CHAPTER IV

MONITORING OF X-RAYS THROUGH IONOSPHERE

4.1. INTRODUCTION:

Extensive investigations by Kreplin (1961) at NRL using rocket borne proportional counters led to the preliminary conclusion that the sun emits X-rays in the wavelength range $0.6\mu m$ more or less continuously. Subsequently satellite observations (Kreplin, Chupp and Friedman 1962, Lindsay 1963) have established a quiet time energy flux of about $10^{-4}$ ergs cm$^{-2}$ sec$^{-1}$ that could increase by an order of magnitude during disturbed periods. These solar X-rays in their propagation through the atmosphere are absorbed at different altitudes depending on their energy thus providing a source of ionization (Swider 1969).

The possible significance of X-radiation in the formation of the D-region was suggested many years ago by Muller (1935) and again by Rawer (1952) and more recently by Chamberlain (1961). Using the data obtained during solar maxima, Poppoff and Whitten (1962) demonstrated the significance of X-radiation in the lower D-region. Owing to the fact that VLF propagation should be affected by the changes in the D-region ionization, Anathanakrishnan (1969) investigated the VLF field strength variation associated with the changes in the solar X-ray emission and came to the conclusion that there is a positive correlation between the two. This confirmed the earlier prediction that solar X-rays comprise a significant
energy input at D-region altitudes from the standpoint of ionization.

These considerations led us to suspect that strong non-solar X-ray sources may also significantly influence the VLF propagation especially during the night time when the effect of solar X-rays is virtually absent. A search of the VLF data recorded at Ahmedabad corresponding to the 164 KHz transmission from Tashkent, was made to look for the effects associated with the transit of Sco X-1. The choice of this source for looking for the VLF effect was made on the consideration of its strength in the 1-10 keV range which is about $5 \times 10^{-7}$ ergs cm$^{-2}$ sec$^{-1}$. The genuineness of this effect was convincingly demonstrated by the apparent shift in the peak absorption on a day to day basis arising from the sidereal effects.

Investigation by Edwards et al (1969) and Kaufman et al (1970) further confirmed the observability of this effect in relation to Cen X-2 and Cen X-4 besides Sco X-1. Burgues and Jones (1969) in their search of the data corresponding to the Omega navigational system, however, could not find positive evidence for ionospheric detection of X-ray sources. From the theoretical standpoint, Whitten and Poppoff (1969) questioned the effectiveness of the extrasolar X-ray sources in providing significant electron density perturbations at D-region altitudes. They computed contributions from the ambient ionization against such as Ly$\alpha$ radiation, galactic cosmic rays and
celestial X-ray background and compared the resultant total effect with that expected from discrete celestial sources thus demonstrating the insignificant role of the latter. Further, they objected to the interpretation by Ananthakrishnan and Ramanathan (1969) on the basis of observed time profile. From a more detailed analysis, Francey (1970) questioned the analysis by Whitten and Popoff and showed that the relative importance of the contributions from the discrete cosmic X-ray sources to the electron production rates in the night time D-region critically depend upon the value of the concentration of NO (which is ionized by Lyα) in the 80-90 km region, used in the calculation. Thus the observability of the effect of the celestial sources on the ionosphere depends on the magnitude of their ionizing effect compared to that from all other sources and, in particular, to the magnitude of ionization due to Lyα.

Considerable uncertainties exist in the experimentally observed values of the different parameters responsible for the night time D-region ionization. Nevertheless, in view of the strong experimental evidence obtained at Ahmedabad and elsewhere in favour of the detectability of the ionospheric effects of the discrete X-ray sources, a reappraisal of the role played by different ionization agencies seems to be highly desirable. Such an investigation, in addition to resulting in a better understanding of the night time D-region processes could also be in principle the first step towards
evolving a simple and relatively inexpensive ground based technique for the long term monitoring of the X-ray sources. With these considerations, the role of the different ionization agencies in having a significant impact on the night time D-region processes with particular reference to the effects of celestial X-ray sources is re-examined in this thesis. First, a critical assessment is made of the relative importance of the various agencies to the ionization of the night time D-region. The computations have been made using the most recent values available of the relevant parameters. Secondly, the effects of the transit of strong X-ray sources Sco X-1 and Tau X-1, are evaluated in terms of the electron density enhancements. The contribution expected due to X-rays from the galactic centre is also estimated. The calculation of electron densities is made by a direct comparison of the electron production rates by different ambient ionization agencies with the experimentally measured electron densities. Towards the end of the chapter, the observed VLF absorption of the 164 KHz signal from Tashkent recorded at Ahmedabad has been shown quantitatively to be related to the computed ionization effects of the X-ray sources and thus the satisfactory agreement between the observations and the theoretical calculations of the magnitude and time profile of VLF absorption is demonstrated.
4.2. IONIZATION DUE TO CELESTIAL X-RAY SOURCES:

It has been shown by a number of authors (Whitten et al 1965, Swider 1969, Francey 1970) that the X-rays in the energy range 1-10 keV impinging on the top of the atmosphere produce ionization mainly in the 80-90 km height interval. At lower altitudes, the effect of X-rays becomes relatively unimportant due to severe exponential absorption they undergo in the atmosphere during their passage downwards. In addition, whereas X-rays below 1 keV are absorbed considerably even at altitudes of 100 km, those above 10 keV for normal power law spectrum of the type $E^{-2}$, contribute very little to the ionization due to their low flux at altitudes below 70 km.

The energy absorption per unit volume from a monoenergetic beam of X-rays of intensity $I(keV.cm^{-2}.sec^{-1})$ passing through a path $dx$ (cm) of the absorber is given by

$$\frac{dI}{dx} = \rho \mu(E) \cdot I \cdot keV.cm^{-3}.sec^{-1}$$

where $\rho$ = density of the absorber (gm. cm$^{-3}$)
$\mu(E)$ = mass absorption coefficient (Photoelectric linear attenuation coefficient, cm$^2$. gm$^{-1}$) and is a function of energy.

The electron production rate in a volume element at altitude $h$ km is correspondingly given by

$$q(h) = \frac{\mu(E)\rho(h) \cdot I(h)}{Q} \cdot \text{electrons.cm}^{-3} \cdot \text{sec}^{-1} \quad \ldots (4.2)$$

where $Q = 0.035$ keV is the average energy for the production of an ion pair, $I(h)$ is the intensity of the X-ray source
at height $h$ and is related to its primary intensity $I_0$, by

$$I(h) = I_0 \exp \left[ - \mu(E) \int_h^\infty \left( \frac{\rho(H)}{\cos Z} \right) dH \right] = F \text{ (say)} \quad \ldots(4.3)$$

where $Z$ is the 'Local' zenith angle at $h$. Using a reasonable approximation for the curved atmosphere (for $H \gg h$ and actual zenith angle $z < 90^\circ$) $Z$ is obtained using the relationship

$$\cos Z = \left[ 1 - \left\{ \frac{R + h}{R + H} \cdot \sin z \right\}^2 \right]^{-\frac{1}{2}} \quad \ldots(4.4)$$

where $R = \text{Earth's radius} = 6371 \text{ kms}$. Thus, if a source has a spectrum of the form

$$J(E) \cdot dE = K \cdot f(E) \cdot dE \cdot \text{keV} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1} \quad \ldots(4.5)$$

The electron production rate due to X-rays having energy in the band $E_1$ to $E_2$ keV, at height $h$ and zenith angle $z$ is calculated from

$$q(h) = \frac{1}{Q} \cdot \frac{\rho(h)}{Q} \cdot I(h) \cdot \int_{E_1}^{E_2} \mu(E) \cdot K \cdot f(E) \cdot dE \cdot \exp \left[ - \mu(E) \int_h^\infty \rho(H) \cdot dH \right] \cdot \left\{ 1 - \left( \frac{R + h}{R + H} \cdot \sin z \right)^2 \right\}^{-\frac{1}{2}}$$

$$\text{electrons cm}^{-3} \cdot \text{sec}^{-1} \quad \ldots(4.8)$$
The electron production due to isotropic background X-rays whose spectrum can be described by

\[ J(E) \cdot dE \cdot d\Omega = K \cdot f(E) \cdot dE \cdot d\Omega \text{ keV cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \]

is obtained by integrating the contribution over all energy elements for the solid angle \( d\Omega \) over the zenith angle \( \theta \) and azimuths from 0 to \( 2\pi \).

Since,

\[ d\Omega = \sin \theta \cdot d\theta \cdot d\phi \cdot dz \]

we get

\[
q(h) = \frac{2\pi \rho(h)}{Q} \cdot K \cdot \int_{E_1}^{E_2} \mu(E) \cdot f(E) \cdot \int_0^{\pi/2} \sin \theta \cdot d\theta \cdot d\phi \cdot dz.
\]

The values of \( \mu(E) \) are taken from the tables computed by Victoreen (1949) and Henke et al (1967). The densities of the atmosphere at various heights used in these calculations are obtained from the 1965 CIRA model. The above equation is then integrated using the appropriate values for the various parameters and the electron production rates are then calculated for different X-ray sources. The X-ray data corresponding to Sco X-1 and Tau X-1 are taken from Gorenstein et al (1969) Chodil et al (1969), Reigler et al (1971). The calculated electron production rates for Sco X-1, galactic center and Tau X-1 are shown in figure 4.1 for two zenith angles, \( \chi = 0^\circ \) and \( \chi = \theta \), where \( \theta \) is the effective zenith angle at the point corresponding to the single hop reflection for VLF transmission between Tashkent and Ahmedabad.
FIG. 4.1 - THE FIGURE SHOWS THE ELECTRON PRODUCTION RATES PRODUCED DURING THE TRANSIT OF TAU X-1, SCO X-1 AND GALACTIC CENTER. THE CURVES ARE SHOWN BOTH FOR 0° ZENITH AND THAT CORRESPONDING TO MID OF SINGLE HOP POINT OF REFLECTION BETWEEN TASHKENT AND AHMEDABAD.
4.3. IONIZATION DUE TO OTHER SOURCES IN THE NIGHT TIME D-REGION:

As the effect due to X-rays from celestial sources depends on the magnitude of their ionization relative to that arising from other ionizing agencies in the night time ionosphere, a critical study of the role of the latter becomes necessary. The various ambient ionizing agencies responsible for the production of electrons in the nocturnal D-region are now identified to be

1. Diffuse cosmic X-rays
2. Galactic cosmic radiation
3. Ly$\alpha$ radiation
4. Ly$\beta$ radiation
5. Meteors.

In addition to the above, possible role of soft electron fluxes at D-region altitudes has been pointed out by Tulinov et al (1969) and Potemra and Zmuda (1970). Precipitation effects from Van Allen belts have been advocated as a source of these low energy electrons by Thomas (1971) and Aikin (1971). However, owing to the inconclusive nature of the evidence of the importance of these fluxes as a source of night time D-region ionization, especially at lower latitudes ($L \sim 1$ to 2) from where all the positive VLF observations of the celestial X-ray effect have been reported, this effect is left out of the present consideration.

In what follows, the effects of the above agencies are described one by one.
FIG. 4.2 - THE FIGURE SHOWS THE ELECTRON PRODUCTION RATES DUE TO DIFFUSE BACKGROUND X-RAYS AND ARE COMPARED TO THOSE PRODUCED BY GALACTIC COSMIC RAYS AT VARIOUS LATITUDES.
4.4. IONIZATION DUE TO THE DIFFUSE COSMIC X-RAYS:

The ionization due to the diffuse cosmic X-ray background in the energy range 1-10 keV can be estimated fairly accurately because of the reasonable accuracy of the available rocket observations in this energy range (Prakasarao et al 1971, Gorenstein et al 1969 and Boldt et al 1969). The electron production rate due to the diffuse cosmic X-ray flux is calculated on the basis of equation 4.7, assuming a spectral distribution of the type,

\[ \frac{dN}{dE} = 13.6 E^{-1.7} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1} \] \hspace{1cm} (4.8)

Such a spectral function is also consistent with that evaluated by Kasturirangan and Rao (1972) who have critically examined all the available data on the background X-ray flux. The resulting electron production rate is shown in figure 4.2. Since the effect due to difference between different atmospheric models is completely negligible below 100 kms (Francey 1970), the CIRA 1965 model of the atmosphere has been used in these calculations.

4.5. IONIZATION DUE TO GALACTIC COSMIC RAYS:

The role of the galactic cosmic radiation on the D-region ionization process was initially investigated by Webber (1962) in some detail. A more thorough analysis including the ionization effects of particles of higher charge numbers has been recently made by Velinov (1968) for locations corresponding to four different geomagnetic latitudes \( \lambda_m = 0^\circ, 30^\circ, 41^\circ \)
and $55^\circ$ for both solar maximum and solar minimum periods. The analysis shows that the electron production due to primary cosmic X-ray flux besides being dependent on the geomagnetic latitude and the degree of solar activity also exhibits seasonal variations due to changes in the density of the atmosphere at any particular altitude. Taking into account the observations of annual variations of the atmospheric density (Spencer et al 1964, Stroud and Nordberg, 1963) and the eleven year variation of the cosmic ray intensity, the calculations indicate that cosmic rays produce minimum ionization during winter of maximum solar activity period and maximum ionization in the summer of minimum activity period. The electron production rates by cosmic rays at geomagnetic latitudes $0^\circ$, $23^\circ$ and $55^\circ$ in the 60-100 kms range based on the calculation of Velinov (1968) are shown in figure 4.2. The extent of variation in the production rates resulting from the solar modulation effects of the cosmic radiation and the seasonal variation of the atmospheric densities are shown by the shaded areas.

4.6. IONIZATION FROM NIGHT TIME $\text{Ly}^\alpha$:

4.6.1. NIGHT TIME $\text{Ly}^\alpha$:

Another important and crucial source of night time D-region ionization, on which considerable uncertainty still exists, is the ionization due to $\text{Ly}^\alpha$ radiation. It is generally believed that 85% of the night time $\text{Ly}^\alpha$ emission originates from scattering of solar $\text{Ly}^\alpha$ by hydrogen in the
geocorona. The rest probably comes from galactic sources such as emission from gaseous nebulae (Tinsley 1969). The Ly$\alpha$ radiation produces ionization in the atmosphere through photo-ionization of nitric oxide (Nicolet and Aikin 1969). Hence a realistic evaluation of ionization due to Ly$\alpha$ requires an accurate knowledge of the night time Ly$\alpha$ intensity as well as the concentration of nitric oxide.

Available observational data on "scattered" Ly$\alpha$ intensity at the top of the atmosphere from various spacecrafts such as OGO III, OGO IV and OSO IV show the existence of a diurnal variation in the intensity of this component from 20 kR at noon down to about 1.1 kR at midnight (Meier, 1970). Over a solar cycle, a change by almost a factor of two in the solar Ly$\alpha$ intensity has also been reported by Hinteregger (1965). In the present case Ly$\alpha$ intensity of 1.1 kR ($\approx 1.5 \times 10^{-3}$ ergs cm$^{-2}$ sec$^{-1}$ sr$^{-1}$) for the solar minimum period and 2.7 kR ($3 \times 10^{-3}$ ergs cm$^{-2}$ sec$^{-1}$ sr$^{-1}$) for the solar maximum period are taken at the top of the atmosphere for the estimation of night time ionization in the D-region.

4.6.2. MOLECULAR OXYGEN DENSITY:

For the determination of the Ly$\alpha$ intensity in the 70-90 km altitude range, it is necessary to fold into calculations the absorption cross-section of O$_2$ $10^{-20}$ cm$^{-2}$ in the narrow band around 1216 $\AA$ (Watanabe 1958), i.e. the intensity of Ly$\alpha$ at any depth is essentially determined by the total molecular
Even though the estimation of molecular oxygen density at higher levels is dependent on the assumed model of the atmosphere, below 120 km altitude, where most of the Ly\alpha absorption takes place, all atmospheric models (CIRA 1965, US Standard 1966, Jacchia, 1970) essentially predict the same value. Further, direct experimental observations of molecular oxygen (Carver et al 1964, Wildman et al 1969, Brannon and Hoffman 1971) are found in good agreement (within 20%) with the molecular oxygen predicted by CIRA model, particularly at altitudes below 110 kms. The recent results measured using rocket borne Ly\alpha detectors in the height range 70-100 km by Subbaraya et al (1972) near geomagnetic equator are also in good agreement with the CIRA model. A diurnal variation of less than about 20% is indicated from the existing measurements (Weeks and Smith 1968) on the density of molecular oxygen.

4.6.3. NITRIC OXIDE DENSITY:

The principal difficulty in the estimation of the Ly\alpha ionization stems from the uncertainties in our knowledge of the NO density profile. Ly\alpha flux attenuated through absorption by molecular oxygen ionizes NO to produce electrons in the D-region ionosphere (Nicolet and Aikin 1960) according to the reaction:

\[ h \nu \ (\text{Ly}\alpha) + \text{NO} \rightarrow \text{NO}^+ + e^- \]
The cross section for the above reaction is $2 \times 10^{-18} \text{ cm}^2$ (Watanabe 1958). Owing to the fact that a realistic evaluation of the extent of contribution to the electron concentration in the night time D-region made through this reaction is most crucial to the present problem, an appraisal of the present status of our knowledge on NO density altitude profile appears to be appropriate.

The information on the NO concentration in the mesosphere has been derived by direct rocket observations of its resonance fluorescence day glow in the gamma bands $\gamma(1,0)$ band; Barth 1966, Pearce 1969, Meira 1971] and from the diurnal and solar cycle variations of the electron density in the D-region (Mitra 1966, Mitra 1968) as well as through photochemical considerations (Nicolet 1965, Wagner 1966). The day glow observations using rocket borne spectroscopic techniques have yielded results which seem to be conflicting with each other at altitudes below 90 km. The recent values of Meira are considerably lower than those from earlier measurements of Barth and Pearce. Revised values of Pearce (Thomas 1971) are, however, close to Meira's results. The major difficulty of interpreting the NO day glow measurements stems from complicated correction from the background radiation resulting from Rayleigh scattering. Meira's results show the NO density to be a minimum around 85 km and gives a value $\approx 10^7 \text{ cm}^{-3}$ for this altitude.
By identifying the atmospheric level at which the Lyα ionization predominates from an examination of the diurnal variation of the electron density profile, Mitra (1969) concludes that the NO density at 75 km should be around $7 \times 10^6$ cm$^{-3}$. Study of solar cycle variations in the electron density yields about $8 \times 10^5$ cm$^{-3}$ for NO concentration at 70 kms (Mitra 1966). Adopting other ionospheric methods such as the use of measured NO$^+$ and O$_2^+$ concentrations together with the relevant rate coefficients (Wagner 1966) or zenith angle variation in absorption (Parthasarathy and Larfald 1965) the NO density has been estimated to be in the range of $1-2 \times 10^6$ cm$^{-3}$ between 75 and 80 kms. These values are also consistent with those expected from photochemical considerations (Mitra 1969) although they are much higher than the earlier estimates of Nicolet and Aikin (1965). In table 4.1 we summarise the values of NO density estimated by different methods at heights around 75 km. It is seen from the table that the NO concentration estimates around this altitude, even though derived from different methods are all in fair agreement with each other, the mean value at 75 kms being $\approx 2 \times 10^6$ cm$^{-3}$.

In addition, some of the altitude profiles of NO concentration obtained by experimental observations and theoretical calculations are shown in figure 4.3. It is seen from this figure that considerable discrepancy exists in the existing data on the value of NO density at different
<table>
<thead>
<tr>
<th>Height (kms)</th>
<th>NO concentration (cm$^{-3}$)</th>
<th>Method of estimate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>$8 \times 10^5$</td>
<td>From solar cycle variation in electron density</td>
<td>Mitra (1966)</td>
</tr>
<tr>
<td>75</td>
<td>$2 \times 10^6$</td>
<td>From diurnal variation in electron density</td>
<td>Mitra (1968)</td>
</tr>
<tr>
<td>75</td>
<td>$2 \times 10^6$</td>
<td>From NO$^+$, O$_2^+$ measurements</td>
<td>Mitra (1968)</td>
</tr>
<tr>
<td>75</td>
<td>$1.8 \times 10^6$</td>
<td>From laboratory measurements of rate coefficients</td>
<td>Kistiakowsky and Volpi (1957)</td>
</tr>
<tr>
<td>75</td>
<td>$2 \times 10^6$</td>
<td>Same as above</td>
<td>Mavo rayannis and Winckler (1961)</td>
</tr>
<tr>
<td>75</td>
<td>$3.5 \times 10^6$</td>
<td>Same as above</td>
<td>Clyne and Thrush (1959)</td>
</tr>
<tr>
<td>75</td>
<td>$3 \times 10^7$</td>
<td>NO Air glow by rocket</td>
<td>Meira (1971)</td>
</tr>
<tr>
<td>80</td>
<td>$1 \times 10^6$</td>
<td>Zenith angle variation in absorption</td>
<td>Parthasarathy and Larfalde (1965)</td>
</tr>
<tr>
<td>80</td>
<td>$6 \times 10^7$</td>
<td>NO Air glow by rocket</td>
<td>Barth (1966)</td>
</tr>
<tr>
<td>80</td>
<td>$1.7 \times 10^7$</td>
<td>Same as above</td>
<td>Meira (1971)</td>
</tr>
<tr>
<td>84-100</td>
<td>$1 \times 10^6$</td>
<td>From NO$^+$, O$_2^+$ measurements</td>
<td>Wagner (1966)</td>
</tr>
<tr>
<td>85</td>
<td>$6 \times 10^7$</td>
<td>NO Air glow by rocket</td>
<td>Barth (1966)</td>
</tr>
<tr>
<td>85</td>
<td>$1.3 \times 10^7$</td>
<td>Same as above</td>
<td>Meira (1971)</td>
</tr>
</tbody>
</table>
FIG. 4.2 - THE FIGURE SHOWS THE VARIOUS PROFILES OF NO IN D-REGION. THE MEAN PROFILE IS PREDICTED ON THE BASIS OF VARIOUS ESTIMATES SHOWN BY POINTS. THE VALUE FITS THE ABSORPTION IN VLF TRANSMISSION SEEN DUE TO TRANSIT OF X-RAY SOURCES.
altitudes. We have therefore used a profile similar to that of Meira but with the value of NO density normalised to 2 x 10⁶ cm⁻³ at 75 kms, at which altitude as explained earlier, the agreement between different independent observations is quite good. Besides, the resulting profile of NO yields densities at other altitudes which are in satisfactory agreement with the corresponding values given in table 4.1. This is further justified by recent theoretical calculations of Strobel (1972a,b) who also has suggested a similar value of NO.

4.6.4. IONIZATION CALCULATIONS:

Ionization rate due to Lyα of intensity I photons cm⁻² sec⁻¹ sr⁻¹ can be computed using the equation,

\[ q(h) = 2 \pi \int_0^\infty N_{NO}(h) \sigma_i \int_0^{89} \exp \left[-\sigma_a \sec Z \right] N_{O_2}(h) \sin Z \, dz \, dh \]

where \( N_{NO}(h) \), \( N_{O_2}(h) \) are the number density of NO and O₂ as a function of h. \( \sigma_i \) is the ionization cross-section of NO at 1216 Å (taken to be 2 x 10⁻¹⁸ cm²) \( \sigma_a \) is the absorption cross section of O₂ at 1216 Å (taken to be 10⁻²⁰ cm²) and Z is the effective zenith angle. In figure 4.4 the electron production rates as a function of altitude are shown for the NO distribution discussed earlier in the cases when Lyα intensities are determined by the molecular oxygen distribution as defined by CIRA 1965 model and by Brannon and Hoffman (1971) measurements. The effect of Lyα intensity variation with
solar cycle is also shown in this figure. The maximum difference in electron production rates due to different molecular oxygen distributions is found to be less than \( \sim 20\% \).

4.7. IONIZATION DUE TO Ly\( \beta \):

Besides Ly\( \alpha \), Ly\( \beta \) component could also cause some degree of ionization. But the high absorption cross section of molecular oxygen, \( \propto 1.5 \times 10^{-18} \text{ cm}^2 \), for this radiation (Young et al 1968) results in the flux of Ly\( \beta \) at depths below 90 kms to be too negligible to cause significant ionization.

4.8. IONIZATION DUE TO METEORS:

Unlike the first three agencies, the ionization effect from meteors is sporadic. Considerable uncertainties exist about the degree of ionization from meteors. However, it is believed that the effect should be much less than \( 10^{-3} \text{ cm}^{-2} \text{ sec}^{-1} \) electrons (Thomas 1971). Owing to the highly infrequent nature of this source, it is not considered in the present work.

4.9. THE ELECTRON DENSITY PROFILES:

Equilibrium density of electrons \( N_e \) from the electron production rate \( q_j \) is calculated using the well known continuity equation

\[
\frac{dN_e}{dt} = \frac{q_j}{1 + \lambda} - (\kappa_e + \lambda \kappa_i). N_e^2 \quad \ldots(4.10)
\]

where \( \kappa_e \) is the ion electron recombination coefficient, \( \kappa_i \) is the ion-ion recombination coefficient and \( \lambda \) is the
ratio of ion density to electron density. The above equation under equilibrium conditions reduces to

\[
\frac{dN_e}{dt} = 0 \quad \ldots(4.11)
\]

or \( \frac{\sum q_i}{N^2_e} = (1 + \lambda) \cdot (\alpha_e + \lambda \alpha_i) \)

\[
= (1 + \lambda) \alpha_{\text{eff}}
\]

\[
= \gamma \quad \text{(say)} \quad \ldots(4.12)
\]

where \( \alpha_{\text{eff}} \) is the effective recombination coefficient.

When \( \lambda \ll 1 \),

\[
\gamma = \alpha_{\text{eff}}
\]

and equation for the equilibrium becomes

\[
\frac{\sum q_i}{N^2_e} = \gamma \quad \ldots(4.13)
\]

Owing to the large uncertainties in the value of the recombination coefficient for the night time D-region, the exact evaluation of the night time electron density profile from the known electron production rates is rendered difficult. Therefore, an attempt has been made to obtain a quantitative estimate of the electron density increase for the transit of a X-ray source such as Sco X-1 in the night time ionosphere by comparing the directly measured electron density profile with the calculated electron production rates.

The experimental observations of the night time D-region electron density profile are rather meagre. In figure 4.5,
FIG. 4.4 - THE FIGURE SHOWS THE ELECTRON PRODUCTION RATE DUE TO NIGHT TIME Lyα DURING SOLAR MINIMA AND MAXIMA.

FIG. 4.5 - THE FIGURE SHOWS A COMPILATION OF NIGHT TIME ELECTRON DENSITY.
some of the available measurements of night time electron density profiles are compiled. The results of Deeks (1966) are obtained from ground based measurements at mid latitudes using VLF propagation technique and are representative of the electron density during the low solar activity. The measurement of Mechty and Smith (1968) correspond to rocket borne probe techniques. The results of the rocket observations of night time ionosphere over the geomagnetic equator in India by Subbaraya et al (1971) using Langmuir probes are also plotted in this figure.

It is apparent from figure 4.5 that the existing measurements are grossly inadequate for resolving the nature of long term variations of the night time D-region electron density which is controlled principally by varying solar activity. Such changes are expected because of the intensity variations of Lyα and galactic cosmic rays over a solar cycle as pointed out earlier. The difficulty could be partially explained by the uncertainties in the normalisation of the different experimental results obtained by using a variety of techniques. Under these circumstances the rocket results of Subbaraya et al (1971) have been used down to 80 kms and summer values of Deeks (1966) have been used between altitudes 75 and 80 kms as representative of the electron density distribution over low and mid-latitudes in computations involving Sco X-1 and galactic center group of sources.
The specific choice of the former results is owing to the fact that the measurement was done in August 1971, around which period of the year, the night time observations on Sco X-1 and galactic center are possible from Ahmedabad. For calculations of the Tau X-1 effects, the winter profile of Deeks (1966) is used for the same reason. Using these observed values of $N_e$ and the computed value of $q_j$ corresponding to ambient ionizing agents $\sum q_j \text{ (ambient)}$, the values of recombination coefficient ($\psi$) for different altitudes are calculated by

$$\psi = \frac{\sum q_j \text{ (ambient)}}{N_e \text{ (ambient)}} \quad \ldots(4.14)$$

The altitude dependence of $q_j$ for different stable sources of ionization are shown together with $q_j \text{ (ambient)}$ in figure 4.6 and are representative of the quiet conditions. The galactic cosmic ray effect, corresponds to $\lambda_m = 23^\circ$ that of Gulmarg, India. All the subsequent discussions will be in relation to this location as the point of single hop reflection of the 164 KHz VLF waves transmitted from Tashkent and received at Ahmedabad should be situated above this place, which is midway between these two stations.

The electron density enhancements due to X-rays from Sco X-1, Galactic Centre and Tau X-1 sources at $10^\circ$, $45^\circ$ and $60^\circ$ zenith angles respectively, correspond to meridian transit of these sources over Gulmarg. These have been calculated using the values for the recombination coefficients at different
Table 4.2

<table>
<thead>
<tr>
<th>Height (kms)</th>
<th>Ambient production rate ( (q_1+q_2+q_3) ) ( \text{cm}^{-3} \text{sec}^{-1} )</th>
<th>Ambient electron density* ( N_e ) ( \text{cm}^{-3} )</th>
<th>Electron density increase due to Sco X-1 ( q(h) ) ( \text{cm}^{-3} \text{sec}^{-1} )</th>
<th>Sco X-1 ( \Delta N ) ( \text{cm}^{-3} )</th>
<th>Sco X-1 ( q(h) ) ( \text{cm}^{-3} \text{sec}^{-1} )</th>
<th>G.C. ( \Delta N ) ( \text{cm}^{-3} )</th>
<th>Sco X-1 ( \Delta N ) ( \text{cm}^{-3} )</th>
<th>G.C. ( q(h) ) ( \text{cm}^{-3} \text{sec}^{-1} )</th>
<th>Electron density increase due to Tau X-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.0</td>
<td>2.995x10^{-3}</td>
<td>6.4</td>
<td>1.21x10^{-3}</td>
<td>1.65x10^{-4}</td>
<td>1.134</td>
<td>0.175</td>
<td>7.0</td>
<td>1.15x10^{-4}</td>
<td>0.133</td>
</tr>
<tr>
<td>77.5</td>
<td>2.675x10^{-3}</td>
<td>7.0</td>
<td>1.365x10^{-3}</td>
<td>1.95x10^{-4}</td>
<td>1.603</td>
<td>0.251</td>
<td>9.6</td>
<td>1.25x10^{-4}</td>
<td>0.223</td>
</tr>
<tr>
<td>80.0</td>
<td>2.413x10^{-3}</td>
<td>7.0</td>
<td>1.500x10^{-3}</td>
<td>2.20x10^{-4}</td>
<td>1.915</td>
<td>0.313</td>
<td>9.4</td>
<td>1.36x10^{-4}</td>
<td>0.263</td>
</tr>
<tr>
<td>82.5</td>
<td>2.287x10^{-3}</td>
<td>7.0</td>
<td>1.565x10^{-3}</td>
<td>2.42x10^{-4}</td>
<td>2.085</td>
<td>0.361</td>
<td>15.0</td>
<td>1.43x10^{-4}</td>
<td>0.470</td>
</tr>
<tr>
<td>85.0</td>
<td>2.284x10^{-3}</td>
<td>10.0</td>
<td>1.600x10^{-3}</td>
<td>2.55x10^{-4}</td>
<td>3.040</td>
<td>0.540</td>
<td>600.0</td>
<td>1.42x10^{-4}</td>
<td>18.300</td>
</tr>
<tr>
<td>87.5</td>
<td>2.674x10^{-3}</td>
<td>2.0x10^{-3}</td>
<td>1.580x10^{-3}</td>
<td>2.60x10^{-4}</td>
<td>523.0</td>
<td>95.0</td>
<td>700.0</td>
<td>1.40x10^{-4}</td>
<td>18.100</td>
</tr>
<tr>
<td>90.0</td>
<td>3.458x10^{-3}</td>
<td>8.0x10^{-3}</td>
<td>1.480x10^{-3}</td>
<td>2.45x10^{-4}</td>
<td>1560.0</td>
<td>278.0</td>
<td>500.0</td>
<td>1.35x10^{-4}</td>
<td>9.700</td>
</tr>
</tbody>
</table>

* \( N_e \) taken from Subbarya et al and Deeks (summer)  
** \( N_e \) taken from Deeks (winter)
FIG. 4.6 - THE FIGURE SHOWS THE ELECTRON PRODUCTION RATE DUE TO ALL QUIET TIME AGENCIES AND COMPARES TO THOSE OF SCO X-1, TAU X-1 AND G.C.

FIG. 4.7 - THE FIGURE SHOWS THE RATIO $\frac{N_{\text{quiet}} + N_{\text{source}}}{N_{\text{quiet}}}$ FOR TAU X-1 AND SCO X-1 FOR THEIR TRANSIT OVER 31° LATITUDE.
altitudes derived from equation 4.14.

The estimates of ambient $q_j \geq q_j$ and the $q_j$ (source), due to both Sco X-1 and Tau X-1 X-ray sources are shown in table 4.2. The table also tabulates the electron density increases at different altitudes for these sources. As the relative absorption effect due to celestial X-ray sources such as Sco X-1 depends only on the relative contribution compared to the ambient ionization, uncertainties in the values of the ambient electron density should have little effect on the final result. The electron density increases over the ambient values at 85 kms altitude as a function of time, around the time of the meridional transit of these sources are shown in figure 4.7.

4.10. 164 KHz VLF OBSERVATIONS AT AHMEDABAD:

In this section, attempt is made to explain the observed attenuation of the VLF radio waves, correlated with the time of transit of Sco X-1, galactic centre and Tau X-1, in terms of the electron density enhancements estimated in the previous section. Typical records showing the variations of the field strength as a function of time for the 164 KHz radio waves from Tashkent registered at Ahmedabad, associated with the passage of these X-ray sources are presented in figure 4.8. On an average basis, the nature of the effect is shown in figure 4.9 and is deduced by superposed epoch analysis of the daily records over a large number of days. In what follows, a brief outline of the main considerations relevant
Figure shows the actual record of VLF transmission at 164 kHz at the time of (upper) SCO X-1 (lower) TAUX-1. Each vertical line represents 15 minute.
to the calculations are given. The complete details of the calculations are published elsewhere (Chakravarty, 1971).

Calculation of absorption is made by deriving the values of complex reflection coefficients of the D-region for the propagation of low frequency waves. Considering the electric field components parallel and perpendicular to the plane of incidence, two reflection coefficients, $R_{\parallel}$ (Parallel R Parallel) and $R_{\perp}$ (Parallel R Perpendicular) are defined to represent the reflected wave, with the first subscript representing the direction of the electric field in the incident wave and the second one that for the reflected wave. In the case of 164 KHz Tashkent signal received at Ahmedabad, the angle of incidence works out to be $80-85^\circ$ for the single hop geometry. The signal intensity measured will correspond to the reflection coefficient as the receiving antenna system is directed so that its main lobe lies in the plane of incidence. Also from a series of long wave radio observations by Bracewell et al (1951) and Belrose (1957) it has been concluded that the reflection coefficient $R_{\parallel}$ in the day time is few orders of magnitude higher than that of $R_{\perp}$ for long transmitter receiver distances. However, in the night time, these two quantities may be of the same order (Belrose 1968). Since we register only the $R_{\parallel}$ in our measurements, the present calculations are limited to $R_{\parallel}$ only, and should, to a good approximation, represent the waves received at Ahmedabad.
For a realistic treatment of the long wave propagation through the ionosphere at oblique incidence, it is necessary to consider the partial reflections from a range of heights rather than the sharp reflection from a particular height. The wave admittance method developed by Barron and Budden (1955) which deals with the problem of such a nature is therefore used here to compute the reflection coefficients. The initial value of the coefficient is determined by considering a height well above that of reflection using the sharply bound model of Sheddy (1968) and involves the solutions of Book's quartic equations (1938). Final value of admittance is obtained by numerically integrating the differential equations representing the variation of admittance with altitude resulting from the changes in electron density and collision frequency. A modified Runge-Kutta method given by Gill (1951) has been used for such an integration. The numerical integration is stopped at a height where the electron density is practically zero. The final value of the wave admittance for the radio waves leaving the ionosphere so calculated gives the final effective value of $\| R_\parallel \|. This in turn can give the total absorption in decibels using the formula

$$ L = -20 \log \| R_\parallel \| \quad \ldots (4.15) $$

The collision frequency profile used in these calculations is taken from the experimental results of Deeks (1966). This profile is also in good agreement with that derived from the theoretical calculations of Sen and Wyler (1960).
FIG. 4.9 - THE FIGURE SHOWS THE CHREE ANALYSIS OF LARGE NUMBER OF DAYS (SUPERPOSED ON EACH OTHER AFTER CORRECTION OF TRANSIT TIME OF SOURCES) FOR SCO X-1 AND TAU X-1. THE EFFECT IN CASE OF SCO X-1 LOOKS TO BE SHIFTED LATER AND IS EXPLAINED IN TEXT DUE TO G.C.
### Table 4.3

<table>
<thead>
<tr>
<th>Source</th>
<th>Calculated excess peak absorption (dB)</th>
<th>Observed excess peak absorption (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sco X-1</td>
<td>4.2</td>
<td>--</td>
</tr>
<tr>
<td>Galactic center</td>
<td>1.5</td>
<td>--</td>
</tr>
<tr>
<td>Sco X-1 + Galactic center</td>
<td>4.4</td>
<td>7</td>
</tr>
<tr>
<td>Tau X-1</td>
<td>1.2</td>
<td>4</td>
</tr>
</tbody>
</table>

Determination of the magnitudes of absorption for the 164 KHz radio waves are made both for the normal electron density profiles when there is no irradiation of the ionosphere by the cosmic X-ray sources as well as for the enhanced electron density conditions arising from the passage of these sources. The effect of the transit of these sources on the VLF propagation is then evaluated as the difference in the absorption values for the enhanced and normal conditions of electron density. In table 4.3, values so obtained are shown together with those of direct observations for Sco X-1, Galactic center and Tau X-1.

As is evident from the theoretically computed time profile of the effect shown in figure 4.7 and its observational counterpart in figure 4.8, the density enhancements should be present for about 2-3 hours on either side of the meridian transit of these sources. In addition, owing to the fact that the galactic center meridian transit takes place 1 hour 25 minutes after the transit of Sco X-1, in the records
THE OBSERVED PROFILE IS COMPARED WITH CALCULATED.

FIG 4.10 - THE PROFILE OF THE FIELD STRENGTH VARIATION DUE TO TRANSIT OF SCO X-1.
such as that presented in figure 4.8, the effects from these two sources are seen as a composite one. Further, it may be noted that this composite effect is seen as a shift in the time of peak absorption, by 20-30 minutes, subsequent to the time of transit of Sco X-1, in the registered 164 KHz data and agrees reasonably well with the computed time profile of electron density at 85 kms shown in figure 4.10. The calculated peak absorption for the resultant effects is 4.4 dB and compares favourably with the observed absorption of 6 to 7 dB in the case of Sco X-1 and galactic center.

In the case of Tau X-1, the agreement between the calculated and observed peak absorption values is less striking. Nevertheless the result of the computation shown in figure 4.7 leads to the conclusion that the expected duration of the effect should be longer for Tau X-1 compared to that for Sco X-1. On an average basis, this aspect is also conspicuous in the observational results presented in figure 4.8 and 4.9.

4.11. DETECTION OF FLARE STARS:

As already pointed out, there exists a class of sources that could be characterized as 'X-ray Novae'. These sources have the property of sudden appearance, sharp intensity increases going through a maximum and disappearance like optical novae. For most of such known sources like Cen X-4, Cen X-2 the intensity at the peak is comparable to or more than that of Sco X-1. Foregoing considerations with regard
FIG. 4†† - IN THIS FIGURE THE ELECTRON PRODUCTION RATE DUE TO TRANSIT OF CEN XR-4 AND SCO X-1 AND GALACTIC CENTER ARE COMPARED. $X = 60, \chi = 46$ CORRESPONDS TO TRANSIT OVER LATITUDE 31°N.
to the ionospheric effect of X-ray sources clearly indicate the possibility that the nova like X-ray sources could be detectable through their effects on the D-region ionosphere. Figure 4.11 shows the results of the calculation of the electron production rate arising due to X-rays from Cen X-4 corresponding to the peak of its emission for $\chi = 60^\circ$. For comparison, the production rates due to Sco X-1 are also shown from which it is clear that the effects from these two sources are comparable. The VLF data for the corresponding period available at Ahmedabad however did not reveal any positive indications. However, it may be noted that the quality of the available data at this time was rather poor and hence definite conclusions could not be drawn. For the same source, there is at least one report of successful ionospheric detection (Kaufman et al. 1972).

A similar analysis was made in connection with Cet X-2 (intensity 0.8 of Sco X-1) which because of its low zenith angle at the meridional transit point over Gulmarg could produce almost the same electron density perturbations as Sco X-1 (figure 4.13). Search of the corresponding VLF data revealed the associated field strength variations demonstrating significant electron density fluctuations. Figure 4.12 shows the results of the superposed analysis of the VLF data corresponding to the transit of Cet X-2 for a number of successive days around the time of its maximum X-ray emission. Evidence as obtained from this analysis is again quite strong for the possible ionospheric detection of X-ray sources. It is also
FIG. 4.12. THE FIGURE SHOWS THE SUPERPOSED EPOCH ANALYSIS OF THE VLF DATA CORRESPONDING TO THE TIME OF TRANSIT OF CET X-2 X-RAY SOURCE.
FIG: 4.3
THE ELECTRON PRODUCTION RATE FOR NOVA-LIKE SOURCE CET X-2 IS SHOWN.
CALCULATIONS CORRESPOND TO $\chi = 0$ AND $\chi = 27^\circ$ OF SOURCE TRANSIT.
interesting to note that this is the only alternate evidence for Cet X-2 other than the rocket detection by Shukla and Wilson (1971).

**4.12. DETECTION OF GAMMA RAY BURSTS:**

Detection of gamma ray bursts of cosmic origin by detectors on board Vela, OGO, IMP-6 and OSO-7 satellites (Kelebesadal et al 1973, Cline et al 1973, L'Heuneux et al 1974) is one of the major surprises of observational astronomy in the recent times. Dictated by the response characteristics of these satellite detectors, the bursts were observed over the energy range 7 keV to 1.5 MeV and further, were found to have the time durations ranging from less than a second to about 80 seconds with integrated flux density lying between a few times $10^{-5}$ and $3 \times 10^{-4}$ ergs sec$^{-1}$ cm$^{-2}$ for different events. Even though their spectra at high energies can be grossly represented by an exponential function the complex time structure with a time scale as short as 16 millisecond seen in their time profiles show the similarity with impulsive X-ray emission often observed during solar flares. Coincidently between spatially separated satellite observations have served to identify genuine events from spurious ones. From the twenty events that have been thus detected so far from data accumulated over 5 years, it is found that these events are distributed almost isotropically on the celestial sphere and occur at a frequency of about five per year, at the level of sensitivity of vela satellite instrumentation. A number of
theories have been proposed, none of which is entirely satisfactory due to the nature of insufficient observations that exist today. In view of the fact that so far no positive associations could be established with other well known transient phenomena (Klebesdal et al 1973, Cline et al 1973b) such as super novae, galactic noise spikes, rapid atmospheric fluorescence increases, Cyg X-3 flare type of events or even with gravitational radiation events, continuous petrol for detecting these events is very important to understand the nature of their origin. Further the importance of carrying out such a patrol through as many independent techniques as possible needs hardly any emphasis from the standpoint of increasing the efficiency of sky coverage and establishing the genuineness of each of these events.

We have, therefore, searched effects on the VLF propagation characteristics in the D-region of ionosphere which is already described in earlier sections. Besides providing a simple ground based technique for monitoring these transient celestial events, such detection, could give valuable information on the source position, if data from different propagation paths could be related. Moreover, the monitoring by this method could establish the frequency of these bursts at the energies to which D-region (2-10 keV) is most sensitive and where no meaningful spacecraft data exists.
FIG. A.14. THE FIGURE SHOWS THE ELECTRON PRODUCTION RATE DUE TO γ-RAY BURST OF 14 MAY 1972 CORRESPONDING TO THE ZENITH OF THE SOURCE AT 0° AND 40°. THE ELECTRON PRODUCTION RATE DUE TO SCO X-1 ARE ALSO SHOWN FOR COMPARISON.
FIG. 4.15 - SHOWS THE CHART ON WHICH VLF SIGNAL FROM TASHKENT IS RECORDED. THE ARROW POINTS TO THE TIME OF OCCURRENCE OF GAMMA RAY BURST ON 28TH MARCH 1972.
To investigate the effects of these bursts on VLF propagation the records taken during the night time between 1900 hours LMT and 0700 hours LMT were searched corresponding to those events which occurred during this period. This is because they could be identified unambiguously in the absence of solar effect. Table 4.4 summarises the results of such a search for a number of bursts selected on the above criterion. From the table it can be seen that there was no observable field strength variations associated with any of the above events. Figure 4.15 shows the relevant portion of a typical field strength recorded at Ahmedabad corresponding to the time of occurrence of the event dated March 28, 1971. The hatched portion shows the expected time profile of the VLF field strength, if the X-ray burst event under consideration had an observable effect on the lower D-region ionosphere.

The absence of a sharp fall in the field strength corresponding to the time scale of the event shows that the X-rays from this event did not have any observable influence on the ionization of the D-region and hence all these events which are not detected through their effect on ionosphere do not sufficiently influence the D-region. This can be understood from the estimated electron production rates in the D-region for a typical event such as of May 14, 1972 for which detailed spectral data (Wheaton et al 1973) are available above 7 keV. Owing to the fact that the atmospheric region between 70 and 90 kms altitude is most responsive to X-rays between 1-10 keV.
<table>
<thead>
<tr>
<th>Vela event No.</th>
<th>Date of observation</th>
<th>U.T. Hr.Mt.</th>
<th>Duration Sec.</th>
<th>Position coordinates for 3 S/C coincidences</th>
<th>Circle of position for 2S/C coincidences</th>
<th>Estimated flux (ergs.cm⁻²)</th>
<th>Observability of the event from the reflection point</th>
<th>Whether the effect is seen</th>
</tr>
</thead>
<tbody>
<tr>
<td>69-4</td>
<td>17-10-1969</td>
<td>21 42</td>
<td>1.5</td>
<td>α₁, δ₁, α₂, δ₂</td>
<td>α, δ</td>
<td>4 x 10⁻⁵</td>
<td>Uncertain</td>
<td>No</td>
</tr>
<tr>
<td>70-2</td>
<td>22-8-1970</td>
<td>16 50</td>
<td>10</td>
<td>143 65 205 25</td>
<td>-</td>
<td>1 x 10⁻⁴</td>
<td>Not visible</td>
<td>No</td>
</tr>
<tr>
<td>70-3</td>
<td>1-12-1971</td>
<td>20 01</td>
<td>-</td>
<td></td>
<td>91 -30</td>
<td>4 x 10⁻⁵</td>
<td>Visible</td>
<td>No</td>
</tr>
<tr>
<td>71-1</td>
<td>2-1-1971</td>
<td>19 11</td>
<td>10</td>
<td>Poor intersatellite timings</td>
<td>1 x 10⁻⁴</td>
<td>Uncertain</td>
<td>No</td>
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</tr>
<tr>
<td>71-3</td>
<td>18-3-1971</td>
<td>15 28</td>
<td>30</td>
<td>75 -5 100 -60</td>
<td>1 x 10⁻⁴</td>
<td>Uncertain</td>
<td>No</td>
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</tr>
<tr>
<td>72-1</td>
<td>17-1-1972</td>
<td>17 39</td>
<td>30</td>
<td>104 +9 136 -29</td>
<td>7 x 10⁻⁵</td>
<td>Visible</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>72-2</td>
<td>12-3-1972</td>
<td>15 53</td>
<td>-</td>
<td>277 +1 298 +35</td>
<td>5 x 10⁻⁵</td>
<td>Not visible</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>72-3</td>
<td>28-3-1972</td>
<td>13 46</td>
<td>-</td>
<td></td>
<td>283 22</td>
<td>1 x 10⁻⁴</td>
<td>Uncertain</td>
<td>No</td>
</tr>
<tr>
<td>72-5</td>
<td>1-11-1972</td>
<td>18 57</td>
<td>-</td>
<td>11 +19 309 -56</td>
<td>7 x 10⁻⁶</td>
<td>Uncertain</td>
<td>No</td>
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</tr>
<tr>
<td>73-2</td>
<td>10-5-1973</td>
<td>-</td>
<td></td>
<td></td>
<td>25 -36</td>
<td>1 x 10⁻⁴</td>
<td>Uncertain</td>
<td>No</td>
</tr>
</tbody>
</table>

α and δ are right ascension and declination respectively in degrees.
(Swider, 1969) we have extrapolated the observed power law number spectrum down to 1 keV for this calculation. Recent observations down to about 2 keV by Appollo 16 justify such an extrapolation (Peterson, LE; private communication). The electron production rates are shown in figure 4.14 for two zenith angles viz. \( \chi = 0^\circ \) and \( \chi = 40^\circ \) together with that of Sco X-1 at \( \chi = 45^\circ \) for comparison. Even though the second peak of the burst appears to be comparable to that from Sco X-1, the average production integrated over the duration of burst (\( \sim 65 \) sec) is found to be at least a factor of two lower and the altitude of maximum production is at \( \sim 70 \) km compared to 85 km due to Sco X-1. An important consequence of such a profile is that the peak electron production rate for these type of bursts results in low equilibrium electron densities owing to the high value of recombination coefficients. The value of recombination coefficients at 70 kms is orders of magnitude higher than that at 85 kms where X-rays from Sco X-1 have maximum influence and where much higher equilibrium electron densities could be produced. Estimates show that the electron density enhancements arising from this burst is insignificant at 70 kms and is much less than 5% over the ambient value at 85 kms. Because of the fact that the burst under consideration is one of the strongest recorded so far, it is clear that the effects to be expected from the bursts listed in table 4.4 should be many magnitudes lower and this explains why it is not possible to detect them by their effect on D-region ionosphere.
In summary, following main conclusions emerge from the present investigation on the ionospheric effects of nonsolar X-ray and gamma emission from the astronomical standpoint:

1) Evidence is quite strong both from the observational and theoretical standpoint for the detection of ionospheric effect due to strong celestial X-ray sources especially from observations at low latitudes. Presently available evidence shows that the contribution to night time ionization of equatorial D-region ionosphere from cosmic X-rays, cosmic rays and Lyα are comparable with each other. There is also reasonable agreement between the theoretically expected nature of the effect and the experimental observations of VLF propagation.

2) The effect of these sources persists for about 2-3 h on either side of the time corresponding to the peak effect, the extent of spread depending on the declination of the source as well as the nature of its energy spectrum. Also the effect of all the sources clustered in intervals of an hour or so in right ascension is seen as a composite one, with the time of peak absorption suitably shifted with respect to the time of expected peak effect from individual sources. In other words, the ionosphere behaves as an X-ray telescope with a large opening angle so far as the transit of celestial sources are concerned.
3) In general, since the contribution from Ly α can become significant during disturbed periods, the effect of celestial X-ray sources should be more frequently observed during solar quiet periods.

4) On an average basis, it should be possible to study systematic long term variations of the intensity of strong X-ray sources, in the time scales of a few months to a few years, using the data on VLF propagation. Study of the systematic day to day variations, however, may be difficult owing to our insufficient knowledge of the variabilities of the corresponding D-region processes.

5) There now exists a real possibility for the detection of such rare celestial events as flaring X-ray stars or supernovae through their transient ionospheric effects using ground based VLF observations.

6) The recently detected cosmic gamma ray bursts however appear to be incapable of producing significant electron density perturbation at D-region altitudes so as to modify VLF propagation characteristics.

7) The controlled irradiation of the ionosphere provided by the discrete celestial X-ray sources, should be of immense value towards understanding the physical processes in the night time D-region. One could, for example, reverse some of the previous calculations and derive the night time
4.46: recombination coefficient at D-region altitudes by relating the observed excess absorption of VLF waves due to X-ray sources with the corresponding computed electron production rate profile.

8) Owing to the fact that NO is a very important minor constituent at D-region altitudes for deciding the ambient electron density, accurate knowledge of its altitude ion-concentration profile is very vital. It is interesting to note that the detectability of X-ray sources implies a concentration of NO at least a factor of 5-10 lower than that determined by the direct experiments.