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Ionization effects from cosmic sources of x-rays in the lower atmosphere

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Abstract. Detectable ionization effects in the ionospheric *D*-region from individual, strong and steady x-ray sources such as Sco X-1 and transient x-ray sources such as Cet X-2 have been reported by us and many others previously based on the field strength and phase variations of the VLF data. As a follow up to these investigations, we have examined the integrated effects of many of the known x-ray sources discovered by UHURU, ANS, Ariel V and SAS-3 satellites, in order to understand the totality of their effects. These effects are examined in the present paper for 0° and +38° geographic latitudes corresponding to midnight conditions and for different times of the year. Such effects are compared, in turn, with those of the known steady sources responsible for *D*-region ionization such as Lyman-alpha and galactic cosmic radiations. The results are presented as profiles of electron production rates as a function of height. Our study leads to the conclusion that there should be detectable annual variations of the electron density which are pronounced around May-August. Further, the results of the computations on electron producton rates corresponding to the spectacular x-ray nova A0620-00 are also included in the present paper.

Keywords. *D*-region ionization; x-ray sources; x-ray nova.

1. Introduction

Cosmic x-rays are primarily investigated by rocket, balloon and satellite borne instruments since atmospheric absorption rules out direct ground based techniques. Absorption in the atmosphere of x-rays, especially in the 1–10 keV range, is predominant in the *D*-region of the ionosphere and results in the ionization of the atmospheric constituents. The resultant electron density changes as revealed by the study of VLF propagation characteristics that include field strength and phase variations can be exploited to detect the x-ray sources (Ananthakrishnan and Ramanathan 1969; Edwards *et al* 1969). Various other techniques, that depend upon the fluorescence effects of the atmospheric constituents in ultraviolet, visible and infrared due to excitation by x-rays have also been employed to detect such phenomenon (Charman *et al* 1969; O'Mongain and Weeks 1974; Elliot 1972; Fazio 1974 and Weeks 1976).

The detection of the ionospheric effect due to nonsolar x-ray sources was first reported by Ananthakrishnan and Ramanathan (1969) and Edwards *et al* (1969) and later by Kaufmann *et al* (1970). More detailed studies were subsequently carried out by Poppoff and Whitten (1969), Francey (1970), Mitra and Ramanamurthy (1972) and Sharma *et al* (1972) who examined the relative strengths of such effects in relation to those of the ambient ionization agents. Whereas, Poppoff and Whitten (1969) and Poppoff *et al* (1975) conclude that the effects of x-ray sources should not be discernible in view of the predominant Lyman-alpha contributions to the night time electron density at *D*-region altitudes, studies by Francey (1970) and Sharma *et al* (1972) reveal that the cosmic x-ray effect should be an observable phenomenon in the case of strong sources such as Sco X-1. Investigations of Mitra and Ramanamurthy (1972) reveal that the effect is likely to be observable at low latitudes where the changes in electron density are larger and the effects of the precipitating electrons are negligible. Further, Sharma *et al* (1972) have shown from the analysis of the VLF data registered at Ahmedabad, India corresponding to 164 kHz transmission from Tashkent, USSR, that sources as weak as Crab Nebula should be detectable.

Detection of nova like x-ray sources such as Cen X-2, Cen X-4 and Cet X-2 has been also reported (Kasturirangan *et al* 1975 and Svennesson *et al* 1972) using such VLF techniques.

More recently, the possibility of detecting cosmic gamma ray bursts has been investigated by Kasturirangan *et al* (1973). These authors find the results to be negative and conclude that the effects of such bursts which last for a few seconds, are comparable to the relaxation times of the ionosphere, resulting in electron density perturbations, too weak to be detectable by VLF techniques.

The present paper examines the integrated effects of several cosmic x-ray sources studied by a number of satellites that include UHURU, ANS, Ariel V and SAS-3. The resultant contributions are discussed in relation to the known ambient ionization agents such as Lyman-alpha and galactic cosmic radiation. These studies are made for different times of the year for two different latitudes (0° and $+38^\circ$) under midnight conditions.

Further, the results of computations of electron production rates and the corresponding electron densities relating to the strongest x-ray nova recorded so far, A0620–00, are also presented. The implication of these results in terms of the known variability characteristics of this source is discussed.

2. Response of ionosphere to x-rays

The nature of the ionization profile due to cosmic x-rays is very much dependent on the strength and emission spectrum of the source. If a spectrum of the type

$$\frac{dN}{dE} = \mathrm{K}E^{-\alpha} \text{ photons cm}^{-2}\text{ sec}^{-1}\text{ keV}^{-1}$$

is assumed to impinge on the ionosphere, then the resultant ionization can be represented by

$$q(h, \chi) = \frac{n(h)}{w} \int \exp\left[-\sigma(E).\sec\chi \int n(h).\, dh \right] \sigma(E).f(E).\, dE \text{ cm}^{-3}\text{ sec}^{-1}$$

where $n(h)$ is the density of the atmosphere at height h, w is the mean energy required to produce an ion-pair ($3{\cdot}5 \times 10^{-2}$ keV), $\sigma(E)$ is the x-ray attenuation coefficient at energy E, χ is the zenith angle of the source and $f(E) = (dN/dE)dE$, the x-ray intensity in keV cm^{-2} sec^{-1}. It can be seen from the above equation that changes in the source spectrum should be reflected in $q(h)$. Figure 1 shows the results of

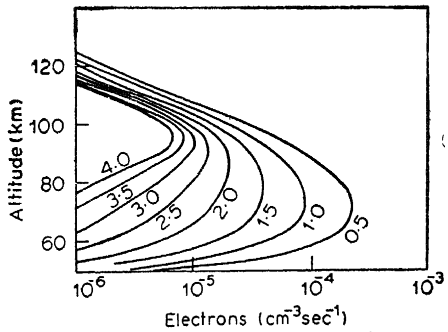

Figure 1. Ionization produced in the *D*-region of the ionosphere due to x-rays of 1-10 keV having a spectrum shape of $dN/dE = E^{-\alpha}$ photons cm^{-2} sec^{-1} keV^{-1} with different values of α.

computation of the electron production rate as a function of altitude for an assumed spectrum of the type

$$\frac{dN}{dE} = 1 \cdot E^{-\alpha} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}$$

for different values of α ranging between 0·5 to 4·0. Profiles shown in the figure correspond to $\chi = 0°$ for photons in the 1–10 keV range. It is obvious that as the spectrum softens, the peak of production rate moves up from about 70 to 95 km considering that photons above 10 keV contribute little for electron production at altitudes below 70 km in view of large recombination effects. In this connection it is of interest to note that even for heights above 80 km extension of the spectral function from 10 keV to 50 keV in the calculations results in about 20% increase in the corresponding ion production rates (Karszenbaum and Gagliardini 1975).

3. Ionization effects from cosmic x-ray sources

The x-ray sources identified for the present investigation correspond to the third UHURU catalogue (Giacconi *et al* 1973) supplemented with data reported from ANS, Ariel V and SAS-3 observations (Heise *et al* 1975; Ricketts *et al* 1975; Matilsky *et al* 1976). The approach for the calculations as well as the various inputs for the same such as the atmospheric model, the seasonal effects, NO concentration, etc., are as outlined in our earlier paper (Sharma *et al* 1972). As a first step towards the evaluation of the integrated ionospheric effects of the cosmic x-ray sources, an estimate of the contributions corresponding to the galactic centre group of x-ray sources has been carried out. The results of the calculations (from individual sources and sum total) carried out for 0° geographic latitude corresponding to the meridinal transit of this group of sources at local midnight on May 25 are presented in figure 2 along with the estimated contribution from the Cygnus group of sources. The details of the sources considered are given in table 1. Only those sources that contribute more than 5% of the total production rates are shown in the figure. As a next step, the combined effect of all the known 'steady' x-ray sources, on the *D*-region of the

Table 1. Details of the x-ray sources used for figure 3.

Sl. No.	Source	Position (deg.) R.A.	Decln.	Spectral parameters*		Reference
1	2	3	4	5		6
1.	3U1516-56 (Cir X-1)	229·18	−56·98	C = 2·33 kT = 0·95 N_H = 0·79 × 10^{22}	(BB)	Cruddace *et al* (1972)
2.	Sco X-1 3U1617-15	244·28	−15·54	—	(E)	Jayanthi (1973)
3.	3U1538-52 (GX327+2·5)	234·56	−52·18	C = 21 kT = 6.13 N_H = 0·79 × 10^{22}	(E)	Cruddace *et al* (1972)
4.	3U1642-45 (GX340+0)	250·53	−45·53	C = 0·45 kT = 1·34 N_H = 1·2 × 10^{22}	(BB)	-do-
5.	3U1630-47 (GX337+0)	247·54	−47·27	C = 14 kT = 3·06 N_H = 7·1 × 10^{22}	(E)	-do-
6.	3U1702-36 (GX349+2)	255·58	−36·36	C = 7·34 kT = 8·63 N_H = 1·1 × 10^{22}	(E)	-do-
7.	3U1705-44	256·35	−44·05	—		Jones (1976)
8.	3U1727-33 (GX340+0)	261·84	−33·70	C = 0·45 kT = 1·337 N_H = 1·2 × 10^{22}	(BB)	Margon *et al* (1971) Jones (1976)
9.	3U1744-26 (GX3+1)	266·19	−26·56	C = 1·11 kT = 0·863 N_H = 0·79 × 10^{22}	(BB)	Cruddace *et al* (1972)
10.	3U1758-20 (GX9+1)	269·64	−20·54	C = 1·0 kT = 1·08 N_H = 0·25 × 10^{22}	(BB)	Cruddace *et al* (1972)
11.	3U1813-14 (GX17+2)	273·29	−14·06	C = 3·94 kT = 0·82 N_H = 1·6 × 10^{22}	(BB)	-do-
12.	GX357+2·5	268·89	−33·80	C = 1·33 kT = 4·83 N_H = 0·35 × 10^{22}	(E)	-do-
13.	Ser X-1 (3U1837+04)	279·33	4·99	C = 0·85 kT = 4·2 N_H = 0·56 × 10^{22}	(E)	Hill *et al* (1975)
14.	Cyg X-1 (3U1956+35)	299·09	35·06	C = 10 kT = 2·6+0·2 N_H = 17 × 10^{22}	(P)	Heise *et al* (1975)

(BB) = Black body — $dN/dE = C.\exp(-N_H\sigma).E^2(\exp(E/kT)-1)^{-1}$
(E) = Exponential — $dN/dE = C.\exp(-N_H\sigma).\exp(-(E/kT))$
(P) = Power — $dN/dE = C.\exp(-N_H\sigma).E^{-\alpha}$

ionosphere, is computed corresponding to a height of 80 km for the geographic latitudes $\lambda=0$ and $\lambda=38°N$. The calculations have been made for the following two conditions:

(i) The first day of each month for the whole year, corresponding to midnight and for sources with zenith angles of 70° or less.

(ii) Effects of the transient x-ray sources not included.

The results for electron production rate at 80 km so obtained are presented in figure 3. Also, the number of sources considered for the calculations is indicated on a monthwise basis in the same figure.

It is seen from figure 3 that the production rate has a broad maximum around July for both the latitudes with minimum occurring around March-April. Further, the ratio of the maximum to minimum production rate is found to be about 10.

As a next step, we have attempted to estimate the resultant increase in the electron density at 80 km for different months. For this calculation, we have examined the available data on the electron loss rate coefficients (ψ) for night time due to different

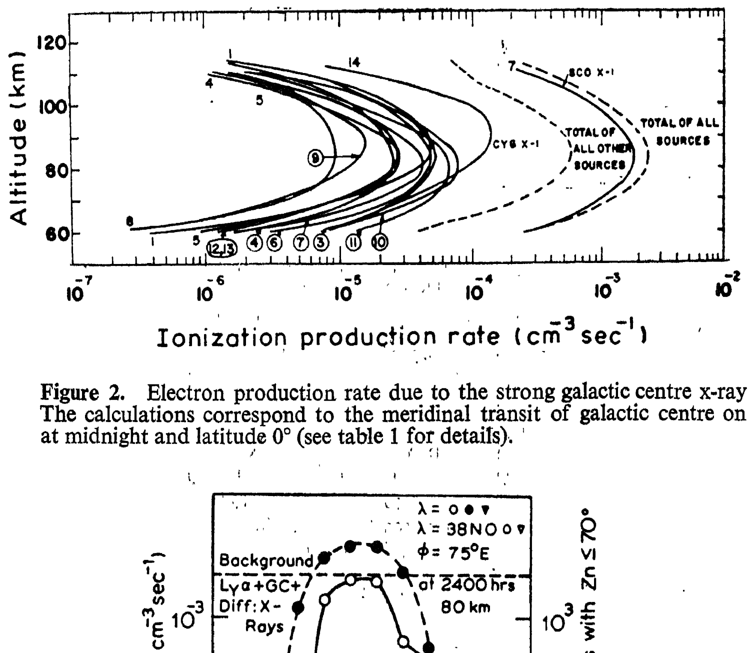

Figure 2. Electron production rate due to the strong galactic centre x-ray sources. The calculations correspond to the meridinal transit of galactic centre on May 25 at midnight and latitude 0° (see table 1 for details).

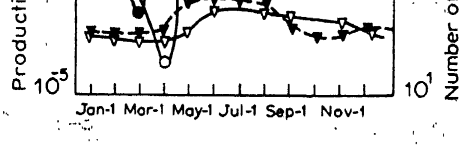

Figure 3. Electron production rate at 80 km due to all the UHURU sources calculated at the different times of the year. Solid points are for 0° latitude and open point for 38°N. Lower two curves denote the number of sources contributing to the production rate and the scale for this is on the right hand side of the figure.

authors (Bailey 1968; Mitra 1968; Potemra 1969; O'Mongain and Baird 1976) as summarised in figure 4. Comparison of the different data shows that there is a fairly good agreement between the various values of the electron loss coefficients as deduced by Bailey (1968), Mitra (1968), Potemra *et al* (1972) and Sharma *et al* (1972) for 80 km height. Using a value of $3{\cdot}5 \times 10^{-5}$ cm^3 sec^{-1} for ψ, the electron density due to x-ray source (N_{source}) has been calculated using the formula

$$\psi = \frac{Q_{\text{amb}} + Q_{\text{source}}}{[N_{\text{amb}} + N_{\text{source}}]^2}$$

where Q_{amb} is the ambient electron production rate due agencies such as Lyman-alpha, cosmic background x-rays, Lyman-beta and galactic cosmic rays (Sharma *et al* 1972). Q_{source} is the electron production rate due to the x-ray sources as shown in figure 3 and N_{amb} is the electron density prevailing under stable conditions. The calculation of the ambient electron production is for solar minimum conditions. The values of N_{amb} and Q_{amb} have been adopted from Poppoff *et al* (1975) and Sharma *et al* (1972) respectively. The results of the calculations are shown in figure 5. It can be seen that for $\lambda = 0°$, about 8 electrons cm^{-3} are produced corresponding to the disposition of sources on the first day of June over the corresponding background level of six electrons cm^{-3}. The resultant electron density is thus found to be more than a factor of two of the ambient value due to the influence of the x-ray sources. In this connection, it may be mentioned that the use of more complete equation

$$\frac{dN}{dt} = Q(t) - \psi N^2$$

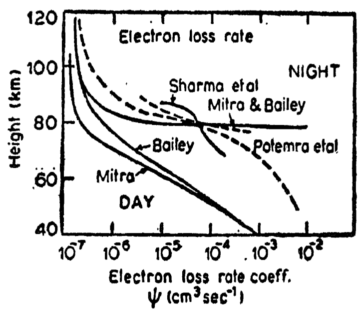

Figure 4. Data on the loss coefficient in the *D*-region.

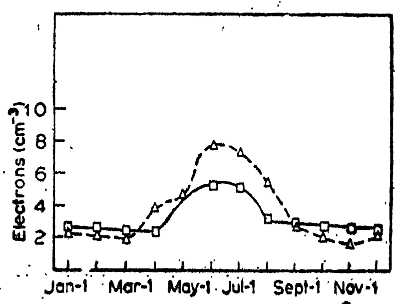

Figure 5. Electron density due to the electron production rates shown in figure 3.

for the present case of near midnight conditions and determining $Q(t)$ with and without the x-ray sources lead to electron density values which are within 10–15% of those reported here using the simpler equation for equilibrium conditions.

4. Ionization effects due to x-ray nova A0620-00

In order to get an idea of the effect of the transient x-ray sources in relation to the steady ones at *D*-region altitudes, we have calculated the ionization effects of the strongest transient x-ray source A0620-00 discovered by Ariel V on 3 August 1975 (Elvis *et al* 1975). At the peak of its active phase (11–16 August 1975) the x-ray flux emitted by this source was almost four times that of Sco X-1, the strongest of the steady sources known so far.

A0620–00 also exhibited remarkable spectral variabilities during its rise and decay phases. In fact, the spectral exponent varied from 0·7 to 5·7 over a period of about 15 days of its rising phase (Ricketts *et al* 1975).

From the available data (Ricketts *et al* 1975) on the intensity and spectrum of this source, the ionization production rates have been computed as a function of altitude over two latitudes viz., 0 and 30°. The results are presented in figures 6 and 7 respectively for the two latitudes for a number of values of the spectral exponent corresponding to the different epochs of the source. As is clear from figure 6, the peak of the production rate shifts from around 75 km to 90 km as the intensity and spectral features change. Whereas a general shifting of the peak of electron in

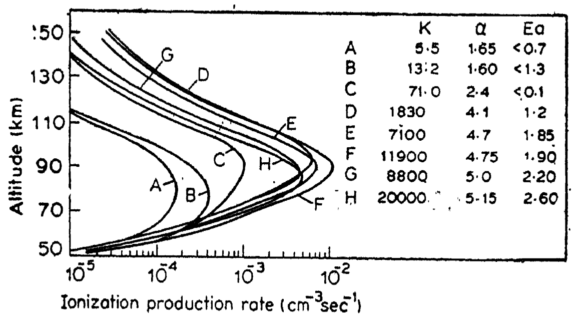

Figure 6. Electron production rate due to the x-rays emitted by x-ray nova A0620-00 at 0°.

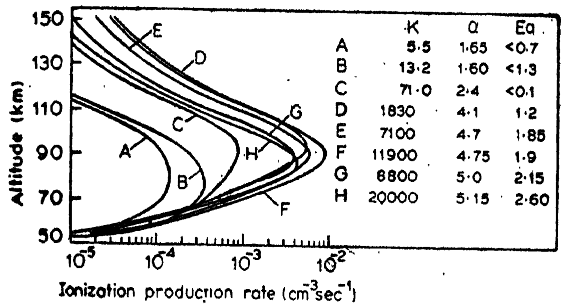

Figure 7. Electron production rate due to the x-rays emitted by x-ray nova A0620-00 at 30°N.

production rate to higher altitudes is observed as the spectrum softens up to $\alpha=4{\cdot}75$ and $E_a=1{\cdot}9$ (curves A to F), further softening results again in the lowering of the altitude of peak production rate due to the increase of the low energy cut off value of the x-ray fluxes (G and H). Further, it is observed that the electron ion production rate around the intensity maximum of this source is as high as 10 times that from ScoX-1 (Sharma *et al* 1972).

5. Conclusions

In conclusion, the present study indicates that the integrated effect from most of the known x-ray sources results in an electron density perturbation in the night time *D*-region of the ionosphere at a level, roughly equal to the ambient value, for midnight conditions, and during the period around the minimum of solar activity. This in turn should lead to a significant variation of the electron density on an annual basis. Based on the earlier studies, it is concluded that this effect should be detectable by the conventional VLF propagation techniques in view of its comparable magnitude to that of Sco X-1. By continuous monitoring of the VLF field strength or phase variations around local midnight over a year, the integiated effects from cosmic x-ray sources should be discernible during the months of May–August. The effect of transient x-ray source A 0620–00 should be significant and search of the available VLF data for the period 3–18 August 1975 should prove rewarding to identify and possibly quantify the effect of this source on the lower ionosphere. Further, distinct changes in the electron production profile are expected due to the spectral variability of the sources.

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