge at the equator, given in Fig. 3.9(a), which shows that the ledge occurs at higher altitudes in the evening than during daytime hours.
Van Zandt et al. (1972) sought an explanation for the ledge formation by a pulse-like sudden enhancement on the diurnal variation of the eastward electric field to produce corresponding increase in the upward $E \times B$ drift of ionisation at the magnetic equator. They solved the continuity equation with an enhanced vertical drift, from 12.5 m/s at 08 hr to 50 m/s at 09 hr LT followed by a symmetrical decrease. In that manner they could generate a ledge at 10.4 hr LT by the numerical simulation. However, they pointed out that there is no experimental evidence of such a spike in the vertical drift velocity at Jicamarca in the morning hours on the day when the ledge of ionisation is observed. There is no a priori physical reasoning to expect such large changes in the electric field in the morning hours in solar minimum period when the ionisation ledges are observed. However, the most serious problem with a mechanism involving a pulse type transient causative source, would be to explain the maintenance (against diffusion) of the ledge throughout the day in the topside ionosphere, where the diffusion time constant $\tau = H^2/D$, as defined in Chapter 1) is a few seconds only.

Raghavarao and Sivaraman (1974) proposed a new mechanism for the ledge formation by invoking the presence of an equatorial anomaly in the distribution of the neutrals (atomic oxygen and molecular nitrogen) similar to that observed in the ionisation. They suggested that the existence of the NA would partially inhibit the ambipolar diffusion of plasma.
that is lifted at the F region altitudes at the magnetic equator due to the $E \times B$ force. The partial inhibition of the plasma diffusion would thus cause a 'pile-up' of the ionisation near the top of magnetic field line passing through the NA crests, thus leading to the formation of ledge.

The experimental evidence for the presence of the NA and the physical process for the ledge formation are discussed in Chapter 1. It is also mentioned there that the NA formation on a particular day requires the presence of strong IA around noon hours at which time the differential motion between the ions and the neutrals starts becoming significant, thus causing the neutral motion to be subjected to a large ion drag force. We now examine the above arguments for explaining the NA and hence the ledge formation on Oct. 6, 1972 at 1240 hr LT (Shown in Fig. 3.15).

Fig. 3.16 shows the latitudinal distribution of electron concentration on Oct. 6, 1972 at 1240 hr at a number of fixed altitudes obtained from the same pass from which the ledge structure is delineated. The contours show the presence of well developed IA; the crest to trough ratio of electron concentration (at the $h_{\text{max}}^{F2}$ level) being 1.711. From the electron concentration contour at a fixed height, the excess percentage concentration at each 2°.5 latitude over the value at the magnetic equator is calculated. In this manner the excess percentage electron concentrations associated with
Fig. 5.16: Latitudinal distribution of electron concentration at constant altitudes on Oct. 6, 1972 at 1240 hr (70° EMT).
the anomaly peaks are calculated for each of the constant height contours and from these values the altitudes where the excess concentrations are 20%, and in steps of 20% thereafter, are interpolated for each one of the latitudes mentioned above. These contours are shown in Fig. 3.17; the outermost being 20% and increasing in steps of 20% towards the centre, the maximum value being 170%. The dashed portions of the contours are drawn on the basis of the field aligned behaviour of the IA in the bottomside ionosphere (Croom et al. 1959). The contours on the southern side of the magnetic equator (denoted by m.e.) are drawn by the assumed symmetry of the IA in the two hemispheres during the equinoctial period. Thus Fig. 3.17 essentially gives the distribution of the excess ionisation associated with the IA peaks in the F region and the topside ionosphere. Such intense ionisation crest formations on either side of the magnetic equator would offer higher resistance to the zonal motion of the neutrals from the dayside to the nightside, thus retaining their kinetic energy leading to higher exospheric temperature at the latitudes of the IA crests than at the magnetic equator, as shown by Hedin and Mayr (1973). The higher exospheric temperatures at the latitudes of the IA crests would give rise to higher concentration of the neutrals at the F region altitudes, characterising the NA. This process of NA formation is described in Chapter 1. The method to calculate the anomaly in the neutral concentration is described in Sec. III.5.
Fig. 5.17: Contours of excess percentage electron concentration on Oct. 6, 1972 at 1240 hr LT obtained from the constant height plot shown in Fig. 5.16 as described in the text.
The calculated magnitudes of the anomaly at the $h_{\text{max}}^F2$ altitude on Oct. 6, 1972 at 1240 hr LT are 12.5% in the neutral temperature and, 91.6% and 37.6% in $N_2$ and $O$ concentrations respectively.

It is also mentioned in Chapter 1 that the NA formation would occur more frequently in sunspot minimum ($S_{\text{min}}$) than in sunspot maximum ($S_{\text{max}}$) period, due to higher crest to trough ratio of electron concentration in the IA during forenoon hours of $S_{\text{min}}$ period. On this basis Raghavarao and Sivaraman (1975) explained the more frequent occurrence of the ledge in $S_{\text{min}}$ period. The IA during $S_{\text{min}}$ period, however, starts weakening after 1400 hr and disappears around 2000 hr LT (Rastogi, 1966). Thus it appears that the IA would not be able to maintain the NA in the evening hours during $S_{\text{min}}$ period. The observations presented in Fig. 3.9(a,b), however, suggest that the ledge in the evening and premidnight hours is maintained at a higher field line than the IA field line.

Raghavarao and Sivaraman (1975) suggested that the maintenance of the ledge at a higher magnetic field line than the anomaly field line in the premidnight period could be explained on the basis of the equatorward winds generated due to the excess pressure bulges, characterising the NA, on either side of the magnetic equator. The magnitudes of the pressure bulges is calculated by Raghavarao (1976) and is shown in Fig. 6.9.
of Chapter 6. The equatorward wind velocities, as shown by the horizontal arrows in Fig. 6.9, at about 10-15° dip latitudes would help in maintaining the ionisation ledge against diffusion in the evening period.

The work of Lindzen (1967) shows that the ion drag is also governed by the vertical distribution of plasma density and the height $h_{\text{max}}^{\text{F2}}$ of the layer peak. Lindzen solved the equation of motion of the neutrals by considering the east-west pressure acceleration and included the effects of inertia and ion drag. Fig. 3.18(a) reproduced from his work shows four $N(h)$ distributions $N_1$, $N_2$, $N_3$ and $N_4$. The distributions $N_1$ and $N_2$ have the same $N_{\text{max}}^{\text{F2}}$ as well as $h_{\text{max}}^{\text{F2}}$. The two ionisation distributions $N_3$ and $N_4$ have the same $h_{\text{max}}^{\text{F2}}$, which is about 200 km lower than that of the distribution $N_1$ or $N_2$. The $N_{\text{max}}^{\text{F2}}$ for the profile $N_3$ is about 5 times higher than that of the profile $N_4$. Fig. 3.18(b) shows the diurnal velocity oscillation of the zonal wind with the ion drags corresponding to the $N(h)$ distributions $N_1$, $N_2$, $N_3$ and $N_4$ and also in the absence of the ion drag (shown by $D = 0$). A comparison of the profiles $N_1$ and $N_2$ of the velocity oscillation with the corresponding ionisation distribution in Fig. 3.18(a) brings out an interesting result that the oscillation of the zonal wind not only depends upon the $N_{\text{max}}^{\text{F2}}$ but also on, 1) the altitude at which the maximum occurs and 2) the shape of the $N(h)$ distribution. In the absence of the ion drag, $D = 0$, the zonal wind has large
Fig. 5.12(a, b)

Fig. 5.12(a, b): (a) Various distributions of ionizations used in calculation of ion drag and (b) amplitude of zonal wind velocity oscillation as a function of altitude without ion drag \((D = 0)\) and with ion drag corresponding to the various ion distributions shown in (a). (After Lindzen, 1967)

Fig. 5.19

Fig. 5.19: Diurnal temperature amplitude, \((T_1 - T_0)/T_0\), for two representative latitudinal distributions of electron concentrations. (After Hedin and Mayr, 1975).
amplitude which increases with altitude. However, in the presence of the ion drag the amplitude of the wind oscillation decreases; the maximum decrease being near the $h_{\text{max}}^{F2}$ level for individual distributions. The decrease in the wind amplitude is more for the ionization distribution N3 having the lower $h_{\text{max}}^{F2}$ and the sharper profile than the distribution N2.

Lindzen's work is of relevance for explaining the maintenance of the NA until the premidnight hours even though the IA becomes very weak (or even collapses) around 2000 hr LT in period. The electron concentration below the F2 peak decreases rapidly with time after the sunset, causing the $N(h)$ profile to become sharp in the evening hours. Rastogi (1971) showed that the $h_{\text{max}}^{F2}$ level is higher (by about 100 km) at the latitude of IA crest than at the magnetic equator until 2100 hr LT. Under these circumstances, following Lindzen's work, the neutral wind oscillation amplitude will be reduced more at the locations of the IA crests than at the trough. The retention of the kinetic energy per unit volume ($= \frac{1}{2} \rho v^2$) of the neutrals would be more at the location of the IA crests where the mass density, $\rho$, is higher, by virtue of the lower value of $h_{\text{max}}^{F2}$, than at the trough. This process would help to maintain the NA in the premidnight hours even though the IA collapses.
It should be mentioned that Raghavarao and Sivaraman (1974, 1975) considered the NA formation because of the ion drag effect of the IA on the neutral motion. However, the neutral density peaks in the low latitude region could exist due to other reasons as well. A.D. Anderson (1973), for example, has shown latitudinal plots of neutral mass density at 406 km altitude, obtained from the Lockheed microphone density gauge on board the OGO-6 satellite, on four successive days, Sept. 27-30, 1969, at 1600 hr LT. The $K_p$ index on these four occasions was 0, 4+, 6 and 8 respectively. It is seen from Anderson's work (Fig. 1 of his paper) that marked density variation occurs at low latitudes during geomagnetic storms. The average density from 10$^\circ$N to 20$^\circ$N geomagnetic latitude is over twice as great for $K_p = 8$ than for $K_p = 0$. The density distribution for $K_p = 8$ showed three peaks between 15$^\circ$ - 35$^\circ$N lat.; for $K_p = 4^+$, a sharp peak around 15$^\circ$N was observed. Although the magnetic field alignment of these peaks was not examined by Anderson, the density minima occurred near the geomagnetic equator, indicating that the peaks would probably be field aligned. Such field aligned peaks of neutral density in the F-region would partially inhibit the plasma diffusion, leading to the ionisation ledge formation on magnetically disturbed days. The ledge observed on Jan. 8, 1975 at 0945 hr LT (the spatial structure shown in Fig. 4.4 in Chapter 4) could be due to the effect of the disturbance in causing the NA. The day is magnetically disturbed, the $K_p$ value being 4
corresponding to the period of the ledge observation. The occurrence of the ledge on this day at 0945 hr LT is one of the rare occasions showing its formation before 1200 hr LT in the present study.

The higher intensity of the ionisation ledge when it occurs lower in altitude around the midday hours, can be explained on the basis of the mechanism proposed by Raghavarao and Sivaraman in the following manner.

During the midday hours altitude of the top of the IA field line is low and therefore the NA would form very strongly due to more effectiveness of the ion drag in controlling the zonal flow of the neutrals, on the basis of the work of Lindzen described above. The ambipolar diffusion of ionisation lifted up at the magnetic equator due to the $E \times B$ force, would be inhibited more due to the presence of strong NA crests. Thus the ledge, during midday hours, being located on the same field line which passes through the strong NA crests, would be of higher strength.

III.5 CALCULATION OF NEUTRAL ANOMALY FROM IONISATION ANOMALY

We now describe a method to calculate the neutral anomaly, based on the work of Hedin and Mayr (1973). These authors solved the energy and continuity equations for neutrals taking into account the ion drag force. They obtained the latitudinal distribution of neutral temperature for a given distribution of $N_{\text{max}}^F 2$. The computed latitudinal exospheric
temperature profile shows enhancement in the neutral temperature at the IA crest, in proportion to the excess electron concentration at the crest with respect to that at the trough.

Fig. 3.19 reproduced from the work of Hedin and Mayr shows the amplitude of the diurnal temperature variation, \( \frac{T_{17} - T_{06}}{T_{av}} \) (hereafter referred to as "temperature amplitude"), as a function of dip latitude: \( T_{17} \) and \( T_{06} \) are the neutral temperatures at 1700 and 0600 hrs LT and \( T_{av} \) is the average diurnal temperature. The two curves A and B showing the temperature amplitude correspond to the electron density distributions A and B respectively. It is easy to see that the excess temperature amplitude at any latitude over that at the equator is linearly proportional to the excess electron concentration at that latitude over that at the magnetic equator. In other words, if \( T_L \) and \( T_O \) represent the value of the temperature amplitude, \( \frac{T_{17} - T_{06}}{T_{av}} \), at a latitude \( L \) and the equator respectively and if \( N_L \) and \( N_O \) denote the electron concentrations at the latitude \( L \) and the equator, then \( \frac{T_L - T_O}{T_O} \) should be linearly related to \( \frac{N_L - N_O}{N_O} \). This is shown in Fig. 3.20 in which the solid and the dashed line show the linear relationship between the rising and the falling portions respectively of the two curves A in Fig. 3.19.

The procedure for calculating the neutral anomaly strength is illustrated below for the case Oct. 6, 1972. The value of \( \frac{N_L - N_O}{N_O} \) on this day at 1240 hr LT, as calculated from the constant height plot at \( h_{max}^{F2} \)
Fig. 3.20: Relation between excess temperature amplitude and excess electron concentration obtained from Fig. 3.19 in the manner described in the text.

Fig. 3.21: Daily variation of the computed anomaly in neutral atomic oxygen (open circles) and the corresponding observed maxima intensity of the ledge (thick dots).
altitude in Fig. 3.16, is 1.711; \( N_L \) and \( N_Q \) represent the electron concentrations at the IA crest and the trough respectively. The 10.7 cm solar flux is 98 units on Oct. 6 and the day is magnetically quiet, the value of \( A_p \) being 2.

Using Jacchia (1970) model, the calculated values of the neutral temperature at the \( h_{max} \) altitude at the equator (350 km in this case) at 0600 and 1240 hrs LT are 789.3°K and 983.6°K respectively. The value of the average temperature, \( T_{av} \), on this day is 866.9°K. By making use of the linear relationship between the parameters \( (N_L - N_Q) / N_Q \) and \( (T_L - T_Q) / T_Q \), given by the solid line in Fig. 3.20, the value of the neutral temperature at the IA crest corresponding to the value \( (N_L - N_Q) / N_Q \) equal to 1.711 can be calculated in the following way:

\[
T_{crest} = 0.37 \times 1.711 \times (983.6 - 783.9) + 983.6 = 1106.6°K
\]

where 0.37 is the slope of the solid straight line in Fig. 3.20. Thus the excess temperature at the latitude of the IA crest with respect to that at the trough is \( \frac{(1106.6 - 983.6) \times 100}{983.6} = 12.5\% \).

The excess concentrations of \( N_2 \) and \( O \) at the IA crest over their respective values at the trough, calculated from the Jacchia (1970) model corresponding to the exospheric temperature 1106.6°K at the crest, are 91.6% and 37.6% respectively.

It may be noted that these calculated values of neutral anomaly strength in \( N_2 \) and \( O \) are considerably higher than
their respective observed values (25% and 11%) by Hedin and Mayr (1973) on Sept. 22, 1969 during sunspot maximum period. The calculated magnitudes of the NA on Oct. 6, 1972 confirm the preliminary calculations of RS2 which show that the NA is expected to form more prominently in $S_{\text{min}}$ as compared to the $S_{\text{max}}$ period.

In a similar manner as described above for Oct. 6, 1972, the magnitudes of the NA are calculated on a number of days (on which the ionisation ledge is present) at different local times, from the experimentally observed values of the electron concentrations at the IA crest and the trough, by means of the ISIS satellite data recorded at Ahmedabad. Fig. 3.21 shows the plot of the calculated anomaly in atomic oxygen (the continuous curve joining the open circles) against local time. The number of data points is rather small, due to the fact that the calculation of the NA necessitates the latitudinal distribution of electron concentration at the $h_{\text{max}}$ altitude, that in turn requires good quality ionograms throughout the pass duration (and especially at the latitude of the IA crest and the trough) on which the X and O echoes are seen up to the penetration frequencies. The NA is seen to maximise around 1400 LT; this behaviour being same as that of the IA in $S_{\text{min}}$ period.
The solid points in Fig. 3.21 represent the observed maximum excess percentage ionisation in the ledge. The diurnal behaviour of the ledge is seen as a decrease in its intensity during the afternoon hours and an increase during the evening hours. Raghavarao et al. (1976a) proposed an explanation for this on the basis that the meridional winds generated by the NA in the lower thermosphere (as shown in Fig. 6.9 of Chapter 6) decrease the eastward electric field in dip latitude region $\sim 4^\circ - 12^\circ$ on both sides of the equator. The effective eastward field communicated to 150 km and up to 600 km would then be reduced and hence the supply of ionisation to the ledge is weakened when the NA ridge is strongest.

III.6 DISCUSSION AND CONCLUSION

We have presented a number of new features of the ionisation ledge in the longitude zone $50^\circ E - 100^\circ E$. The observations of earlier workers are also presented and the explanations put forth by them are critically discussed in view of our own observations. It is found that the mechanism of the ledge formation proposed by Raghavarao and Sivaraman (1974), which invokes the presence of the neutral anomaly, explains many of its observed features.

A method to calculate the strength of the anomaly in the neutral temperature as well as the constituents $N_2$ and $O$, is described. It is shown that the strength of the NA in sunspot minimum period is much higher than that observed.
experimentally by Hedin and Mayr (1973) for the solar maximum period. Thus the occurrence of the ledge during sunspot minimum period is explainable on the basis of the mechanism proposed by Raghavarao and Sivaraman which invokes the presence of the neutral anomaly. The observation of the ledge and the ionisation anomaly in a narrow longitude zone, on occasion, reveals that the ion drag, caused by the ionisation anomaly, acting over a limited longitude zone can effectively quench the neutral motion thereby causing the neutral anomaly in the limited longitude zone.