IONOSPHERIC EFFECTS OF X-RAYS FROM SCORPIO X-1 AND TAURUS X-1 (CRAB)

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1. Introduction

An X-ray source in the constellation Scorpio in our galaxy was discovered in 1962 by R. Giacconi, H. Gursky, P. R. Paolini and B. Rossi in the course of a rocket flight instrumented to detect X-rays. Subsequent flights using improved resolution, and search by optical astronomers for unusual objects in the vicinity of the X-ray source located the source with Right Assension $\alpha = 16$ hr. 17 m. and Declination $\delta = -15° 31'$ as a blue star of magnitude 12 to 13. The source is now known as SCO X-1. The discovery by Giacconi *et al.* stimulated efforts by several research teams, and in the succeeding few years, evidence quickly accumulated that X-ray sources are not uncommon and some of them could be identified with astronomical objects (*see* reviews by Friedman, 1967; Rossi, 1968). The results of measurements of X-ray fluxes from all sources, carried out so far, reveal that by far the brightest X-ray source as seen from the earth is SCO X-1.

In a letter to *Nature* (Ananthakrishnan and Ramanathan, 1969) which will be referred to as AR I, the idea was followed up that there could be an effect of X-rays from these sources on the night-time field strength of 164 kHz radio waves transmitted from Tashkent and received at Ahmedabad over a distance of 2,100 km. The region of reflection of one-hop transmission from Tashkent to Ahmedabad lies near 32° N., 71° E. and the equivalent vertical incidence frequency for one-hop reflection is about 28 kHz. From an examination of the field strength records of Tashkent broadcasts received at Ahmedabad since 1960, it was found that a minimum in the field strength was observed on many nights and that its time of occurrence roughly coincided with the time of meridian transit of SCO X-1 across 71° E.

The present report deals with this problem in greater detail. The first section deals with observational aspects of the effect of X-rays from SCO X-1, the second is devoted to an examination of the effect of two other

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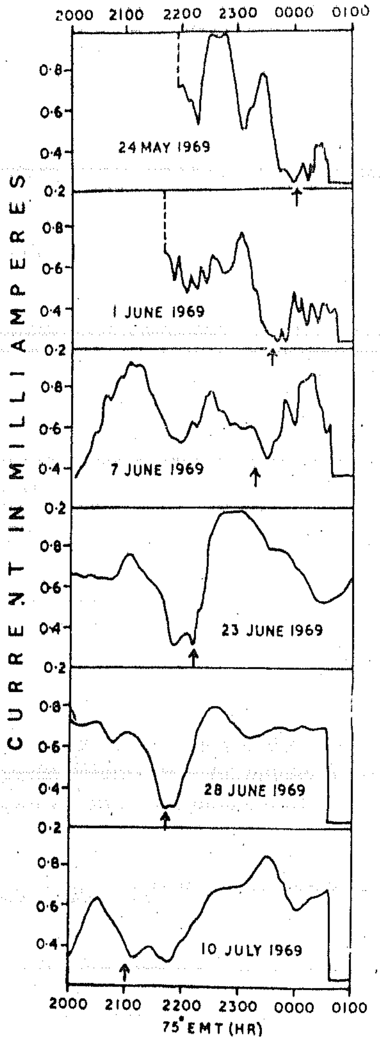
X-ray sources on the night-time field strengths and the final section is concerned with a comparative study of the X-ray spectra of SCO X-1, TAU X-1 and the quiet sun during periods of high and low activity. Also included in this section are calculations of ion-production and the resulting electron density due to these X-ray sources.

2. CHANGES IN NIGHT-TIME FIELD STRENGTHS PRODUCED BY SCO X-1

In AR I, we gave an example of the effect on the night-time field-strength produced by the transit of SCO X-1 across the one-hop reflection meridian in June 1961. Figure 1 is a similar diagram using the observational



FIELD STRENGTH OF TASH-KENT 164 KHz AT AHMEDABAD
(ARROWS INDICATE TRANSIT OF SCO X-1)

FIG. 1. Night-time field strengths of 164 kHz radio waves transmitted from Tashkent and received at Ahmedabad, showing a minimum at about the time of the meridian transit of SCO X-1 (June–July, 1969).

data of 1969. Examining the data of May–June of three years, it was found that in the useful records of May of each year, the absorption was present on 60–65% of the nights and in those of June, on 65–70% of the nights. An examination of the times of occurrence of these minima shows that in addition to a pronounced minimum which is nearly coincident with the transit of SCO X-1 there are other weaker minima present on either side. These have been examined carefully and Fig. 2 shows the results of the analysis of data of May–June 1961. The straight line represents the time of meridian transit of SCO X-1 and the black dots correspond to the minima which occurred within ± $\frac{1}{2}$ hour of the transit. The crosses represent all other minima seen on the records. While the black dots are crowded round the line of transits, the crosses above and below the line appear to show no systematic trend. It is believed that some of the minima appearing in the second half of June in the upper right-hand half of Fig. 2 are due to the flux from another X-ray star in Cygnus, CYG X-1. This is considered in more detail in Section 3.

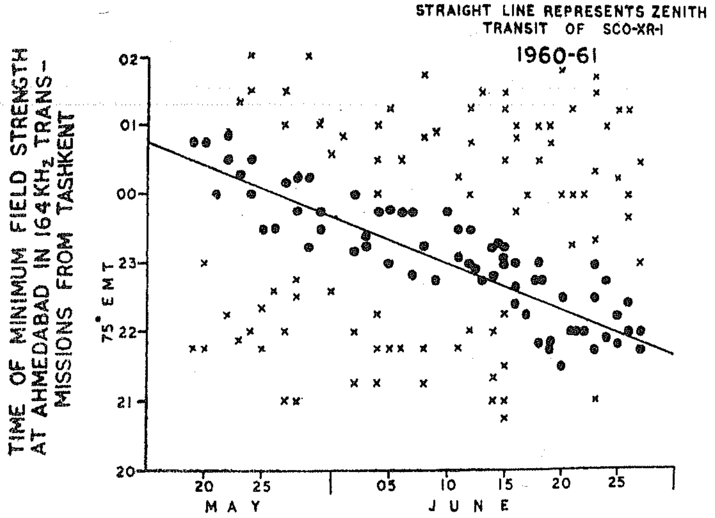


FIG. 2. Times of occurrence of minima in the field strengths of 164 kHz observed at Ahmedabad. The minima which occurred within ± 1/2 hr. of the transit of SCO X-1 are shown by circles and the others by crosses.

Figure 3 shows the results of a further analysis using a slightly different method. Taking the transit time as zero epoch, the values of the field strengths at fifteen-minute intervals on either side of the transit time were tabulated. These values were then divided by the value of the observed field strength at the transit time. For the following day, the zero epoch was shifted by four minutes and the procedure repeated. The results of this analysis for June 1961 are shown in Fig. 3.

The low values of the field strength at transit and the higher values on either side bring out clearly the increased absorption when the X-ray source transits over the reflection meridian.

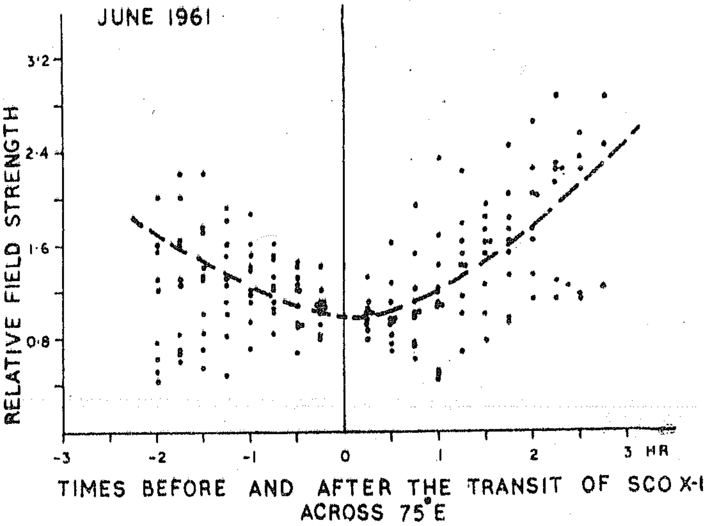


FIG. 3. Relative field strengths (normalised) at different times before and after the transit of SCO X-1 (June, 1961).

3. POSSIBLE EFFECTS BY OTHER X-RAY SOURCES

The results of the previous section and those presented in AR I demonstrate that there is noticeable absorption produced at certain sidereal hours in the night-time by the X-ray flux from Scorpio. The question now arises as to whether a detectable effect is produced by other X-ray sources. An examination of all the known sources listed by Friedman (1967) showed that the only ones of importance, as far as the present propagation path is concerned, are the Crab Nebula (Taurus X-1, $\alpha = 5^h 31^m$ and $\delta = +22\cdot 1°$) and Cygnus X-1 ($\alpha = 19^h 58^m$, $\delta = +34\cdot 5°$). The integrated flux of radiation from these two sources in the 1–10 Kev range (as listed by Friedman, 1967) is $4\cdot 3 \times 10^{-8}$ erg/cm.^{2} sec. from Cygnus X-1 and $3\cdot 2 \times 10^{-8}$ erg/cm.^{2} sec. for Taurus X-1. These values are about an order of magnitude smaller than the value for Scorpio $2\cdot 5 \times 10^{-7}$ erg/cm.^{2} sec. What makes TAU X-1 and CYG X-1 of interest for the present analysis is their location in the galaxy with respect to the reflection point of the radio waves from Tashkent. Both these sources at their transits pass within 10° of the zenith at the latitude of reflection of the radio waves from Tashkent. The lower fluxes of these two stars in comparison with that of Sco X-1 would therefore be partly compensated by their smaller zenith angles at transit.

Figure 4 shows the results of an analysis carried out for Crab similar to that presented in the last section for SCO X-1. It will be noted that both the dots and crosses shift with time as one moves from December towards February.

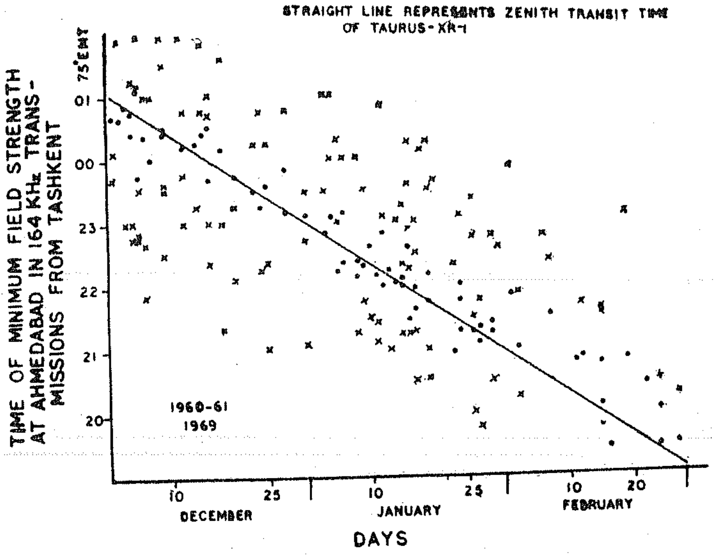


FIG. 4. Times of occurrence of minimum field strengths at different times before and after the meridian transit of Crab (TAU X-1).

It does appear therefore that there is a weak absorption due to radiation from Taurus also. This can be further seen from Fig. 5 in which values of the field strength before and after the transit of Taurus X-1 are plotted. Figure 6 shows the effect due to the transit of Cygnus X-1. It seems reasonable to connect the additional minima observed in the SCO curve of Fig. 2 between 01 and 02 hours in the second half of June with the meridian passage of Cyg. X-1.

In summary, the results of the analysis indicate that Taurus X–1 and Cygnus X-1 also produce weak absorptions. The effect produced by Scorpio is much stronger. In the following section, we shall examine whether the X-ray emissions from SOC X-1, TAU X-1 and CYG X-1 are sufficiently intense to produce the observed ionospheric effects.

4. ELECTRON PRODUCTION BY SCO X-1 AND TAU X-1

The X-ray spectra of SCO X-1 and TAU X-1 from 1–10 A are shown in Fig. 7; they have been taken from Friedman (1967). For purposes of comparison, two X-ray spectra of the quiet sun are also included, one relates to "quiet sun, solar minimum" and the other to "non-flare sun, solar maximum" (Poppoff, Whitten and Edmonds, 1964). It will be noted that photons of higher energy become relatively more important in fluxes from the X-ray stars than in the fluxes from the quiet sun. However, as in the height-range 90–75. km., X-rays of 2–5 Kev. energy are the

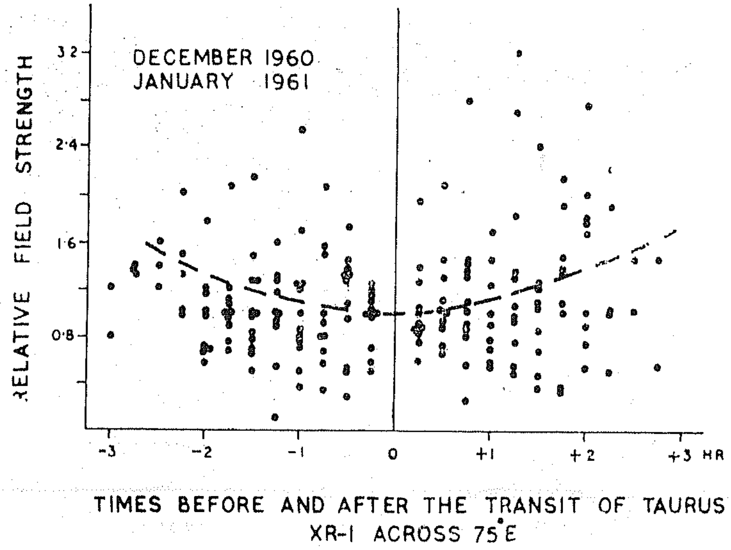


FIG. 5. Relative normalised field strength, at different times before and after the meridian transit of Crab.

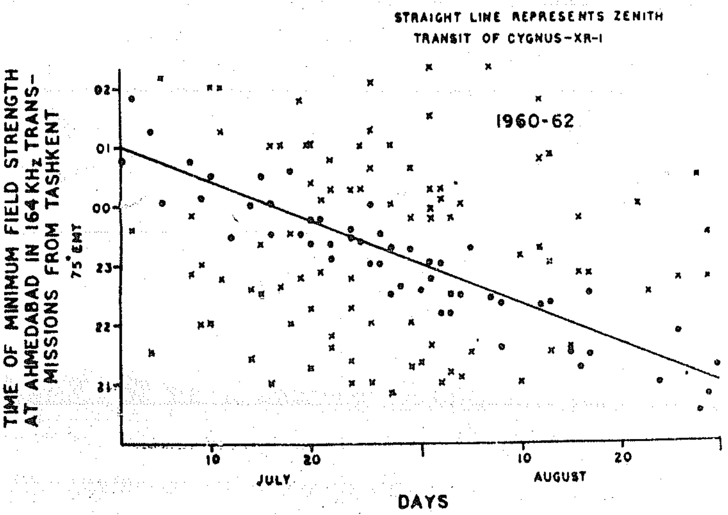


FIG. 6. Times of occurrence of minimum field strength at different times before and after the meridian transit of CYG-1 (July–August, 1960–62).

most efficient ionizers and as the loss-rate of electrons increase with decreasing altitude, we shall consider the electron production by X-rays in the energy range 1–10 Kev only.

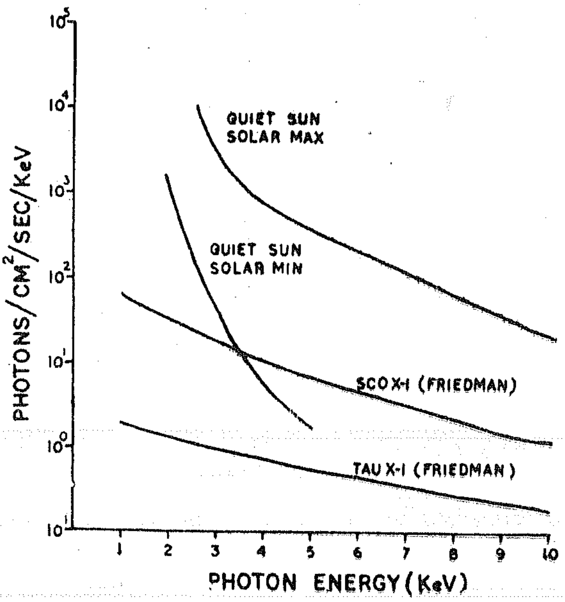


FIG. 7. Fluxes of photons of 1–10 Kev energy from the quiet sun under solar minimum conditions, from the non-flare sun under solar maximum conditions, and from SCO X-1 and TAU X-1.

The rate of electron production $q(z)$ in an atmospheric layer of thickness dz at height z due to a flux of I_j photons/cm.^{2} sec., each of average energy W_j, is given by

$$q(z)\,dz = I_j W_j \sigma_j \rho(z)\, r dz$$

where

σ_j is the mass absorption coefficient of air for X-rays of species j and energy W_j,

$\rho(z)$ is the density of atmospheric air at height Z'',

and

r is the electron yield per electron-volt of X-ray energy $\approx 1/34$.

I_j at any level is determined from the relation

$$I_j = I_{0j}\left[\text{Exp.}\left(-\sigma \sec \chi \int_z^\infty \rho(z)\, dz\right)\right]$$

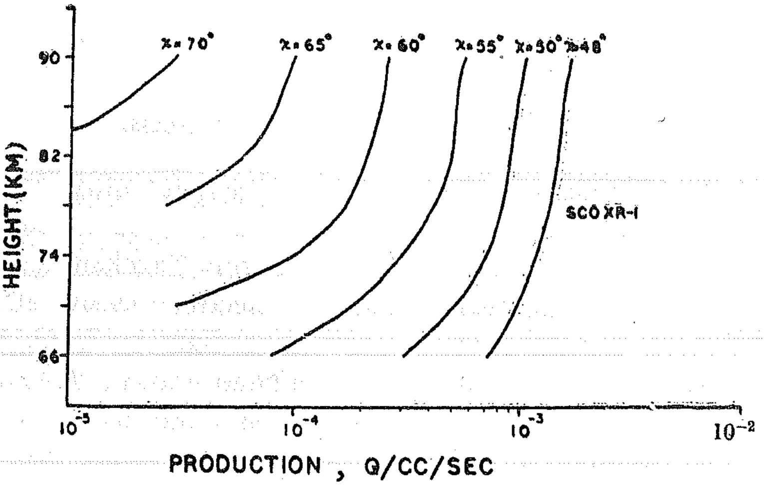
where

I_{0j} is the intensity outside the atmosphere

and

χ is the zenith distance of the source (D. W. Swift, 1961).

The rates of electron production at different levels between 90 and 65 km. due to SCO X-1 and TAU X-1 at different values of their zenith distance from 32° N., 71° E. are given in Figs. 8 and 9.



IFG. 8. Electron production rates at 65–90 km. due to SCO X-1.

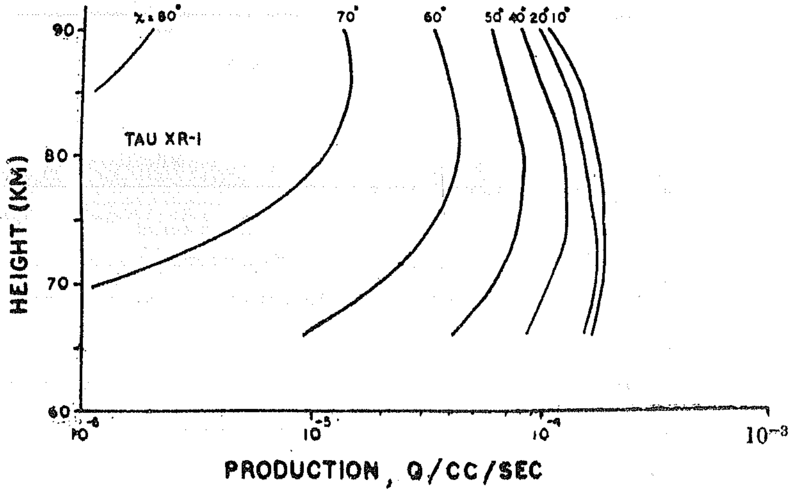


FIG. 9. Electron production rates at 65–90 km. due to TAU X-1.

Combining the electron production rates with electron loss rates due to formation of negative ions and recombinations of electrons and ions, we obtain the equilibrium electron densities from the relation.

$$\sum \frac{q_j}{N_e^2} = (1 + \lambda)(\alpha_D + \lambda \alpha_i) = \psi$$

where

λ is the ratio of the density of negative ions to that of electrons,

α_D, α_i are the re-combination coefficients of electrons and ions,

and

ψ is the effective loss coefficient of electrons.

There is much uncertainty about the night-time values of λ and ψ at 75–90 km., the region with which we are most concerned in dealing with the problem of reflection of 164 kH z radio waves from Tashkent to Ahmedabad. We have only a few direct measurements of electron density at night. The smoothed electron density profiles obtained at night by L. G. Smith *et al.* (1961 and 1964) at Wallops Island and by Hall and Fooks (1964) in Woomera have been taken from Belrose and Bourne (1967) and are shown in Fig. 10. These are not significantly different from the night-time profile obtained at Armidale by R. A. Smith *et al.* in 1963.

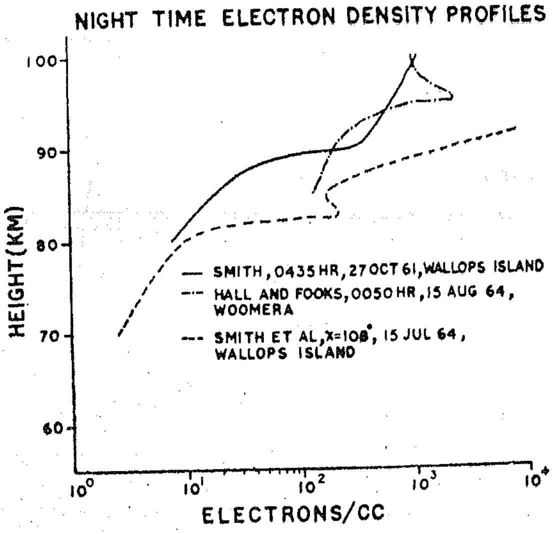


FIG. 10. Some night-time electron density profiles in middle latitudes.

The equivalent vertical incidence frequency of 164 kHz waves which arrive in Ahmedabad from Tashkent after one reflection in the ionosphere is 28 kHz. and the electron density at the height of reflection is about 10 cm.$^{-3}$. This density of electrons may normally be expected to prevail at night at 80–82 km.

The following table gives the mean night-time values of ψ (1) as estimated by A. P. Mitra (1968) from the rocket observations of McDiarmid and Budzinoky (MB) and of Belrose, Bode and Hewitt (BBH) in Canada and (2) as calculated from Moler's night values of $\alpha_D + \lambda\alpha_i$ and Sagalyn and Smiddy's values (SS) of λ at night.

TABLE I

Height (km.)	Night-time values of ψ (Loss rate of electrons)		
	(1) MB, BBH and APM	(2) Moler+SS	(3) F *et al.*
90	$1{\cdot}4\times10^{-7}$	$1{\cdot}4\times10^{-7}$	..
86	2×10^{-7}	$2{\cdot}5\times10^{-7}$	3×10^{-7}
82	5×10^{-6}	5×10^{-7}	2×10^{-6}
78	$>>10^{-4}$	8×10^{-7}	10^{-5}
74	..	4×10^{-6}	*c.* 10^{-4}

A recent analysis of auroral observations made at night in Norway by Folkestad *et al.* (F *et al.*) gives values of ψ which are in reasonable agreement with those of (1) at levels above 83 km. but are much smaller at lower levels. Accepting (1) and (2) as two extreme estimates available, we can calculate the equilibrium electron densities due to SCO X-1 and TAU X-1 at different levels below 90 km. at the time of their transits across 71° E. and at different times within ± 3 hrs. of the transit time. The calculated electron densities due to SCO X-1 and TAU X-1 are shown in Figs. 11 and 12.

The effect on the absorption of 164 kHz radio waves due to the addition of these electron densities below the normal night-time ionosphere has now to be calculated. Tentative calculations have been made of the reflection coefficients of the equivalent vertical incidence frequency 28 kHz at 32° N., using the wave admittance matrix method of Budden (1961). The calculated curves of attenuation associated with the transit of SCO X-1 and TAU X-1 agree in a broad way with the observed curves and justify the conclusion that X-rays from these two stars can produce the observed changes in the field strengths of the reflected L.F. radio waves. More detailed calculations have been started.

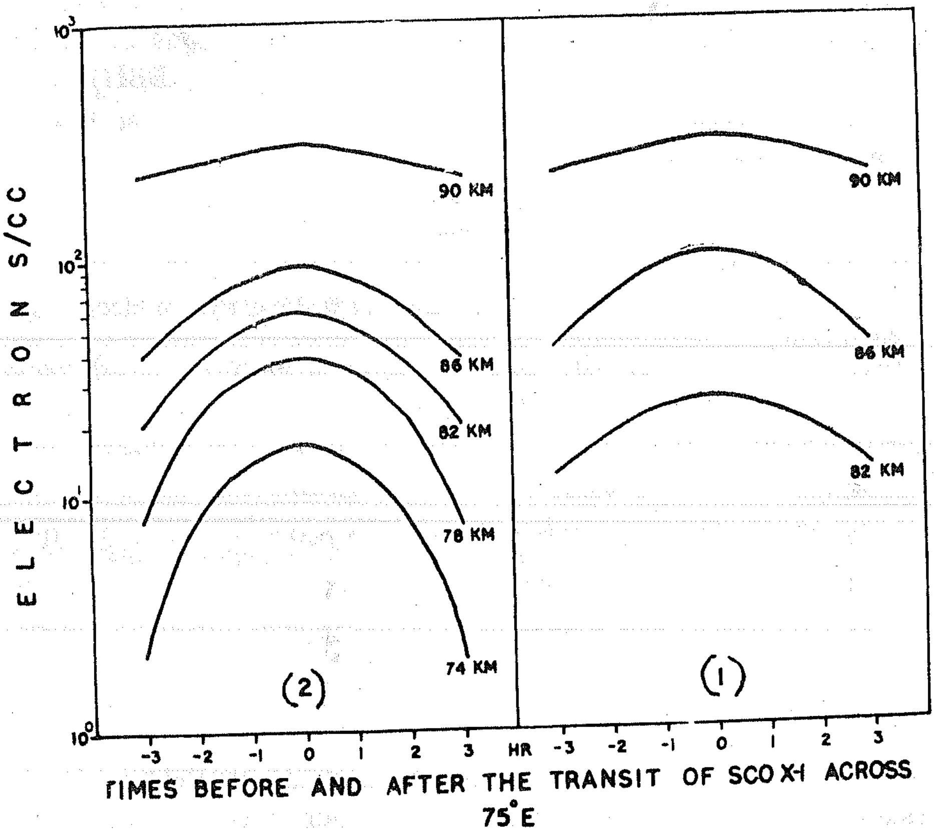


FIG. 11. Profiles of equilibrium electron density produced by SCO X-1 during night assuming two extreme loss rates of electrons.

We have recently had the opportunity to see through the courtesy of the authors, the pre-print of a note by P. J. Edwards, G. J. Burtt and P. Knox of New Zealand on "An ionospheric effect due to celestial X-rays" in which they report the discovery of a reduction in the times of propagation of 20 kHz. radio waves transmitted during night from Boulder and received at Wellington by 6–8 μs. The average time of the maximum effect approximately coincides with the sidereal time of the transit of SCO X-1 across the meridian of the mid-point of the Boulder-Wellington path. The phase advance was found to change by about 2 hours per month between

February and May. This finding of the New Zealand scientists is in agreement with the results of our independent study.

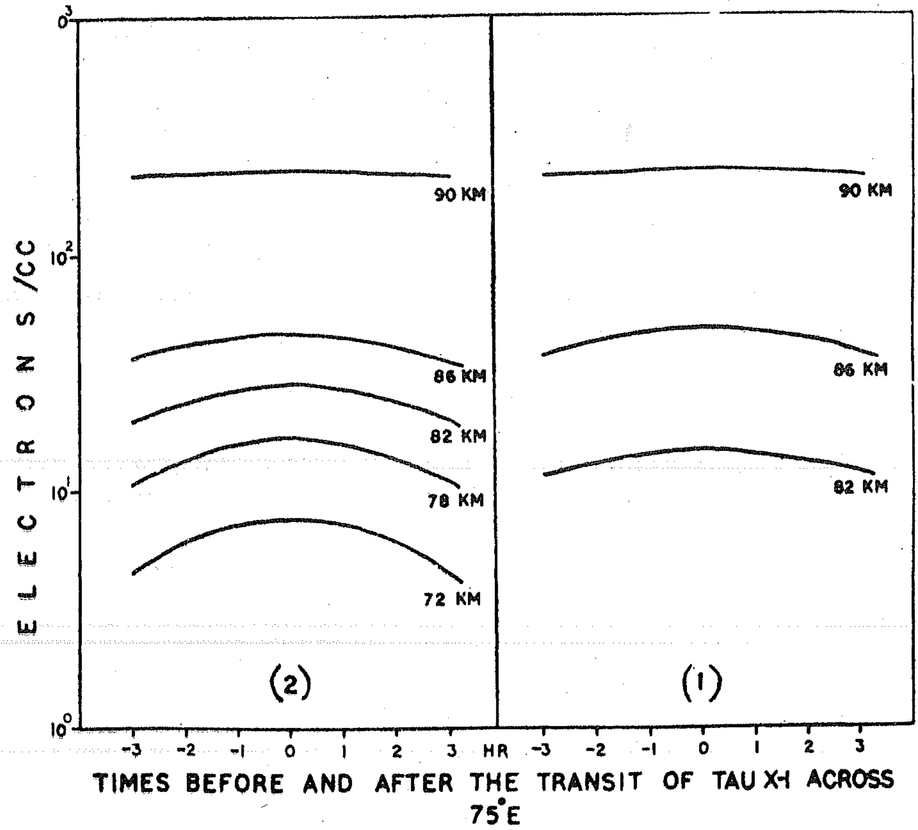


FIG. 12. Profiles of equilibrium electron density produced by TAU X-1 during night assuming two extreme loss-rates of electrons.

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