Some Studies on D-Region Electron Density Profiles

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Model electron density profiles in the D-region have been prepared for various solar conditions and for mid-latitude and equatorial locations on the basis of production and loss rates of electrons established from the study of a large number of electron density profiles measured under various conditions. It is found that below 85 km, electron density variations follow a linear law of the type \( q = \beta N_e \) and above this altitude a square law of the type \( q = \alpha N_e^2 \). The electron production rate for any condition of solar activity has been calculated after establishing variations connecting solar activity and solar \( L_x \) and X-ray intensities in various ranges as obtained from rocket and satellite observations made under various conditions since 1954.

1. Introduction

Observations of electron density in the D-region have been taken by different techniques and at different places and times of the day. While these show major differences, certain trends are discernible. In any theoretical approach these trends should appear. Amongst the major trends that the theoretical models should reproduce are the sharp ledge around 85 km, the near symmetry of the diurnal variation and the rapid loss of ions at night below 80 km.

Two different theoretical approaches are possible. One is the use of a reaction scheme that includes all major positive and negative ion reactions. Although such an approach would have been desirable, it has been shown by Mitra and Rowe that the currently available information on all the reactions is inadequate. An alternative approach is based on the assumption of lumped electron loss coefficient. This latter approach has been chosen to compute electron densities in the present work.

The values of lumped electron loss coefficient which we have used are obtained from the simultaneous use of information of the ionizing fluxes and electron density profiles obtained with rockets for low and middle latitude stations.

2. Production Rates

2.1 Day-time—As currently believed the predominant sources of ionization in D-region during day-time are (a) \( L_x \) ionizing NO, (b) ultraviolet rays in the range of 1027-1118 Å ionizing \( O_2 \) \((^3P)\) and ionization of all the constituents by (c) X-rays less than 100 Å and (d) galactic cosmic rays.

In this work the values of production rate due to cosmic rays have been taken from Velinov. The calculation of rate of ionization of NO by \( L_x \) requires both NO profile and \( L_x \) flux. We have used the NO distribution given by Meira as obtained from rocket observation of \( \gamma \)-bands of the molecule in the day-glow. \( L_x \) flux has been taken from Fig. 1 in which a plot of all the available \( L_x \) flux measurements against 10-7 cm solar radio flux is shown. Photon ionization rates of \( O_2 \) \((^1D_g)\) by \( uv \) in the range of 1027-1118 Å are taken from Huffman et al.

To calculate the rate of electron production due to X-rays less than 100Å we need the spectrum and particle density. The spectrum has been built up from the X-ray flux measurements in the three wavelength regions, viz. 0-8, 8-20 and 44-60Å taken by the Naval Research Laboratory group of USA with SOLRAD satellites. X-ray fluxes are taken from Figs. 2a, b, c in which plots of all the available, quiet time X-ray fluxes in the three wavelength regions 0-8, 8-20 and 44-60Å against 10-7 cm solar flux are respectively shown. The detailed reference of all the data is not given here. The representative data may be obtained from ESSA Solar Geophysical Data Bulletin. A comparison of Figs. 1 and 2a, b, c shows

![Fig. 1 — Variation of Lyman-alpha flux with 10^-7 cm solar flux.](image-url)
Fig. 2a—Variation of solar X-ray flux in 0–8 Å band with 10.7 cm solar flux

Fig. 2b—Variation of solar X-ray flux in 8–20 Å band with 10.7 cm solar flux
that while \( I_m \) flux increases by a factor of about 1.4, X-rays in 0-8, 8-20 and 44-60Å bands increase by factors of about 400, 150 and 15 respectively between solar minimum and maximum periods. To construct the spectrum, we have assumed exponential distributions with effective temperatures of \( 2 \times 10^8 \), \( 1.5 \times 10^8 \) and \( 0.5 \times 10^8 \) K for 0-8, 8-20 and 44-60Å bands respectively. The spectrum thus constructed is shown in Fig. 2d. For the neutral atmospheric density the model given by Groves has been used.

2.2 Night-time D-region — Although all sources of ionization of the quiet night-time D-region have not yet been established, the mechanisms which are at present favoured are galactic cosmic rays scattered \( H_L \), and precipitated electrons. The rate of ion production due to galactic cosmic rays does not have any day to night variation and has been considered earlier.

Ionization of NO by scattered \( H_L \) radiation has long been recognized as a major source for the night-
Measurements show that the intensity of scattered HLα radiation lies between 1 and 4 kR. For our present work we have used energy flux of scattered HLx radiation equal to 1 and 4 kR for the minimum and the maximum solar activity conditions. For the production rate due to precipitated electrons, the values adopted here are those from Manson and Merry.

3. The Ψ and β Models for Electron Loss

Several electron loss models are available but most of them refer to disturbed conditions prevailing during polar cap absorption events in high latitude during both day and night. A quiet day-time model constructed by Reid from $q/N_{e}^2$ and a quiet night-time estimation by Belrose are also available. For quiet conditions in low and middle latitudes the main difficulty in obtaining electron loss model is the uncertainty concerning the contribution through the ionization of NO by Lα. In what follows, we have used the NO concentration given by Meira and have obtained Ψ − h and β − h profiles with several cases of rocket measurements of electron density profiles for low latitude and middle latitude zones from the equations:

$$\Psi = q/N_{e}^2$$

For low latitude we have used the profiles obtained at Thumba (summarized by Somayajulu and Avadhana) and for middle latitude we have used the profiles obtained at Wallops Island (summarized by Mechtly et al). The Ψ − h and β − h profiles thus obtained are shown in Fig. 3 for mid-day condition. In Fig. 4 comparison plot of these profiles for low and middle latitudes is shown. These profiles appear to be in fairly good agreement. Also the Ψ − h and β − h distributions estimated here are consistent with those given by Reid and Megill et al.

In Fig. 4 are also shown the night-time distribution of Ψ − h and β − h for middle latitude station (not enough electron density profiles are available in low latitudes at night). These distributions are valid for

![Fig. 3 - Ψ−h (top) and β−h (bottom) profiles for mid-day condition for low (Thumba) and middle latitude (Wallops Island) stations](image-url)
midnight condition and have been obtained by assuming \( dN_e/dt = 0 \). This assumption appears to be justified on the basis of the study made by Macay and Knight on the night-time rocket measurements of electron densities. They showed that there is almost negligible change in the value of electron density at night after about 0000 hrs local time. Since electron density below 85 km is very low and measurements are also not reliable, the night-time estimates of \( \Psi - h \) and \( \beta - h \) are limited to 80 km and above only.

4. Nature of Electron Loss in D region

Since a large number of electron density measurements in D-region for different times of the day are available and the electron production rates can also be calculated, one can examine the nature of electron loss at different heights of D region. The relation between \( q \) and \( N_e \) is of the type \( q = KN_e^p \), where \( q \) is the electron production rate, \( K \) is a constant and \( p \) is the index of power. If the recombination coefficient is of the \( \alpha \)-type, then the exponent \( p \) should be 2 and if it is of the \( \beta \)-type \( p \) should be 1. A few plots of \( q \) versus \( N_e \) and of \( q \) versus \( N_e^2 \) for various heights are shown in Fig. 5. It is to be noted from these plots that the value of \( p \) at 70 and 80 km is 1 and at 90 km it is 2. Thus, electron density at 90 km appears...
to follow the simple recombination law \( q = \alpha N_e^2 \). The effective recombination coefficient at 90 km deduced from Fig. 5 is \( 8 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1} \) which is of the same order as the laboratory values for the dissociative recombination coefficient for \( \text{O}_2^+ \) and \( \text{NO}^+ \). But the situation is different at 80 and 70 km altitudes, where a linear relationship of type \( q = \beta N_e \) clearly applies. The values of \( \beta \) at 80 and 70 km derived from Fig. 5 are respectively \( 8.4 \times 10^{-8} \) and \( 6.4 \times 10^{-8} \text{ sec}^{-1} \). In one of the diagrams in Fig. 5 is shown a plot of \( q \) versus \( N_e^2 \) for 80 km. \( N_e \) does not appear to follow \( q = k \) \( N_e^2 \) relationship. A relationship of type \( q = \beta N_e \) has been shown to hold good at 80 km during eclipse by Landmark et al., and during normal day-time at 77.5 km by Haug and Thrane and by Thrane. Their values are also \( \sim 10^{-8} \text{ sec}^{-1} \).

5. Models of D-region Electron Density Profiles

It has been shown in Sec. 4 that the loss of electrons at a height 90 km follows a square \( \alpha \) law and at heights 80 and 70 km it follows a linear \( \beta \) law. Keeping this in mind, electron density profiles above 85 km have been computed by using the equation

\[
\frac{dN_e}{dt} = q - \alpha N_e^2 \tag{1}
\]

and below this height by using the equation

\[
\frac{dN_e}{dt} = q - \beta N_e \tag{2}
\]

In this computation we have used \( \Psi - h \) and \( \beta - h \) models for day and night conditions estimated by us (Sec. 3) and \( \alpha, \beta \) values calculated from laboratory values of reaction rates and ion composition measurements. It is to be remembered that the calculation of \( \beta \) has been done from 70 to 85 km for day-time conditions and for 80 and 85 km for night-time conditions. Since estimation of \( \beta \) below 80 km for night-time condition is not possible because of lack of \( N_e \) profiles at night, in the present work, we have extrapolated night-time \( \beta \) profile down to 70 km. Also day-to-night variations in \( \Psi \) and \( \beta \) values exist and we start with only day and night time values. An interpolation through sunrise and sunset periods is, therefore, necessary. This interpolation has been done by trial and error method till one gets satisfactory agreement with the observed electron density. The variations of \( \Psi \) and \( \beta \) thus obtained are shown in Fig. 6. It may be noted that for lower heights the variation of \( \beta \) is very large and as the height increases this variation decreases and afterwards becomes nearly constant. The relation between \( \Psi \) and \( \alpha \) is \( \Psi = \alpha (1 + \lambda) \), where \( \lambda \) is the ratio of negative ions to electrons.

Taking the values of \( q, \Psi \) and \( \beta \) mentioned above, Eq. (1) (for heights 85-95 km where \( \lambda \approx 0 \)) and Eq. (2) (for heights 85-70 km) are integrated numerically by using Runge-Kutta method for the period from one midnight to next midnight. This gives rise to a set of electron density profiles, some of which are discussed below.

Fig. 7 gives a plot of computed electron density with local hours of the day for specific heights in the range of 70-95 km. For comparison, observed values of Thrane for low solar activity condition are also shown. The nature of the diurnal variation of electron density is quite apparent from Fig. 6 and consistent with the observation. Diurnal symmetry is also noticed around local noon.

In Fig. 8 the computed electron density profile is compared with that obtained by other workers for a solar zenith angle of about 60°, mid latitude and high solar activity condition. The present model is found to be within the range of measured values at heights about above 60 km. It may, however, be noted that although higher values are observed at about 60 km as compared to rocket-measured profiles,
Fig. 7 — Variation of computed electron density with local time of the day for specific heights in the range 70 - 95 km along with the observed values of Thrane for low solar activity period.

Fig. 8 — Comparison of height distribution of computed electron density profile with other profiles for high solar activity condition and for solar zenith angle 60°.

Fig. 9 — Height variation of computed electron density for different values of solar zenith angle (θ) for high and low conditions of solar activity (S. A.)

the high values below 60 km obtained from wave interaction and If and elf experiments are not reproduced in this model.

Theoretical models of electron density distribution at latitude of 10°N, corresponding to the equatorial rocket launching station, Thumba, India for various solar zenith angles and for both high and low solar activity periods are given in Fig. 9. One can notice from this figure that we are able to reproduce low electron density below 80 km at night and a ledge around 85 km during day-time. But the building of electron densities during sunrise as observed (Thomas and Harrison, Smith et al.) could not be reproduced with the present approach.

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