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POSSIBILITY OF CONTINUOUS MONITORING OF CELESTIAL X-RAY SOURCES THROUGH THEIR IONIZATION EFFECTS IN THE NOCTURNAL D-REGION IONOSPHERE

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Abstract. The electron production rates in the night-time D-region arising from the transit of strong celestial X-ray sources Sco X-1, Tau X-1 and Galactic Center are estimated and compared with the ambient electron production rates resulting from other known stable agencies. Using the experimentally measured values of the night-time electron densities, the number of additional electrons/cc expected from the passage of these sources is computed. For the 164 kHz transmission from Tashkent, received at Ahmedabad, the associated enhancement in the attenuation is calculated using the full wave admittance technique of Barron and Budden. Reasonable agreement is shown to exist between the calculated values of the attenuation and those of direct observations.

1. Introduction

Opinions published in the literature regarding the importance of X-rays from stellar sources like Sco X-1 to the nocturnal D-region ionization are conflicting. While the ground-based experimental observations of Ananthakrishnan and Ramanathan (1969), Edwards *et al.* (1969) and Kaufmann *et al.* (1970) on Sco X-1 and other X-ray sources such as Cen XR-2 and Cen XR-4 using VLF propagation techniques indicate that the effect of X-ray sources on the night-time ionosphere is an observable phenomenon, those of Burgess and Jones (1969) suggest otherwise. Theoretically, comparing the relative contributions from ambient ionizing agents like Lα radiation and galactic cosmic rays to the electron production rates in the night-time D-region, with that expected from Sco X-1, Poppoff and Whitten (1969) have ruled out the effectiveness of the extra solar X-ray sources in producing significant electron density perturbations over the ambient conditions. The above authors have also objected to the interpretation by Ananthakrishnan and Ramanathan (1969) on the basis of the observed time profile. From a similar, but more detailed analysis, Francey (1970) has shown 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 depends on the assumed concentration of NO (which is ionized by Lα) in the 80–90 km region. That is, the observability of the effect due to strong celestial X-ray sources like Sco X-1 depends on the magnitude of their ionization effect in relation to that from all other causes and in particular to the magnitude of ionization due to Lα.

Considerable uncertainties exist in the experimentally observed values of the different parameters responsible for the night-time ionization. Nevertheless, in view of the

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strong experimental evidence obtained at Ahmedabad and elsewhere for the detectability of the effects from 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 in mind, we have re-examined the role of different ionization agencies in the night-time D-region processes with particular reference to the effects of celestial X-ray sources. In the first section of the paper, 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 of the relevant parameters. In the second section, the effect of the transit of strong X-ray sources Sco X-1 and Tau X-1 is evaluated in terms of the electron density enhancements. The contribution expected due to X-rays from galactic center is also estimated. The calculation of the electron densities is made by a direct comparison of the electron production rates by different ambient ionizing agencies with the experimentally measured electron densities. In the concluding section, we have attempted to quantitatively relate the observed VLF absorption of the 164 kHz signal from Tashkent recorded at Ahmedabad to the computed ionization effects of the X-ray sources and demonstrate the satisfactory agreement between the observations and the theoretical calculations of the magnitude and time profile of VLF absorption.

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 the severe exponential absorption they undergo in the atmosphere during their transport downwards. In addition, whereas X-rays below 1 keV are considerably absorbed 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. The electron production rate due to X-rays at any altitude h km can be calculated using the formula

$$q(h) = \frac{\mu\varrho(h)\, I(h)}{Q} \text{ electrons cm}^{-3}\,\text{s}^{-1},$$

where $Q \approx 0.035$ keV is the average energy for the production of an ion pair in air, $\varrho(h)$ is the density of air in gm cm^{-3} at height h, μ is the mass absorption coefficient of X-rays in cm^2 gm^{-1} in the atmosphere and $I(h)$ is the intensity of the X-ray source in keV cm^{-2} s^{-1} at depth h.

Using the linear absorption coefficient defined as $\mu\varrho$ appropriate to the atmosphere having a composition and density as given by the 1965 CIRA model, the electron production rates for the X-rays from the two sources Sco X-1 and Tau X-1 as well

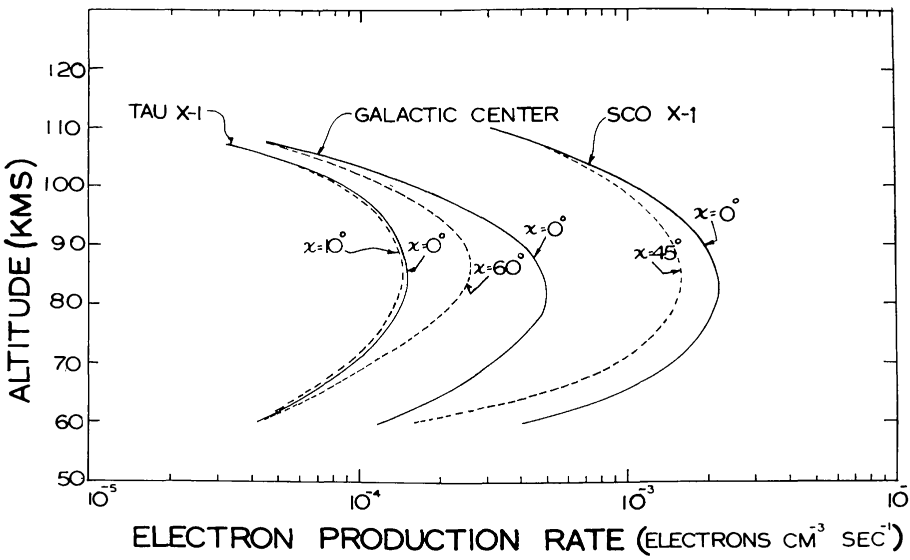

Fig. 1. The altitude profile of electron production rates due to Sco X-1, galactic center and Tau X-1. The production rates are given for the zenith angle $\chi = 0°$ and that corresponding to the meridional transit for the geographic location of 32°N latitude (mid-way between Tashkent and Ahmedabad; see text).

as from galactic center incident at various zenith angles have been calculated on the lines of Francey (1970) and are shown in Figure 1. The values of the relevant parameters of these sources used in the calculations are taken from the measurements of Gorenstein *et al.* (1969), Chodil *et al.* (1968), and Riegler *et al.* (1968).

3. Other Important Ionization Sources in the Night-Time D-Region

Since the observability of the effect due to X-rays from celestial sources depends on the magnitude of their ionization relative to that arising from other ionization 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 (*i*) diffuse cosmic X-rays (ii) galactic cosmic radiation (iii) Lα radiation and (iv) meteors.

In addition, the 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 on the importance of these fluxes as a source of night-ime D-region ionization, especially for lower latitudes ($L \sim 1$ to 2) from where all the positive VLF observations of the celestial X-ray effect have been reported, this aspect is left out from the present consideration.

A. THE DIFFUSE COSMIC X-RAYS

The ionization of D-region due to the isotropic cosmic X-ray background in the energy range 1–10 keV can be estimated fairly accurately. A number of background observations, mostly rocket-based, have been made on this radiation in this energy range (Boldt *et al.*, 1969; Gorenstein *et al.*, 1969; Prakasarao *et al.*, 1971). The electron rate due to the diffuse cosmic X-ray flux is calculated, again on the lines of Francey, but assuming a spectral distribution of the type,

$$dN/dE = 13.6\,E^{-1.7}\ \text{photons cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{keV}^{-1}$$

and is shown in Figure 2. Such a spectral function is also consistent with the recent findings of Kasturirangan and Rao (1972) who have critically examined all the available data on background X-ray flux. Since the effect due to the difference between different atmospheric models is completely negligible below ~100 km in these computations (Francey, 1970), we have used the CIRA 1965 model.

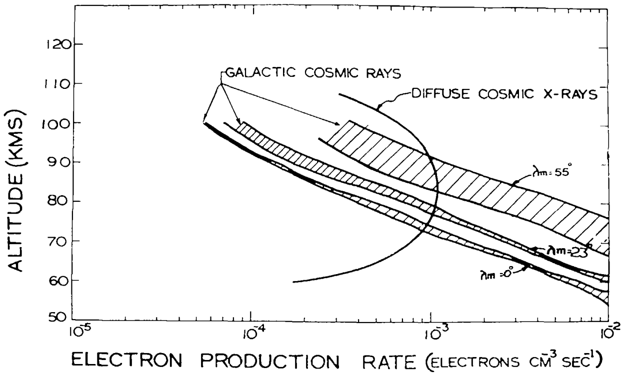

Fig. 2. Altitude profile of the electron production rate due to galactic cosmic rays and diffuse cosmic X-rays. The extent of variability of the galactic cosmic ray effect due to solar modulation of cosmic rays and the seasonal changes in the atmosphere is shown by shaded areas for geomagnetic latitudes $\lambda_m = 0°$, 23° and 55° – the minimum ionization corresponding to winter of maximum solar activity and the maximum corresponding to summer of solar minimum.

B. 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 recently been made by Velinov (1968) for locations corresponding to four different geomagnetic latitudes $\lambda_m = 0°$, 30°, 41° and 55°, for both solar maximum and solar minimum activity periods. The analysis shows that the electron production due to primary cosmic 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 11-yr variation of the cosmic ray intensity, the calculations indicate that cosmic rays cause minimum ionization during winter of maximum solar activity period and maximum ionization in summer of minimum activity period. The electron production rates by cosmic rays at geomagnetic latitudes 0°, 23° and 55° in the 60–100 km range are shown in Figure 2, and are based on the calculation of Velinov (1968). 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 shaded areas.

C. HYDROGEN Lα RADIATION

Another important and crucial source of night-time D-region ionization on which considerable uncertainty still exists, is the ionization due to Lα radiation. It is generally believed that 85% of the night-time Lα emission originates from scattering of solar Lα by hydrogen in the geocorona; the rest being probably from galactic sources such as emission from gaseous nebulae (Tinsley, 1969). The Lα radiation produces ionization at around 85 km in the atmosphere through photoionization of nitric oxide (Nicolet and Aikin, 1960). Hence a realistic evaluation of ionization due to Lα requires an accurate knowledge of the night-time Lα intensity as well as the concentration of nitric oxide.

Available observational data on 'scattered' Lα intensity at the top of the atmosphere from various spacecraft, such as OGO 3, OGO 4 and OSO 4, 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 Lα intensity has also been reported by Hinteregger (1965). In the present case, Lα intensities of 1.1 kR or $\sim 1.5 \times 10^{-3}$ ergs cm^{-2} s^{-1} sr^{-1} for the solar minimum period and 2.2 kR or $\sim 3 \times 10^{-3}$ ergs cm^{-2} s^{-2} sr^{-1} for the solar maximum period are assumed at the top of the atmosphere for the estimation of night-time ionization in the D-region.

For the determination of the Lα intensity in the 70–90 km altitude range, which is of relevance to the problem under study, it is necessary to fold into the calculations the absorption of Lα by molecular oxygen which has an absorption cross section of 10^{-20} cm^2 in the narrow band around 1216 Å (Watanabe, 1958), i.e. the intensity of Lα at any depth is essentially determined by the total molecular oxygen concentration above that height in the atmosphere. Even though the estimation of O_2 density at higher levels is dependent on the assumed model of the atmosphere, below 120 km altitude, where most of the Lα absorption takes place, all atmospheric models (CIRA, 1965; U.S. Standard, 1966; Jacchia, 1970) essentially predict the same value. Further, the direct experimental observations of molecular oxygen (Brannon and Hoffman, 1971; Carver *et al.*, 1964; Wildman *et al.*, 1969) are found to be in good agreement (within 20%) with the molecular oxygen concentration profile predicted by the CIRA model, particularly at altitudes below 110 km. The results of the recent measurements using rocket-borne Lα detectors in the height range 70–100 km by Subbaraya *et al.* (1972) near geomagnetic equator are also in reasonable 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.

The principal difficulty in the estimation of the Lα ionization stems from the uncertainties in our knowledge of the NO density profile. Lα flux attenuated through absorption by O_2 ionizes NO to produce electrons in the D-region ionosphere (Nicolet and Aikin, 1960) according to the reaction.

$$h\nu(\mathrm{L}\alpha) + \mathrm{NO} \rightarrow \mathrm{NO}^+ + e^- .$$

The cross section for the above reaction is 2×10^{-18} 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 problem under study, an appraisal of the present status of our knowledge on NO density height profile appears to be appropriate.

The information on the NO concentration in the mesosphere has been derived by direct rocket observations of the resonance fluorescence day glow in gamma bands (Barth, 1966; Pearce, 1969; Meira, 1971), from the diurnal and solar cycle variations of N_e in 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 the complicated correction for the background radiation resulting from Rayleigh scattering. Meira finds the NO density to be a minimum around 85 km and gives a value $\sim 10^7$ per cc for this altitude.

By identifying the atmospheric level at which the Lα ionization predominates from an examination of the diurnal variation of the electron density profiles, Mitra (1969) concludes that the NO density at 75 km should be around 2×10^6 per cc. Study of solar cycle variation in N_e, yields about 8×10^5 per cc for NO concentration at 70 km (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 (Parthasarthy and Larfald, 1965) the NO density has been estimated to be in the range of 1 to 2×10^6 per cc between 75 and 80 km. These values are also consistent with those expected from photochemical considerations (Mitra, 1969), though much higher than the earlier estimates of Nicolet and Aikin (1965). In Table I 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 km being $\sim 2 \times 10^6$ per cc.

In addition some of the altitude profiles of NO concentration obtained by experimental observations and theoretical calculations are shown in Figure 3. It is seen from this figure that considerable discrepancy exists in the existing data on the value of NO density at different altitudes. We have therefore used a profile similar to that of Meira but with the value of NO density normalized to 2×10^6 per cc at 75 km at which altitude, as explained earlier, the agreement between different independent

TABLE I

Height (km)	NO concentration (cm^{-3})	Method of estimate	Reference
70	8×10^5	From solar cycle variation in electron density	Mitra (1966)
75	2×10^6	From diurnal variation in electron density	Mitra (1968)
75	2×10^6	From NO^+, O_2^+ measurements	Mitra (1968)
75	1.8×10^6	From laboratory measurements of rate coefficients	Kistiakowsky and Volpi (1957)
75	2×10^6	-do-	Mavorayannis and Winckler (1961)
75	3.5×10^6	-do-	Clyne and Thrush (1959)
75	3×10^7	NO air glow by rocket	Meira (1971)
80	1×10^6	Zenith angle variation in absorption	Parthasarathy and Larfald (1965)
80	6×10^7	NO air glow by rocket	Barth (1966)
80	1.7×10^7	-do-	Meira (1971)
84–100	10^6	From NO^+, O_2^+ measurements	Wagner (1966)
85	6×10^7	NO air glow by rocket	Barth (1966)
85	1.3×10^7	-do-	Meira (1971)

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 I.

Ionization rate due to Lα of intensity I (photons $cm^2\ s^{-1}\ sr^{-1}$) can be computed using the equation

$$q(h) = 2\pi n_1(h)\, I\sigma_i \int \exp\left[-\sigma_a\, s\chi n_2(h)\, dh\right] \sin\chi\, d\chi\,, \tag{1}$$

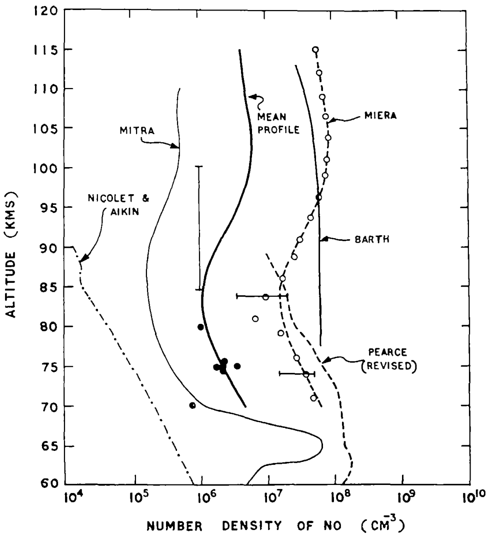

Fig. 3. Some of the available experimental and theoretical results on the vertical distribution of the NO density. The solid curve indicates the mean profile used in the present work and points correspond to those referred in Table I.

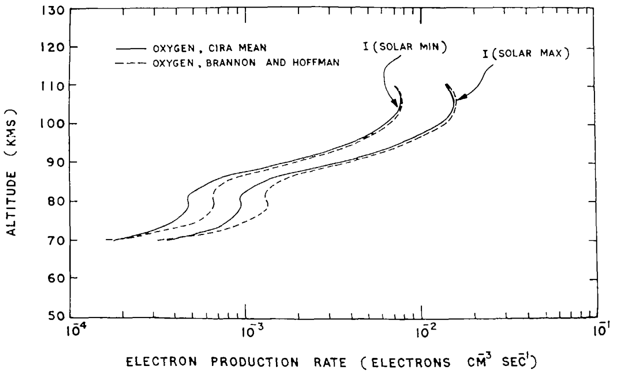

Fig. 4. Altitude profile of electron production rates due to Lα during sunspot maximum and sunspot minimum. Calculations are made for two types of O_2 distributions – one defined by the CIRA (1965) model and the other corresponding to the experimental observations of Brannon and Hoffman (1971).

where $n_1(h)$ and $n_2(h)$ are the number densities of NO and O_2 respectively at height h, χ is the zenith angle, σ_a is the absorption cross section of O_2 at 1216 A and σ_i is the photo-ionization cross section of NO at the same wavelength. In Figure 4, the electron production rates as a function of altitude are shown for the NO distribution discussed earlier in the cases when the Lα intensities are determined by the O_2 distribution as defined by the CIRA and by Brannon and Hoffman (1971) measurements. The effect of the Lα intensity variation with solar cycle is also shown in this figure. The maximum difference in electron production rates due to different O_2 distributions is found to be less than about 20%.

Besides this, the Lβ component could also cause some degree of ionization. But the high absorption cross section of O_2 ($\sim 1.5 \times 10^{-18}$ cm^2) for this radiation (Young *et al.*, 1968) results in the flux of Lβ at depths below 90 km to be too negligible to be a significant source of ionization.

D. 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} cm^{-3} s^{-1} (Thomas, 1971).

4. Electron Density Profiles

The calculation of electron density N_e from electron production rate q_j can be done using the well-known continuity equation

$$\frac{\mathrm{d}N_e}{\mathrm{d}t} = \frac{\sum q_j}{(1+\lambda)} - (\alpha_D + \lambda\alpha_i)\, N_e^2\,, \tag{2}$$

which reduces under conditions of equilibrium to

$$\frac{\sum q_j}{N_e^2} = (1+\lambda)(\alpha_D + \lambda\alpha_j) = (1+\lambda)\,\alpha_{\text{eff}} = \psi\,, \tag{3}$$

where α_{eff} is the effective recombination coefficient, α_D is the ion electron recombination coefficient and α_i is the ion-ion recombination coefficient. When λ, the ratio of negative ion to electron concentration is small compared to unity, $\psi = \alpha_{\text{eff}}$. 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, we attempt to make a quantitative estimate of the electron density increase for the transit of an X-ray source such as Sco X-1 in the night-time ionosphere by comparing the directly measured night-time electron density profile with the calculated electron production rates.

Unfortunately, the experimental observations of night-time D-region electron density profile are very meagre. In Figure 5, 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 low solar activity. The measurements of Mechtly and Smith (1968) correspond to the rocket probe technique. The results of the rocket observations of the night-time ionosphere over the geomagnetic equator in India by Subbaraya *et al.* (1971) using Langmuir probes are also plotted in the figure.

It is apparent from Figure 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 the varying solar activity. Such changes are expected because of the intensity variations of Lα and galactic cosmic rays over a solar cycle as pointed out before. Also no systematic differences in the electron

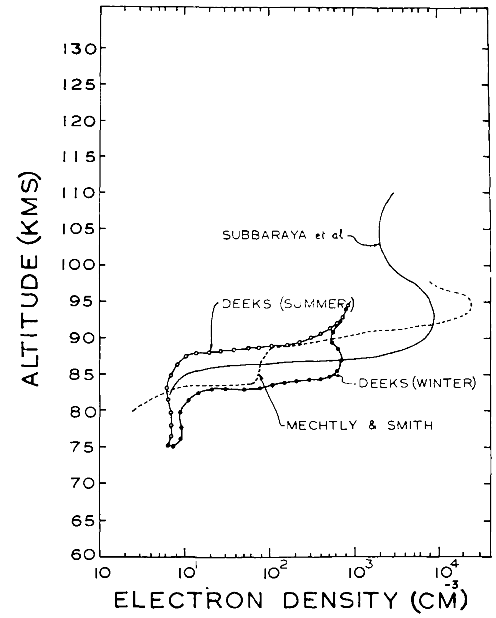

Fig. 5. Experimental observations of the electron density profiles in the night-time D-region ionosphere. The presented results pertain to mid and low latitude observations only.

density values between low latitudes and mid latitudes are evident in the available data. The difficulty could be partially explained by the uncertainties in the normalization of the different experimental results obtained by using a variety of techniques. Under these circumstances we use the rocket results of Subbaraya *et al.* (1971) down to 80 km and the summer values of Deeks (1966) between 75 and 80 km as representative of the electron density distribution over low and mid latitudes in computations involving Sco X-1 and galactic center effects. The specific choice of the former result results from 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 Ne and the computed value of q_j corresponding to the ambient ionization agents, the values of the recombination coefficient as a function of altitude are calculated. The altitude dependence of q_j for the different stable sources of ionization are shown together with $\sum q_j$ in Figure 6, and are representative of the average conditions. The galactic cosmic ray effect, which is the only latitude-dependent variable among these corresponds to $\lambda_m = 23°$ 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.

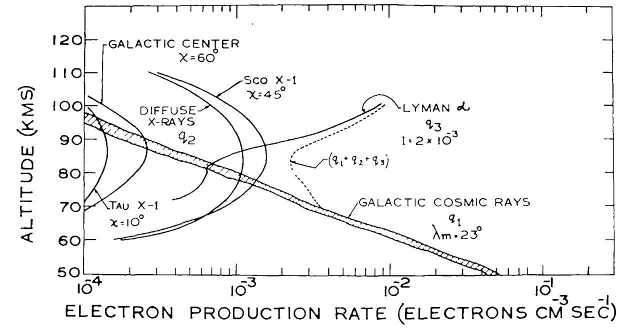

Fig. 6. The altitude profile of the electron production rates due to stable background agencies, viz. galactic cosmic rays, diffuse cosmic X-rays and Lα. A mean value of 2×10^{-3} ergs cm^{-2} s^{-1} Sr^{-1} is used for Lα flux. Also shown are the transient effects arising from the passage of Sco X-1, Galactic Center and Tau X-1. All the results correspond to geographic latitude of 32°N ($\lambda_m = 23°$), mid way between Tashkent and Ahmedabad. The total ambient effect from all the background agencies is shown by the dotted curve.

The electron density enhancements due to X-rays from Sco X-1, galactic center and Tau X-1 sources at 45°, 60° and 10° zenith angles respectively, corresponding to meridian transit of these over Gulmarg have been computed using the values for the recombination coefficients at different altitudes derived from Equation (3) with the experimental observations of the electron density and the calculated electron production rates. In Table II, the electron density increases at different altitudes for different sources along with the ambient electron density are given. We strongly

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TABLE II

Height (km)	Ambient production rate $q_1+q_2+q_3$ cm^{-3} s^{-1}	Electron density increase due to Sco X-1 and galactic center					Electron density increase due to Tau X-1		
		Ambient electron density Subbaraya *et al.* and Deeks (summer) =Ne cm^{-3}	$q(h)$		ΔN		Ambient electron density Deeks (winter) $=N_e$ cm^{-3}	$q(h)$ Tau X-1 cm^{-3} s^{-1}	ΔN Tau X-1 cm^{-3}
			Sco X-1 cm^{-3} s^{-1}	G. C. cm^{-3} s^{-1}	Sco X-1 cm^{-3}	G. C. cm^{-3}			
75.0	2.996×10^{-3}	6.4	1.210×10^{-3}	1.65×10^{-4}	1.184	0.175	7.0	1.15×10^{-4}	0.133
77.5	2.675×10^{-3}	7.0	1.365×10^{-3}	1.95×10^{-4}	1.603	0.251	9.6	1.25×10^{-4}	0.223
80.0	2.413×10^{-3}	7.0	1.500×10^{-3}	2.20×10^{-4}	1.915	0.313	9.4	1.36×10^{-4}	0.263
82.5	2.287×10^{-3}	7.0	1.565×10^{-3}	2.42×10^{-4}	2.085	0.361	15.0	1.43×10^{-4}	0.470
85.0	2.284×10^{-3}	10.0	1.600×10^{-3}	2.55×10^{-4}	3.040	0.540	600.0	1.42×10^{-4}	18.300
87.5	2.674×10^{-3}	2.0×10^{3}	1.580×10^{-3}	2.60×10^{-4}	523.0	95.0	700.0	1.40×10^{-4}	18.100
90.0	3.458×10^{-3}	8.0×10^{3}	1.480×10^{-3}	2.45×10^{-4}	1560.0	278.0	500.0	1.35×10^{-4}	9.700

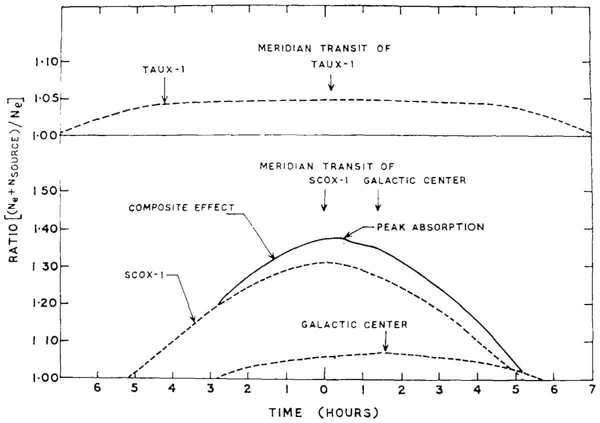

Fig. 7. Time profile of excess ionization shown as the ratio of the total electron density including the contribution from discrete sources to the ambient value. The values correspond to 85 km altitude. The composite effect expected from Sco X-1 and galactic center is also shown.

emphasise that any uncertainties in the values of electron density used in these calculations do not affect our results. The relative absorption due to celestial X-ray sources such as Sco X-1 only depends on the percentage contribution by these sources compared to the background ionization due to various other agencies discussed earlier.

In Figure 7, the electron density increases over the ambient values at 85 km height are shown as a function of time, both before and after the meridian transit of these sources.

5. 164 kHz VLF Observations at Ahmedabad

In this section, we have attempted to explain the observed attenuation of the VLF radio waves, correlated with the time of transit of Sco X-1, galactic center 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 8. On an average basis, the nature of the effect is shown in Figure 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 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 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° for the single hop geometry. The signal

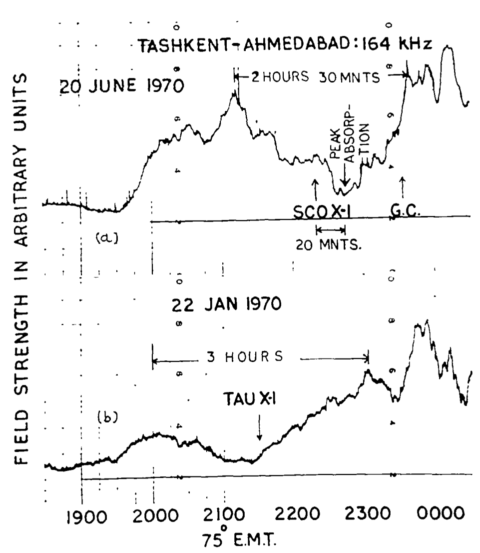

Fig. 8. Typical records of the 164 kHz Tashkent transmission received at Ahmedabad. The field strength variation associated with the passage of Sco X-1 and galactic center is shown in (a) whereas (b) represents that for Tau X-1.

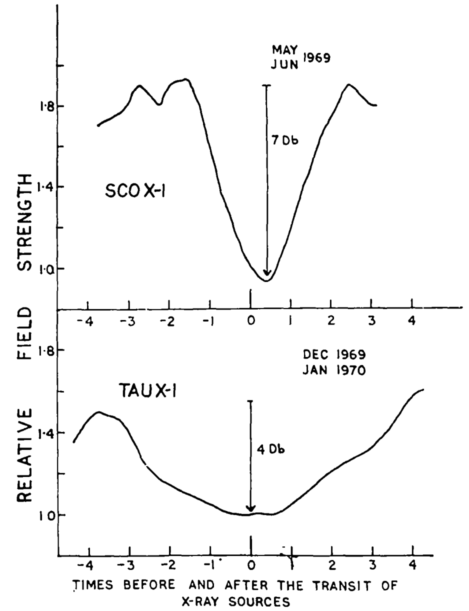

Fig. 9. Average time profile of the 164 kHz field strength variations related to the transit of Sco X-1 and Tau X-1. In the case of the profile corresponding to Sco X-1, the shift of 30 min in the position of the peak absorption arises due to Galactic Center. The curves are derived by superposed epoch analysis of the daily records obtained at Ahmedabad.

intensity measured will correspond to the reflection coefficient ${}_{\|}R_{\|}$, 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 ${}_{\|}R_{\|}$ in the day time is a few orders of magnitude higher than that of ${}_{\|}R_{\perp}$ for long transmitter-receiver distances. However, in the nighttime, these two quantities may be of the same order (Belrose, 1968). Since we register only the $_{\|}R_{\|}$ in our measurements, the present calculations are limited to $_{\|}R_{\|}$ 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 (1959) which deals with the problem of such a nature is therefore used here to compute the reflection coefficients. The initial value of the reflection 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 Booker'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 $_{\|}R_{\|}$. This in turn can give the total absorption in decibels using the formula

$$L = -20 \log {}_{\|}R_{\|}\,.$$

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).

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 III, the 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 7 and its observational counterpart in Figure 9, the density enhancements should be present for about 2–3 h 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 h 25 min after the transit of Sco X-1, in the records such as that presented in Figure 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 about 20–30 minutes, subsequent to the time of transit of Sco X-1, in the registered 164 kHz data and agrees reasonably with the computed composite time profile of electron density at 85 km shown in Figure 7. The calculated peak ab-

TABLE III

Source	calculated excess peak absorption (dB)	Observed excess peak absorption (dB)
Sco X-1	4.2	–
Galactic Center	1.5	–
Sco X-1 + Galactic Center	4.4	7
Tau X-1	1.2	4

sorption for the resultant effect is 4.2 dB and compares favourably with the observed absorption of 6–7 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, result of the computations shown in Figure 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 9.

The following main points emerge from the present study:

(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 Lα 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 oı 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 Lα 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 X-ray flares from stars or supernovae through their transient ionospheric effects using ground-based VLF observations.

(6) The controlled irradiation of the ionosphere provided by the discrete celestial X-ray sources, should also 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 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.

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