Height Variation of Electron Loss Coefficient in the Mesosphere

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Electron loss at mesospheric heights is characterized by the parameter $\Psi$, the effective electron loss coefficient. The value of $\Psi$ is known to be drastically reduced for the disturbed D-region and is more than two orders of magnitude larger than the normal day values for eclipse and nighttime conditions. A log-log plot of $\Psi$ against height, $h$, gives a linear relation of the form $h = K \Psi^{-n}$; here, the constants $K$ and $n$ are different for different D-region conditions. An attempt is made to find a relation between $n$ and the D-region disturbance.

1 Introduction

Several research workers have determined the effective electron loss coefficient $\Psi$ at mesospheric heights for different D-region conditions such as eclipse, solar flare, PCA, winter anomaly, etc. For D-region heights $\Psi$ is given by the relation

$$\Psi = \left( \alpha_d + \lambda \alpha_i \right) \left( 1 + \lambda \right)$$

where

$\alpha_d$ Effective dissociative recombination coefficient of positive ions with electrons

$\alpha_i$ Ion-ion recombination coefficient

$\lambda$ Ratio of negative ion to electron number density

The height below which $\lambda$ becomes significant varies with D-region condition. For $\lambda \ll 1$, we have $\Psi = \alpha_d$. The parameter $\Psi$ is then sometimes referred to as effective recombination coefficient $\alpha_{\text{eff}}$ or simply $\alpha$. The values of $\alpha_d$ is the weighted average of the dissociative recombination coefficients $\alpha_{\text{eff}}$ of all the ion species $N_i^+$ and is calculated as $\alpha_d = \Sigma \alpha_{\text{eff}} N_i^+ / \Sigma N_i^+$. Positive ion species at D-region heights comprise primary ions (NO$^+$ and O$^+_2$) and the hydrated cluster ions (derived from O$_2^+$ and NO$^+$) with varying recombination coefficients. Hydrated cluster ions are dominant below the cluster ion cut-off level. Above the cluster ion cut-off level, the ion species are predominantly O$_2^+$ and NO$^+$. The cluster ion cut-off level is at a height of around 82 km for normal D-region and this level is found to be drastically reduced for the disturbed D-region such as winter anomaly and PCA events. The reverse trend of the cluster ion cut-off level, being at a higher level, is found for eclipse and nighttime conditions. The value of $\Psi$ is of the order of $10^{-7}$ cm$^3$s$^{-1}$ in the molecular ion region and this value becomes larger than $10^{-5}$ cm$^3$s$^{-1}$ in the cluster ion region and at lower D-region heights. Thus we find a sharp change in the $\Psi$ value around the cluster ion cut-off level.

At E-region heights and upper mesosphere under normal conditions, the ion species are NO$^+$ and O$_2^+$, and $\alpha_{\text{eff}}$ is written as

$$\alpha_{\text{eff}} = \alpha_{\text{NO}^+} C_{\text{NO}^+} + \alpha_{\text{O}^+_2} C_{\text{O}^+_2}$$

Here $\alpha_{\text{NO}^+}$ and $\alpha_{\text{O}^+_2}$ refer to the dissociative recombination coefficients of NO$^+$ and O$_2^+$, and $C_{\text{NO}^+}$ and $C_{\text{O}^+_2}$ are relative concentrations of NO$^+$ and O$_2^+$, respectively. Empirical relation of the form

$$\alpha_{\text{eff}} = 2.5 \times 10^{-6} \exp (-Z/51.2)$$

is used in the study of E-region ion production and loss processes (Here $Z$ is in km). Schlegel has discussed the conditions under which $\alpha_{\text{eff}}$ is drastically reduced in the polar E-region due to enhanced electron temperature.

Goyal and Mitra have found an empirical relation for the height variation of $\alpha$ for the range 50-300 km. They have used the experimental values of $\alpha$ (mostly for post-solar flare conditions) and the relation of the form

$$h = K \Psi^{-n}$$

where $K = 2.95$ and $n = 0.23$ (There is an apparent error in this value of $K$ since Fig. 4 in the paper of Goyal and Mitra shows this value to be nearer to 300). The height range 50-300 km encompasses both the cluster-ion dominated region (lower D-region heights) and the molecular-ion region (upper D-region and E-region). Since the height extent of the cluster ion dominated region is known to vary with D-region conditions the values of $K$ and $n$ would be different if we consider the $\Psi$ values for the cluster ion and molecular ion regions and also the normal and disturbed conditions of the D-region. Since the variation of $\alpha_{\text{eff}}$ with height is shown to be exponential for the E-region (Oran et al.), we have attempted, in this paper, to check the validity of the relation $h = K \Psi^{-n}$ for the
D-region using the available $\Psi$ values for different D-region conditions.

2 Results and Discussion

Fig. 1 shows the height variation of $x_d$ and $\Psi$ for a normal day (equatorial) and two winter anomalous days. The values of $x_d$ are calculated from the rocket data on ion composition\(^{15-17}\) and the appropriate values of $x_d$ are taken from literature\(^{10-11}\). The maximum values of $x_d$ for hydrated cluster ions is known\(^{18}\) to be $10^{-5}\text{cm}^3\text{s}^{-1}$. However, the presence of negative ions result in larger $\Psi$ values ($> 10^{-4}\text{cm}^3\text{s}^{-1}$) at lower heights and for nighttime and eclipse conditions (Figs 3 and 4). In calculating the temperature dependent $x_d$ values, we have used the temperature data from Groves\(^{19}\), appropriate to the season and latitude of the rocket data. The temperature data for winter anomalous days are likely to be in error because of the possible temperature fluctuations associated with winter anomaly. The $\Psi$ values in Fig. 1 are taken from the results\(^8\) of the analysis of the rocket data on positive ion and electron densities using a simplified D-region model. The model analysis takes into account the presence of negative ions below 70 km and gives results on mesospheric temperature and NO concentration also, but these are not discussed here. We note that $x_d$ and $\Psi$ values agree well at heights above the cluster ion cut-off level where the ion species are molecular ions ($O_2^+$ and NO$^+$). Below this level, $x_d$ values are lower than $\Psi$ values. This is attributed to the fact that during rocket sampling heavier clusters are fragmented resulting in lower order clusters. The smaller $x_d$ values for the lower order clusters result in a correspondingly smaller values for the calculated $x_d$. In the model analysis, the relative concentration of total clusters is considered and this remains the same even in the presence of fragmentation of heavier clusters.

Fig. 2 shows the $\Psi - h$ profiles for normal D-region and normal nighttime condition. Profiles 4 and 5 are from the equatorial noon electron density model\(^6\). Profile 5 shows a decrease in $\Psi$ values at lower D-region heights which is not realistic. The profile 4 is based on electron density model which takes into account the errors associated with the ground-based and rocket measurements\(^6\). This profile is also in good agreement with the other $\Psi$ profiles for normal D-region.

Profiles 1, 3 and 4 (Fig. 2) for equatorial and midlatitudes show small variations in cluster ion cut-off level. The midlatitude summer day profile (profile 2) is of limited height extent but shows a sharp ledge at the cluster ion cut-off level. This feature can be explained in terms of a gradient in the thermal structure at these heights. Also shown in Fig. 2 is the $x_d$ profile from the empirical formula [Eq. (3)] of Oran et al\(^{12}\) since the empirical formula assumes the existence of molecular ions only, these values are much lower than the $\Psi$ values for heights below the cluster ion cut-off level.

Fig. 3 shows the $\Psi - h$ profiles for PCA day and nighttime conditions and also the profiles for eclipse conditions. These latter profiles are similar to the normal nighttime $\Psi - h$ profile. The PCA nighttime profiles show the reduction in cluster ion cut-off level as compared to the normal nighttime profile. It is seen that the $\Psi$ values are reduced for PCA daytime conditions also (Figs 2 and 3).
Fig. 3—Height variation of $\Psi$ for PCA, eclipse and nighttime conditions.

Fig. 4—Height variation of $\Psi$ for different D-region conditions.

Profiles 1-6 in Fig. 4 refer to winter anomalous days and all these profiles show the decrease in cluster ion cut-off level as compared to the normal day profile (shown as 8.5°N). The $\Psi$ values in the cluster ion dominated region are nearly the same for winter anomalous and normal conditions of D-region. The extent of the cluster ion dominated region is vastly reduced for winter anomalous conditions and consequently the effective electron loss coefficient is reduced over a considerable height range. In Fig. 4 we have also shown the PCA daytime and normal nighttime profiles and a few of the experimental $\alpha$ values used by Goyal and Mitra14. These experimental $\alpha$ values (see Fig. 4 of Ref. 14) can be grouped as (i) those above about 100 km and (ii) those below this height. The first group of data are typical of the effective electron recombination coefficients for the molecular ion region. The second group of data which are shown in Fig. 4 are indicative of the disturbed D-region. These $\alpha$ values are smaller than the effective recombination coefficients for PCA daytime conditions. We note that the experimental data of Goyal and Mitra14 are mostly from the post-solar flare measurements.

In Fig. 4 the $\Psi - h$ profiles for PCA and solar flare conditions show the reduction in effective electron loss coefficient over a larger height range compared to winter anomalous (and normal daytime) conditions. We note that the $\Psi$ values for solar flare conditions are comparable to normal daytime values at heights above 82 km (approx). Rocket measurements during PCA events20 and model studies for solar flare conditions show well defined cluster ion cut-off level.

Fig. 5 shows the log-log plots similar to that used by Goyal and Mitra14. The $\Psi$ values of the present study for normal D-region, viz. 38°N, 8.5°N and equatorial noon, and $\alpha$ values of Goyal and Mitra14 for lower D-region heights are used for the plots.

The straight line graph (a) is drawn through the $\alpha$ values of Goyal and Mitra14 to have $n = 0.23$ in the relation $h = K\alpha^n$. The value of $K$ happens to be different from that given by Goyal and Mitra14 because of the smaller height range taken.

The $\Psi$ values of this study as plotted in Fig. 5 show two distinct groupings. One group refers to cluster ion region [graph (b)] and the other molecular ion region [graph (c)]. The $\Psi$ values of the latter are spread near the $\alpha$ values of Goyal and Mitra14. A few of the $\Psi$ values for the transition region (transition from molecular ions to cluster ions region) lie between the groups, i.e. between the graphs (b) and (c).

In Fig. 5, for the normal D-region condition, the relation $h = K\Psi^{-n}$ is satisfied both for the cluster ion region and molecular ion region [graphs (b) and (c)]. The values of $n$ from the graph (b) and (c) are nearly the same as that found by Goyal and Mitra14 [graph (a)]. It is to be noted that the $\alpha$ values of Goyal and Mitra14 are representative of the disturbed D-region rather than the normal D-region (see Fig. 4).

Fig. 6 shows the log-log plots of $\Psi - h$ values for a number of disturbed D-region conditions considered.
Fig. 6—Log-log plot of $\Psi$ against $h$ for different D-region conditions in this study and the straight line graphs are through the $\Psi$ values representing the cluster ion region. Individual plots for the data of Fig. 3 are not shown here for the sake of clarity. But the results of our analysis for all the $\Psi - h$ data of this study are considered (Table 1) for plotting Fig. 6. It is evident that the relation $h = K\Psi^{-n}$ is satisfied for all the D-region conditions but the values of $n$ are not the same. Interestingly, the slope of the graph for solar flare condition (Fig. 6) is the same as that obtained by Goyal and Mitra\textsuperscript{14}. This is understandable since these authors have used the $x$ values from post-solar flare decay measurements.

Figs 5 and 6 show that the relation $h = K\Psi^{-n}$ is satisfied in the cluster ion region for normal and disturbed D-region conditions but the values of $K$ and $n$ are different for different D-region conditions. The values of $K$ represented by the intercept on the Y-axis, may not be of much significance since this value varies with the height extent of $\Psi$ used in the analysis. We look for the possible relation, if any, between the exponent $n$ and the D-region condition.

One of the distinguishing features of the disturbed D-region is the lowering of the cluster ion cut-off level which results in pushing down the molecular ion region (Fig. 4). Within the cluster ion region (below 70 km) the height variation of $\Psi$ is not the same for all conditions of the D-region as indicated by the values of $n$ (Fig. 6). The $\Psi$ values at 85 and 70 km can be considered as typical of the molecular ion and cluster ion regions, respectively, for any of the D-region condition considered in this study. The ratio of $\Psi$ at 85 km to $\Psi$ at 70 km (i.e. $\Psi_{85}/\Psi_{70}$) is taken as an index of D-region disturbance and as stated earlier, the exponent $n$ indicates the variation of $\Psi$ with height within the cluster ion region. The values of $\Psi_{85}, \Psi_{70}, n$, etc. are tabulated in Table 1 and a graphical representation of $n$ versus ($\Psi_{85}/\Psi_{70}$) is shown in Fig. 7. It is seen that for the normal D-region the ratio ($\Psi_{85}/\Psi_{70}$) is nearly the same as that for winter anomaly and daytime PCA, but the values of $n$ are very much different. Similarly the values of $n$ for normal D-region and solar flare conditions are nearly the same but the values of ($\Psi_{85}/\Psi_{70}$) are different. Eclipse, nighttime PCA and normal nighttime conditions have the lowest value of $n$ and ($\Psi_{85}/\Psi_{70}$).

**Table 1—Values of $n$ and the Ratio ($\Psi_{85}/\Psi_{70}$) for Different D-region Conditions**

<table>
<thead>
<tr>
<th>D-region</th>
<th>$-n$</th>
<th>$\Psi_{85} \times 10^{-6}$</th>
<th>$\Psi_{70} \times 10^{-6}$</th>
<th>$\Psi_{85}/\Psi_{70}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal day</td>
<td>0.23</td>
<td>1.00</td>
<td>11.5</td>
<td>0.09</td>
</tr>
<tr>
<td>Post-solar flare (GM)</td>
<td>0.23</td>
<td>0.48</td>
<td>1.0</td>
<td>0.48</td>
</tr>
<tr>
<td>Solar flare (strong)</td>
<td>0.23</td>
<td>1.70</td>
<td>3.1</td>
<td>0.55</td>
</tr>
<tr>
<td>PCA (day)</td>
<td>0.09</td>
<td>0.26</td>
<td>2.3</td>
<td>0.11</td>
</tr>
<tr>
<td>Winter anomaly -do-</td>
<td>0.03</td>
<td>0.65</td>
<td>8.0</td>
<td>0.08</td>
</tr>
<tr>
<td>PCA (night)</td>
<td>0.03</td>
<td>0.35</td>
<td>9.0</td>
<td>$&lt;0.01$</td>
</tr>
<tr>
<td>PCA (night)</td>
<td>0.04</td>
<td>0.30</td>
<td>200.0</td>
<td>$&lt;0.01$</td>
</tr>
<tr>
<td>Eclipse (Cassino)</td>
<td>0.02</td>
<td>1.90</td>
<td>$&gt;100.00$</td>
<td>$&lt;0.01$</td>
</tr>
<tr>
<td>Eclipse (WIs)</td>
<td>0.05</td>
<td>60.00</td>
<td>$&lt;0.01$</td>
<td>$&lt;0.01$</td>
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<tr>
<td>Eclipse (EQ)</td>
<td>0.02</td>
<td>4.50</td>
<td>$&gt;100.00$</td>
<td>$&lt;0.01$</td>
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<tr>
<td>Nighttime (Normal)</td>
<td>0.05</td>
<td>10.00</td>
<td>$&lt;0.01$</td>
<td>$&lt;0.01$</td>
</tr>
</tbody>
</table>

Note: WIs—Wallops Island\textsuperscript{1}; EQ—East Quoddy\textsuperscript{3}; and GM—Goyal and Mitra\textsuperscript{14}.
Fig. 7 shows a linear relation (broken line) between the parameters ($\Psi_{85}/\Psi_{70}$) and $n$ for the daytime disturbed condition viz., winter anomaly, PCA (daytime) and solar flare. The limited data in Fig. 7 indicate a sudden transition from night to daytime condition for the disturbed D-region and a gradual transition for the normal condition. It is to be noted that the index of disturbance taken as ($\Psi_{85}/\Psi_{70}$) may not be unique in view of the extended height range of molecular and cluster ion regions. More experimental data and a more appropriate index for D-region disturbances would be necessary to reach any further quantitative relation using our results on $K$ and $n$ values.

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References