CHAPTER II  
NIGHT TIME ION COMPOSITION IN THE  
EQUATORIAL E-REGION  

2.1  Introduction  

The night time ionosphere had been an object of, the study of electron removal processes, since it was believed that there were no ionizing sources at night. Ground based, and rocket borne measurements have revealed that electron densities in the E and lower F-regions are of the order of $10^3 \text{ cm}^{-3}$. Sometimes electron densities even exceed $10^4 \text{ cm}^{-3}$ below 160 km (Ratcliffe and Weaks, 1960, Satyaprakash et al 1969, 1970). The general tendency as observed from the profiles, is that it increases abruptly from below $10^2 \text{ cm}^{-3}$ at 80 km over to $10^3 \text{ cm}^{-3}$ and more at 105 km. Another remarkable feature would be the presence of a deep valley in the altitude between 120-150 km. After all, in night-time there is the E-layer which has a density reduced to several tenths of its day time value, and which has pronounced stratifications, more distinguishable than in day time. Figure 2.1 (page 49a) depicts some of the measured profiles over Thumba and brings out the above said features.

The equatorial ionosphere is unique because of the large vertical electric fields (by an order of magnitude larger than the east-west electric field) generated due to the limited dynamo height region and the magnetic field lines being horizontal. The E-region dynamo
Fig. 2.1: Typical evening and mid-night electron density profiles obtained over Thumba (Gupta 1980).

1857 IST
12th Mar 1967
Thumba

NIKE APACHE 20-08
AUG 29, 1968, 23:00 HRS IST
THUMBA, INDIA

---

ELECTRON DENSITY / CC

ALITUDE (km)

180
160
140
120
100
80

10^3 10^4 10^5
ELECTRON DENSITY / CC

ALITUDE (Km)

180
160
140
120
100
80

10 100 1000 10000
ELECTRON DENSITY / CC
Electric fields correlate well with the F-region vertical drifts at the magnetic equator (Balsley, 1973). Rocket studies of electron density (Aikin and Blumle, 1968), and incoherent backscatter soundings have demonstrated that at night the equatorial F-region moves downward. It is necessary to carry out composition measurements in the night-time at electrojet latitudes, in order to give a detailed description of the night-time equatorial ionosphere.

2.2 Night-time measurements

The change of electron density at any height can be formulated as

\[ \frac{\partial N_e}{\partial t} = Q - L - \text{div}(N_e \mathbf{V}) \quad \ldots (2.1) \]

where \( Q \), \( L \), and the divergence term represent respectively, the production by various ionizing processes, the loss through recombinations and change by any dynamical processes and where \( N_e \) is the electron density and \( \mathbf{V} \) the velocity.

The electrons in the E-region disappear through the dissociative recombination processes namely

\[ \text{NO}^+ + \text{e} \rightarrow \text{N} + \text{O} \quad (\alpha_1 = 4.5 \times 10^{-7} (300/T_e)) \quad \ldots (2.2) \]

\[ \text{O}_2^+ + \text{e} \rightarrow 2\text{O} \quad (\alpha_2 = 2.2 \times 10^{-7} (300/T_e)) \quad \ldots (2.3) \]

\[ \text{N}_2^+ + \text{e} \rightarrow \text{N} + \text{N} \quad (\alpha_3 = 2.8 \times 10^{-7} (330/T_e)) \quad \ldots (2.4) \]
The rates of dissociative recombination adopted in the present study are listed above. Some of the more recent results from satellite data are depicted in figure 2.2 (page 55 a) for NO\textsuperscript{+} as given in the literature.

At the above specified rate the electron density in the E-region at night should decrease to below 10\textsuperscript{2} cm\textsuperscript{-3} within a few hours, provided no ionization sources were present and there were no external supply of charges. The value of the recombination coefficient which is deduced in order to keep the electron density above 10\textsuperscript{3} cm\textsuperscript{-3} is less than 10\textsuperscript{-8} cm\textsuperscript{3} sec\textsuperscript{-1} (Bates and Nicolet, 1960). However, the adoption of such a low rate is a dilemma in the ionospheric theory, because it may cause too high electron density in the day time ionosphere as far as the solar radiation fluxes are correctly evaluated.

Other possible factors which may govern the night-time ionization are the temperature dependence of the dissociative recombination coefficient i.e. slow recombination at reduced temperatures and dynamics. Experimental data has shown that in fact the recombination effect is a decreasing function of electron temperature like $k \propto T_e^{-1+0.5}$ (Biondi, 1964).

The existence of night-time ionizing radiation also becomes one of the alternatives (Swider, W, 1965).
The hydrogen LY γ night glow was considered as a source of ionization for NO. This particular wave length inspite of its outstanding intensity, its ionizing efficiency is poor because a large part of it is spent in the photo-dissociation of O₂. Further the Lyγ glow becomes important only above 80 km and upto 120 km. It is because, the neutral NO density decreases rapidly above 105 km (Barth, 1965).

The other ionizing radiations considered in detail by Ogawa and Tohmatsu (1966) are the Lyman β (1026 Å) radiation, the (584 Å) He I and the (304 Å) He II (Helium Lyα).

2.3 The Lyman β radiation

Though the intensity of this radiation is known to be small (2-50R), its estimated ionizing efficiency is 60% (Table 2.1) and it can ionize O₂ producing ion electron pairs at a rate exceeding 0.5 cm⁻³ sec⁻¹ in the altitude range of 100-130 km.

Therefore the Ly β instead of the Lyγ may actually be controlling the electron density at night. It is consistent with the view of Nicolet (1965); Donahue (1966) and Ferguson, et al., (1965). Otherwise the reaction

\[ O_2^+ + NO \rightarrow NO^+ + O_2 \]

with a rate coefficient of \(8 \times 10^{-10} \text{ cm}^3 \text{ sec}^{-1}\) removes the \(O_2^+\) ions too rapidly.
Table 2.1
Absorption and ionization cross sections for H and He
UV emissions

<table>
<thead>
<tr>
<th>Ionizable species</th>
<th>Cross sections (10^-18 cm^2)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absorption</td>
<td>Ionization</td>
</tr>
<tr>
<td>HI Lyα(1216Å) NO</td>
<td>2.42</td>
<td>2.02</td>
</tr>
<tr>
<td>HI Lyβ(1026Å) O₂</td>
<td>1.52</td>
<td>0.97</td>
</tr>
<tr>
<td>He I 584Å O</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>22.7</td>
<td>22.7</td>
</tr>
<tr>
<td>N₂</td>
<td>23.1</td>
<td>23.1</td>
</tr>
<tr>
<td>He II Lyα</td>
<td></td>
<td></td>
</tr>
<tr>
<td>304Å O</td>
<td>6.3</td>
<td>6.3</td>
</tr>
<tr>
<td>O₂</td>
<td>16.6</td>
<td>16.6</td>
</tr>
<tr>
<td>N₂</td>
<td>12.1</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Therefore the Lyβ instead of the Lyα may actually be controlling the electron density at night. It is consistent with the view of Nicolet (1965); Donahue (1966) and Ferguson, et al., 1965. Otherwise the reaction

$$O_2^+ + NO \rightarrow NO^+ + O_2$$

with a rate coefficient of 8x10^{-10} cm^3 sec^-1 removes the O_2^+ ions too rapidly.
Ion composition measurements of the ratio $\left[\text{NO}^+\right]/\left[\text{O}_2^+\right]$ as obtained by sounding rockets also favours the suggestion that there must be a source for the ionization of $\text{O}_2$.

Likewise one may expect significant contribution from $584\AA$ and $304\AA$ glows in the form of ionization of $\text{N}_2$, $\text{O}_2$ and $\text{O}$.

Some of the more recent experiments by Young et al (1975) reveal, the importance of solar H Lyman $\alpha (1216\AA)$, Lyman $\beta (1026\AA)$, He I (584\AA), and He II (304\AA), in the ion production, using rocket borne UV photometers in the band $140\AA - 1400\AA$. The hydrogen Ly $\alpha$ and Ly $\beta$ radiations are the ones resonantly scattered from the geocoronal regions while the He I line is from the neutral 'He' in the interstellar wind and doppler shifted so that it penetrates the earth's 'He' blanket. The He II line has its origin in the ionized 'He' in the earth's plasmasphere. Also star light in the wavelength region of $912\AA - 1400\AA$, primarily from the early types of stars from the Orion origin, can also contribute to the ionization processes. The intensities vary from several kilo Rayleighs for H Ly $\alpha$ to several Rayleighs for He II lines.

Other possible night-time ionizing sources:

1) **Particle Precipitation**: This is important especially in the low altitudes below 80 km. The contribution is significant at mid latitudes. (Ivanov Kholodany, 1970; Nesterov, 1974)
ii) **Meteor Ionization**: Precipitation of meteoritic particle is a possible source of ionization around 100 km altitude. It is important in connection with sporadic E-layers (Nicolet, 1955).

iii) **Cosmic Rays**: Cosmic rays may cause a weak ionization in the D-region (Nicolet and Aikin, 1960). They would give the lower limit of ionization when the solar electromagnetic radiation is entirely absent. The contribution due to cosmic rays is usually negligible above 80 km.

iv) **Galactic X-rays**: The contribution due to this agency is extremely small, the number of electrons produced in the unit column of atmosphere is less than $10^{-3}$ cm$^{-3}$ sec$^{-1}$ in the lower region of the ionosphere (Giacconi and Gursky, 1965; Ananthakrishnan and Ramanathan, 1969).

Therefore the possibilities of these agencies alone being solely responsible for the maintenance of the night-time ionosphere is remote.

In fact night-time UV measurements have suggested that an irradiance of only 10 Rayleighs of Ly$\beta$ are sufficient to maintain the mean ionization level above $10^3$ cm$^{-3}$ between 100-130 km region. Figure 2.3 (page 55a) depicts the production rate due to scattered UV radiation during night-time (Ogawa and Tohmatsu 1966).
Fig. 2.3: Night time production of ionization due to scattered EUV (Ogawa and Tohmatsu 1966).

Fig. 2.2: Variation of NO+ recombination coefficient: shaded curve (Walls and Torr 1977) and ——— Mehr and Biondi (1977, 1978).
2.4 The insitu mass spectrometer measurements:

Measurements of the different ionic constituents at night, over the dip equator THUMBA (8.53°N 76.95°E 0.65° dip angle) were made in two flights as per the Table I (page 10; ISRO 05.21 and ISRO 05.50).

The actual launch times were 2330 IST and 0230 IST, respectively. The zenith angles at the time of the launches were 170° and 140° respectively. Since the launchings were close to and well after midnight, it is expected that the day time after effect would have completely ceased, and because the mornight twilight becomes significant only in late hours due to the long relaxation time of the ion formation, the conditions would be closer to those which are favourable for the equilibrium approximation.

The results as discussed by Shirke et al (1977), revealed NO⁺ as the only ion constituent in 05.21 all through the flight. Figure 2.4 (page 57a) depicts the variations in NO⁺ as obtained with altitudes. This is an indication that the other usually dominant ion O₂⁺ was less than 10% at 110 km and less than 2% above 130 km. Within the same altitude O⁺ must have been less than 1% of the total concentration. The electron density data then directly reflects the NO⁺ density variations.
In the second night-time flight 05.50 (Danilov et al., 1980b) NO⁺ dominated as the only major ion. Densities were less than 1% all through the flight and beyond the sensitivity of the detector. Interestingly, Si⁺(28), silicon ions were measured from 120 to 160 km altitude with relative densities ranging from 10% that of the total. Absolute densities were around 50 ions cm⁻³. Figure 7.17 (page 188a) represents the variations of [Si⁺][NO⁺] with altitude on this occasion. The period of launch of 05.50 flight coincided with the peak activity of Geminid Ursids meteor showers and this could be the reason for the detection of metallic ions like silicon. This aspect is discussed in detail in the chapter VII, on metallic ions.

With the available laboratory measurements of the dissociative recombination coefficients and the simultaneously measured electron density profile, computations are made to arrive at the effective recombination coefficient for both the flights. Under photochemical equilibrium conditions, when there is no significant transport, the loss of electrons and ions due to recombination is balanced due to production by the scattered UV radiation. A simple equation of the type written below holds true:

\[ \alpha' \left( \frac{N_e}{N_e} \right)^2 = \left( \frac{N_e}{N_e} \right)^2 \left[ \frac{[NO^+]}{[N_e]} \alpha^*_{NO^+} + \frac{[O_2^+]}{[N_e]} \alpha^*_{O_2^+} \right] \]  \hspace{1cm} (2.5)
Fig. 2.4: Variation of the ion current due to NO$^+$ ions with altitude in flight (05.21) (21.4.1975).
Where \( \alpha^* \), \( \alpha_{NO^+}^* \), and \( \alpha_{O_2^+}^* \) are, the effective recombination coefficient, dissociative recombination coefficient of \( NO^+ \) and \( O_2^+ \) respectively; also, \( [N_e] \), \( [NO^+] \) and \( [O_2^+] \) represent the densities of the respective species. When there is no direct measurement of scattered radiation it would be useful to derive the \( \alpha^* \left( \frac{[N_e]}{e} \right)^2 \) values and compare them with the available EUV production data.

Since there is no information available on the vertical drift parameter, as an approximation it is taken to be negligible. Under such purely chemical equilibrium conditions \( \alpha^* \left( \frac{[N_e]}{e} \right)^2 \) in the L.H.S. would correspond to the ionization production due to scattered EUV radiation. The consequences of this approximation are discussed later.

The dissociative recombination coefficients \( \alpha_{NO^+}^* \) and \( \alpha_{O_2^+}^* \) which correspond to the respective species are known to depend only on the electron temperature.

For example

\[
NO^+ = 4.5 \times 10^{-7} \times \left( \frac{300}{T_e} \right) \hspace{1cm} \cdots (2.6)
\]

\[
O_2^+ = 2.2 \times 10^{-7} \times \left( \frac{300}{T_e} \right) \hspace{1cm} \cdots (2.7)
\]

(Biondi, 1969)
At E-region altitudes especially during night the electron temperature could be equated to the neutral temperature $T_n$. Model temperatures (Jacchia 1977) obtained for the time of the experiments were used for $T_n$. Thus derived values of the effective recombination coefficient $\alpha'$, measured electron density $[N_e]$ and the parameter $\alpha'_{[N_e]}^2$ are tabulated in Table 2.2. The altitude variation of $\alpha'_{[N_e]}^2$ is plotted in figure 2.5 (page 630). The $Q$ values derived by Ogawa and Tohmatsu (1966) are also included for comparison. The interesting aspect of the present exercise is that above 120 km and upto 150 km the derived $Q$ values on the basis of the scattered EUV radiation is consistently larger all through the altitude of measurements. However, above 150 km altitude He I and He II lines also contribute significantly for the ion production. The discrepancies observed are discussed later.

**TABLE 2.2**

<table>
<thead>
<tr>
<th>ALT' km</th>
<th>$N_e$ cm$^{-3}$</th>
<th>$s_1^+$ cm$^{-3}$</th>
<th>NO$^+$ cm$^{-3}$</th>
<th>$T_n$ oK</th>
<th>$N_e^2$ cm$^{-3}$ sec$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>6.5x10$^2$</td>
<td>10%</td>
<td>5.85x10$^2$</td>
<td>347</td>
<td>1.5x10$^{-1}$</td>
</tr>
<tr>
<td>130</td>
<td>5x10$^2$</td>
<td>11%</td>
<td>3.9x10$^2$</td>
<td>463</td>
<td>5.7x10$^{-2}$</td>
</tr>
<tr>
<td>140</td>
<td>6.5x10$^2$</td>
<td>10%</td>
<td>5.85x10$^2$</td>
<td>571</td>
<td>9x10$^{-2}$</td>
</tr>
<tr>
<td>150</td>
<td>7x10$^2$</td>
<td>10%</td>
<td>6.3x10$^2$</td>
<td>657</td>
<td>9.1x10$^{-2}$</td>
</tr>
<tr>
<td>160</td>
<td>7x10$^2$</td>
<td>8%</td>
<td>6.44x10$^2$</td>
<td>723</td>
<td>8.4x10$^{-2}$</td>
</tr>
</tbody>
</table>
TABLE 2.3

<table>
<thead>
<tr>
<th>ALT (km)</th>
<th>$N_e$ (cm$^{-3}$)</th>
<th>NO$^+$ (cm$^{-3}$)</th>
<th>$T_n$ (°K)</th>
<th>$N_e^2$ (cm$^{-3}$ sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.3x10$^3$</td>
<td>2.3x10$^3$</td>
<td>200</td>
<td>3.57</td>
</tr>
<tr>
<td>110</td>
<td>2x10$^3$</td>
<td>1.8x10$^3$</td>
<td>240</td>
<td>2.03</td>
</tr>
<tr>
<td>120</td>
<td>9x10$^2$</td>
<td>7x10$^2$</td>
<td>355</td>
<td>2.4x10$^{-1}$</td>
</tr>
<tr>
<td>130</td>
<td>1.7x10$^3$</td>
<td>1.5x10$^3$</td>
<td>470</td>
<td>7.3x10$^{-1}$</td>
</tr>
<tr>
<td>140</td>
<td>2.2x10$^3$</td>
<td>2.1x10$^3$</td>
<td>580</td>
<td>10.75x10$^{-1}$</td>
</tr>
<tr>
<td>150</td>
<td>2.5x10$^3$</td>
<td>2.3x10$^3$</td>
<td>670</td>
<td>11.6x10$^{-1}$</td>
</tr>
<tr>
<td>160</td>
<td>1.8x10$^3$</td>
<td>1.5x10$^3$</td>
<td>710</td>
<td>5.1x10$^{-1}$</td>
</tr>
</tbody>
</table>

In order to check the consistency of the results obtained from the analysis of data from two flights, similar calculation of $\alpha [N_e]^2$ is made for yet another night-time composition measurement from the same station Thumba (NASA 18.98). The experiments formed a part of the investigation of the night-time equatorial ionospheric composition and dynamics, by Goldberg et al. (1974). The E-region measurements alone are considered here for comparison purposes. The major features of the composition namely the dominance of NO$^+$ ion by at least an order of magnitude compared to the O$_2^+$ ion is consistent. But the overall densities are larger by an order of magnitude compared to the author's earlier referred measurements.
The parameter $\alpha[N_e]^2$ was calculated following the same method. The values obtained show larger values of $\alpha[N_e]^2$ above 120 km and up to 150 km. The electron temperature that was used in the calculation was obtained by equating $T_e = T_n$: the $T_n$ (neutral temperature) values were obtained from Jacchia (1977) model temperature profile for an exospheric temperature ($T_\infty$) of 1005°K. The values of $\alpha[N_e]^2$ with altitude and other relevant parameters are given in Table 2.3.

2.5 Discussion

The comparison of the $\alpha[N_e]^2$ values of the three flights viz., 05.21, 05.50, and NASA 18.98 is interesting. In the first two cases the values of $\alpha[N_e]^2$ arrived at, are consistently lower as compared to the predicted production rates. Under normal circumstances the total production term

$$\dot{Q} = \alpha[N_e]^2 + T$$

$$\alpha[N_e]^2 = Q - T \quad \ldots (2.8)$$

Where $T$ stands for the transport.

Instead, $\alpha[N_e]^2$ was directly equated to $Q$ by making $T = 0$ in the above calculations. Under such circumstances the values of $\alpha[N_e]^2$ obtained would be the lower limit of the production due to scattered EUV radiation as the effect of transport would be to accumulate ionization at these altitudes at night. As the derived values of $\alpha[N_e]^2$ are consistently
smaller than the theoretical values of \( Q \) it is possible that there must have been an upward drift, prevailing at the time of the measurements. Reddy (1981) has discussed the possibilities of the primary field changing its directions during magnetically disturbed periods. As the two flights 05.21 and 05.50 took place during magnetically disturbed periods, this possibility cannot be ruled out. At this stage when there is no direct measurement on the drifts of ionization, it is difficult to pinpoint the exact cause of the discrepancy.

Further, the exospheric temperature on these two occasions were 699°K and 966°K. Nearly 300°K difference in \( T_{\infty} \) and the corresponding shift of the whole temperature profile had not changed the \( \alpha [N_e]^2 \) values. It is also to be noted that the electron density \( N_e \) values were nearly of the same order.

At the time of NASA 18.98 flight, the \( T_{\infty} \) value, as obtained from Jacchia '77 model was 1005°K. The enhanced value of \( \alpha [N_e]^2 \) obtained for this occasion could not be due to the temperature dependence of the dissociative recombination coefficient, because of its inverse relation with \( T_e \). The possibility that on this occasion there could have been enhanced production, also exists there. UV photometers carried on rockets on the same day 35 minutes later than the NASA 18.98 flight, were used to study the scattered EUV radiations. Measurements were made on the
He I and He II lines only. The fluxes of these wavelengths were observed to be 16R and 8R for He I and He II lines (Parasec et al., 1973a, b) which are more by a factor of 1.6 and of 8 respectively. The presence of N\(^+\) and O\(^+\) in measurable quantities below 200 km also suggests the enhanced EUV radiations. It is to be noted that He I and He II lines had their maximum from 150-200 km and are important above 150 km (Figure 2.2 (page 55a)). The region of interest for our present study is below 150 km where only Lyman \(\beta\) radiation is important. There had been no measurements in this wavelength band. At this juncture it is difficult to extend the analogy of the He I and He II lines to the larger wavelength suggesting a corresponding increase in its flux too.

One of the important parameters in the equatorial ionosphere is the mobilities of ionization. Electric fields generated in the dynamo region at mid latitude pervade by Maxwell equation, the equatorial latitude dynamo region, as the East-West electric fields; eastward during day and westward during night. This primary electric field which drives the equatorial electrojet gives rise to a large vertical electric field, upward during day and downward during night. This enhanced vertical field takes the same shape as the spatial distribution of the electrojet current density. Figure 2.6 (page 63a) depicts the distribution of the vertical electric field with altitude and latitude (Ananda Rao, 1977) for a primary field of
Fig. 2.5: Variation of $\chi(N_e)^2$ with altitude for the three night time flights via ISRO (05.21), ISRO (05.50) and NASA (10.98).

Fig. 2.6: The theoretically derived vertical electric field $E_r$ vs. altitude for different dip latitudes for a primary field $E = 0.5$ mv/m (Ananda Rao 1977)
0.5 mV/m. The horizontal east-west winds have no significant effect on the electrojet and therefore are not taken into account. The E-region primary field is known to have very good correlation with the F-region drifts at the equator (Balsley and Woodman 1969).

Goldberg et al (1974) while discussing the composition of the equatorial ionosphere have concentrated explaining only the F-region ionization density profiles ignoring the possibility of the drift becoming important lower below 200 km. While discussing the distribution of metallic ions obtained in the same flight Aikin and Goldberg (1973) have discussed the possibility of the metallic ion distribution getting affected by the electric field. They had compared the ion density profiles obtained from a similar instrumented flight from THUMBA in the evening hours (19.38 LMT), about 6 hours prior to the flight under discussion at present. By comparing the magnitude of the observed displacements of the metallic ions they had concluded that a downward velocity of the order of 1 m/sec in phase with the F-region downward velocity as deduced from ionograms, could account for the redistribution of metallic ions. From the theory of equatorial electrojet it is now established that ions and electrons have differential velocities in the 100-180 km region; the ion velocities being by double the electron ExB velocities at certain altitude region (Hanson et al 1972) as will be seen in the following sections. From this
angle it appears that downward velocities assumed to be of the order of 1 m/sec is unrealistic.

With a view to establish the importance of the drift term on this occasion a theoretical exercise was done starting from the ion composition data of the evening (1938 LMT) flight and trying to arrive at the profiles obtained during mid night. Suitable drift terms are included and the production term is taken as the one evaluated by Ogawa and Tohmatsu (1966).

2.6 Importance of the ion drift due to Pedersen currents:

In the case of the NASA flights, as two flight data are available within a span of 6 hours in the night time, the importance of the vertical drift due to Pedersen currents could be brought out.

Goldberg et al (1974) have discussed the features of the drift of ionization above 200 km. They have obtained the F-region drift by studying the altitude variations at two constant densities one near the minimum \( N_e = 5 \times 10^4 \text{ cm}^{-3} \) and one near the maximum \( N_e = 4 \times 10^5 \text{ cm}^{-3} \) values for the \( F_2 \) layer. These figures were obtained from ionograms taken during the same night. Both portions of the layer moved downwards at the same rate implying a preservation of the layer shape during the motion. Figure 2.7 (page 70a) depicts the trends of the movements of the layer in the 'F' region. The layer motion was approximated to the drift
motion at the night-time equator as proposed by Balsley (1969). Vertical velocity profiles obtained from the slope of the curve that depicts the change of isopleith altitude with time are presented in the lower half of Figure 2.7 (page 70a). The launch sequence shows that the first lunch occurred at a time when the drift direction was upward and the second when the downward drift had virtually become zero. It is to be borne in mind that the drifts that are discussed so far, are F-region drifts where the electrons and ions move with the same velocity.

2.7 THEORETICAL DERIVATION OF IONIZATION PROFILES:

2.7.1 Calculation of the velocity term in the continuity equations:

Untiedt (1967) was the first to recognize that vertical current flow was not completely inhibited at the equator, as was assumed by Cowling, and Borger (1948) using a two dimensional meridional model of the electrojet which neglects the effects of local winds and local time variation. Untiedt found that permitting vertical current flow results in a doubling of the equatorial northward magnetic variation over the thin shell model of the equatorial electrojet. The physics of the equatorial electrojet was investigated in more detail by Sugiura and Poros (1969), Richmond (1973a, b), Forbes and Lindzen (1976b), Ananda Rao and Raghavarao (1979) and Raghavarao and Ananda Rao (1980). The vertical Hall polarization field which drives the equatorial electrojet is the one
which gives rise to vertical Pedersen currents that extend into the lower F-region and are closed by symmetric meridional current cells. It is the ion velocity associated with these equatorial Pedersen currents that allows the lifting up of the ionization like for instance metallic ions from the source region around 100 km (Hanson et al 1972).

The ion velocities for different primary east-west fields are calculated with altitude and for an equatorial station. The method of analysis is similar to that of Ananda Rao (1976).

The conditions of the model are, that the current density \( \mathbf{J} \) is divergent free, the electric field is irrotational and steady state conditions exist. A scalar function \( \psi(r, \theta) \) is used in deriving the current density vector, such that

\[
\frac{\mathbf{J}}{\partial r} = \frac{r_0}{r^2 \sin^2 \theta} \frac{\partial \psi}{\partial \theta} \quad \ldots (2.9)
\]

\[
\frac{\mathbf{J}}{\partial \theta} = \frac{r_0}{r \sin \theta} \frac{\partial \psi}{\partial \theta} \quad \ldots (2.10)
\]

Where \( r_0 \) is the earth's radius, \( \theta \) is the colatitude and \( \psi \) is the solution of the differential equation

\[
f_1 \frac{\partial^2 \psi}{\partial r^2} + 2 f_2 \frac{\partial^2 \psi}{\partial r \partial \theta} + f_3 \frac{\partial^2 \psi}{\partial \theta^2} + f_4 \frac{\partial \psi}{\partial r} + f_5 \frac{\partial \psi}{\partial \theta} + f_6 = 0 \quad \ldots (2.11)
\]
The coefficients $f_1, f_2 \ldots f_5$ are functions of the electrical conductivities and the spherical co-ordinates $\varphi, \theta$ and $\phi$ are given by Sugiura and Poros (1969).

The electric field $E$ is obtained from the current density $J$ and the direct conductivity tensor $\sigma$ by the relation,

$$J = \sigma E,$$  \hspace{1cm} ...(2.12)

The conductivity tensor in the $r, \theta, \phi$ coordinates is given by

$$\sigma = \begin{pmatrix}
\sigma_c \sin^2 I + \sigma_i \cos^2 I & (\sigma_v - \sigma_p) \sin I \cos I & -\sigma_z \cos I \\
(\sigma_v - \sigma_i) \sin I \cos I & \sigma_o \cos^2 I + \sigma_i \sin^2 I & \sigma_z \sin I \\
\sigma_2 \cos I & -\sigma_z \sin I & \sigma_1
\end{pmatrix}$$  \hspace{1cm} ...(2.13)

Where $\sigma_c, \sigma_i$, and $\sigma_z$ are the longitudinal, Pedersen, and Hall conductivities respectively and $I$ is the magnetic inclination (dip angle).

The conductivities are calculated following the model of Anand Rao and Raghavarao (1979) wherein the collision frequencies given by Richmond (1972) and later modified by Gagnépain et al (1976) are made use of.

The neutral densities are taken from J71 model and the $N_e$ profile adopted was a typical noon time profile. The magnetic field value and the evaluation of the primary electric field are adopted from Ananda Rao (1976).
In the absence of any neutral wind the force on the ions is \( \mathbf{F} = e \mathbf{E} \). The velocity imparted to the ions by such a force could be represented as

\[
\mathbf{V} = \mathbf{k} \cdot \mathbf{F} \quad \ldots \quad (2.16)
\]

The mobility tensor \( \mathbf{k} \) is given by

\[
\mathbf{k} = \begin{pmatrix}
  k_0 \sin^2 \theta + k_1 \cos \theta & (k_0 - k_1) \sin \theta \cos \phi & k_2 \cos \theta \\
  (k_0 - k_1) \sin \theta \cos \phi & k_1 \cos^2 \theta + k_2 \sin \theta & -k_2 \sin \theta \\
  -k_2 \cos \theta & k_2 \sin \theta & k_2
\end{pmatrix}
\]

\[
(2.17)
\]

\[
k_0 = \frac{1}{m_0 \nu_0} \; ; \; k_1 = \frac{1}{m_0} \left( \frac{\nu_0}{\nu_0^2 + \lambda_0^2} \right) \; ; \; k_2 = \frac{1}{m_0 \nu_0} \left( \frac{\nu_0^2}{\nu_0^2 + \lambda_0^2} \right) \quad (2.18)
\]

Where \( k_0, k_1 \) and \( k_2 \) are the longitudinal, Pedersen and Hall mobilities, respectively.

In calculating the ion velocities the current density \( \mathbf{J} \) was obtained at each point by the differentiation of \( \psi \) numerically; the electric field \( \mathbf{E} \) was obtained by the inversion of the equation (2.12), by using the conductivity tensor; and finally the ion velocities were obtained by using the mobility tensor. Except that the collision frequency model for the evaluation of the ion mobilities being different essentially the methodology is the same, as adopted by Hanson et al (1972) in order to explain the uplifting of metallic ions from their source region (\( \sim 100 \) km) to F-region altitudes and above.
Figure 2.8 (page 70a) depicts the plot of the radial velocity at different latitudes as a function of height. These radial velocity values are used in the present calculations. It is clearly seen that at altitude ranges from 100-150 km the ion velocities exceed the electron velocities; the maximum difference occurring at an altitude of 118 km. At about 200 km the ion velocity is the same as the electron velocity or the F-region drift velocity. The F-region drift velocity by itself is dependent on the primary E-W electric field. Therefore the variation in the F-region vertical drift velocity could be taken as a direct measure of the E-region dynamo field variation.

2.7.2 Solution of the continuity equation:

In order to study the effect of the velocities derived above, on the ionization profiles the time dependent continuity equation is solved to obtain the concentration of NO\(^+\), the major ionic constituent in the E-region with altitude and time. The velocities calculated using the method described above for 0° dip latitude were used in the transport term.

The equation is given by

\[
\frac{\partial N_i}{\partial t} = \mathcal{Q} - \alpha_{NO^+}^* [N_e] - \nabla \cdot (N_i V_i)
\] ...

(2.19)

\[
= \mathcal{Q} - \alpha_{NO^+}^* [N_e] - N_i \left( \nabla \cdot V_i \right) - V \cdot \nabla N_i
\] ...

(2.20)
Fig. 2.7: Top: F-region electron density isopleths as a function of time, for the night corresponding to the flight NASA (18.98) 
Bottom: Vertical drift velocity as a function of time. (Goldberg et al 1974) 

Fig. 2.8: Theoretically derived radial velocity \( V_r \) for a primary field of 1 mV/m, at various latitudes and as a function of altitude.
Where $Q$ is the production term at any altitude, $\alpha_{NO^+}$ the dissociative recombination coefficient of NO$^+$, $[N_e]$ the electron density at the altitude, and $V'$ the radial component of the ion velocity at the same altitude.

As, only the gradients of $N$ and $V$ in the vertical direction are significant as compared to those in the horizontal direction, variations of $V_i$ and $N_i$ along $Z$ alone are considered. The equation now takes the form

$$\frac{\partial N_i}{\partial t} = Q - \alpha_{NO^+} [N_e]^2 - V_i \frac{\partial N_i}{\partial Z} - N_i \frac{\partial V_i}{\partial Z} \quad \ldots (2.21)$$

Here $Q$ is assumed to have the values given by Ogawa and Tohmatsu (1966) and $\alpha_{NO^+}$ is equated to the dissociative recombination coefficient of NO$^+$, with electrons. The electron temperature $T_e$ appearing in the expression for $\alpha_{NO^+}$ is equated to $T_n$, the neutral temperature, as obtained from Jacchia 1977 model for the time of the flight. The $N_e$ values are equated to the total ion density at the altitude $Z$ and $V_i$ to the radial velocity at $Z$, corresponding to the F-region drift velocity at that time.

The first NASA flight (18.97) data are taken to represent the initial conditions.

When the first measurement was made, the drift direction was upward, with an upward velocity increasing from 5 m/sec to 12.5 m/sec within about 40 minutes.
subsequently changing over to approximately 28 m/sec downward. The changeover is treated to be linear over a time period of 3 hrs. After this duration the downward velocity magnitude got reduced, approaching zero by 2300 hrs. Subsequently up to the time of the second measurement the drift term is taken to be negligibly small. The dotted line in figure 2.7 (page 70a), represents the assumed velocity variations.

At the time of computation, the F-region drift velocity and the corresponding E-region dynamo field is obtained. From this field, the vertical profile of the ionic velocities \( v_f \) is derived and substituted for the transport term.

2.7.3 Results of the theoretical calculations:

Importance of the different parameters in the continuity equation.

The method of analysis presented above has enabled one to bring out the importance of the production and transport terms and their contributions to the maintenance and redistribution of the night-time ionization in the equatorial electrojet region.

Case (i) \( V=0 \): Initially the velocity term was equated to zero in order to study the effect of production due to scattered EUV alone. The time evolution of the profiles as obtained at intervals of approximately one hour are depicted
in figure 2.9 (page 73a). The densities of the derived profiles are very close to $10^3$ cm$^{-3}$ indicating that the most important role in the night-time equatorial ionosphere is played by scattered EUV radiations. There is hardly any change in the observed profiles even after nearly 5 hours. The valley is observed to be less pronounced than the actual measurement and the altitude of minimum density is also around 135 km. The agreement with the measured profile cannot be said to be good.

Case (ii) $Q=0$: To study the relative importance of the transport term, the production term $Q$ was equated to zero and the variation in velocities were used as obtained from ionograms.

The derived profiles are depicted in figure 2.10 (page 74a). Initially the density is seen to deplete to very low values because of the upward drift and the production being absent to replenish the loss of ionization. After 2030 hrs since downward drift commences the build up of ionization is seen to occur. The features of the measured profiles are observed to get developed. At 2230 hrs the development of the valley nearly of the same relative magnitude and at the same altitude of 120 km, as the measured profile, is to be noted. In the calculations the drift is equated to be zero at 2300 hrs, and only loss due to recombination is assumed to prevail.
Fig. 2.9: The time evolution of the ion density profiles for a case when the vertical ion motion $V$ is equated to zero.
The depletion of the density to the order of $10^2 \text{ cm}^{-3}$ is brought out. From this exercise it becomes clear that the vertical downward ion drift has a significant role to play in the equatorial ionospheric distributions.

**Case (iii) $O+V$:** Finally a more realistic case pertaining to the actual measurements was considered by taking both production and transport. The profiles as obtained are represented in figure 2.11 (page 75a). Also represented are the actual measured profile for comparison.

The development of the valley, and the build up of ionization are brought out. The valley minimum altitude is seen to be maintained at 120 km up to the time, when the drift was downward. Once the drift was equated to zero, the profiles behave similar to the 'no-transport' case discussed earlier and the valley is observed to get shifted to 135 km, the altitude where actually the production minimum is situated, by 2330 hrs. As for the agreement with the measured profiles are concerned, fairly good representation is made by profile obtained at 2212 hrs. Though there is agreement in the altitude of the dip of the valley, the measured profile has a more pronounced valley by a factor of 1.2. The variations are seen to be symmetrical with respect to the derived values, larger by a factor of 1.2 from 130-155 km and smaller by the same factor from 160-200 km. The discrepancy in time and the possible cause for the same are discussed below.
Fig. 2.10: Ion density profiles with time when the production due to scattered radiation $Q$ is equated to zero and the effect of transport alone is considered.
2.8 Limitations of the calculations:

Though the importance of the transport parameter in the equatorial latitudes has been brought out by the theoretical exercise, some of the limitations are to be noted.

The vertical F-region downward drift as derived from ionograms could be treated only as a rough estimate of the actual conditions. More precise values and the time variations of the velocities may be required.

Secondly while solving the continuity equation using stream line functions and a moving coordinate system, in order to end up with data at least up to 180 km, one has to feed input data at least up to 300 km. Care is taken to change the recombination coefficient from the dissociative rate of NO to the effective rate corresponding to O, which happens to be the dominant species above 200 km. But diffusion of ionization along the field lines is not taken into account in the present analysis.

Finally as had been shown by Harris and Tohma (1972) and McLeod et al (1973) horizontal winds play an important role in the redistribution of ionization at mid latitudes. The cross overs between the theoretical profile (without horizontal wind) and the measured profiles were indicative of the horizontal winds being important. However, horizontal winds are not known to be effective in redistributing ionization at the dip equator (Ananda Rao and Raghavarao 1979). But vertical winds at these latitudes are known...
Fig. 2.11: A realistic case where both transport and production are taken into account and variations in the ion density profiles represented.
to be very effective as had been shown by Raghavarao and Ananda Rao (1980), and Somaiyajulu et al (1980).

No wind measurements are available for the cases under study and this aspect is not taken into account.

These limitations discussed above are thought to be the cause of the discrepancy as seen in the measured and derived profiles.