A COMPARISON OF FIELD-STRENGTHS OF 164 kHz RADIO WAVES TRANSMITTED FROM TASHKENT AND RECEIVED AT AHMEDABAD WITH FLARE-TIME SOLAR X-RAY EMISSIONS MEASURED IN SATELLITES

By S. C. Chakravarty and K. R. Ramanathan, F.A.Sc.

(*Physical Research Laboratory, Navrangpura, Ahmedabad-9*)

Received March 6, 1972

1. Introduction

During solar flares, sudden changes in the field-strength of 164 kHz radio waves transmitted from Tashkent and received at Ahmedabad have been recorded since 1962 (Alurkar, 1963). A detailed study of such events by Shirke and Alurkar (1963) and by Ananthakrishnan (1967) showed that the type of variation of intensity due to the flares depended on the time of the day and the season. It is now generally recognised that the ionisation in the D-region increases during solar flares, mainly because of the enhancement of the flux of X-rays in the 1–8 Å wavelength band (Friedman *et al.*, 1958; Chubb *et al.*, 1960; Kreplin *et al.*, 1962). From a statistical study of the published data of X-ray flares during 1968–70 and the corresponding effects on the 164 kHz field-strength, it has been inferred that on the average, an X-ray flare with peak flux greater than 4×10^{-3} ergs/(cm^2 sec) ($\lambda = 1$–8 Å) causes an SID sufficient to affect the radio intensity of 164 kHz for the path mentioned above (Chakravarty, unpublished). The exact character of the response depends on the distribution of flux intensity within the band and the zenith distance of the sun. The direct measurement of electron density in the D-region during a flare by Somayajulu and Aikin (1969) and the electron densities estimated by the spectral distribution of X-rays show agreement within 20·25% up to about 85 km (Ananthakrishnan, 1971). In this study, we have made a comparison of the effects of a few flares on the field intensity of 164 kHz with the detailed X-ray flux data as measured in the satellites SOLRAD 9 (Explorer 37) and Explorer 35.

It is observed that the type of field-strength change at Ahmedabad and Poona depends on the hardness ratio of X-rays within the 1–8 Å band and on the zenith distance of the sun. It has also been shown that the type of change is related to the step-wise character of ionization in the daytime D-region.

2. X-RAY DATA

The solar X-ray data have been taken from a publication by Kreplin (1970). The times of the flares have been compared with the times of sudden changes in the field intensity of 164 kHz radio waves transmitted from Tashkent and received at Ahmedabad. The X-ray fluxes in the 2–12 Å wavelength band measured by Explorer 35 (Van Allen and Teske) are well suited for this comparison because of good time resolution during sudden changes. The SOLRAD 9 data ($\lambda = 1$ to 8 Å) have also been used when data of Explorer 35 were not available. Table I gives a summary of the data used. Some flare-time fluxes of X-rays have also been taken from Solar-Geophysical Data Bulletins (USA).

3. RESULTS

All the observed sudden intensity variations of 164 kHz signals and the corresponding X-ray flux-changes in the 2–12 Å wavelength band during the period 27 October to 3 November 1968 are listed in Table I. It will be noted that all the X-ray events observed during the hours 0200–1200 U.T. (07–17 hr L.T.) produced nearly simultaneous effects in the radio signal. The minimum X-ray flux which was able to induce a measurable effect was about $4 \cdot 5 \times 10^{-3}$ ergs/cm^2 sec). The starting time and time of peak intensity of the sudden ionospheric disturbance and of the X-ray flare agree well, in general, within a few minutes. The end time of the SID effect on the 164 kHz signal cannot be accurately determined and hence the time mentioned in Table I only indicates the time of the first minimum after the flare effect started. After reaching the minimum value, the field strength slowly recovers to its normal level. The re-establishment of the original signal level takes place about an hour or more after the X-ray flare has ended. There is no definite relation between the end time (as given in Table I) of changed signal intensity and the end time of the X-ray flare.

Figure 1 shows examples of two flares on 3 November 1968 during which observations were made on 164 kHz intensity and the sudden enhancements of X-ray flux. The first X-ray flare around 0540 U.T. gave rise to a small drop in intensity of radio signal (Type C) whereas the second bigger flare produced an enhancement in the signal with a small initial drop (Type B).

TABLE I

X-ray flares observed in satellites and the corresponding SID effects observed in the field-strengths

Date	Satellite	Time of X-ray flares as recorded in satellite			Peak Flux erg/(cm² sec) 1–8 Å or 2–12 Å	SID effect observed in 164 KHz field-strength		
		Start time	Peak time	End time		Start time	Peak time	End time
27–10–1968	Exp. 35	1102	1113	..	8×10^{-3}	1108	1114	..
	do.	1130	1150	U 1302	1×10^{-2}	1130	1149	1200
28–10–1968	Exp. 35	0200	0205	0300	$8 \cdot 5 \times 10^{-3}$	0200	0244	0320
	do.	0500	0516	0555	$1 \cdot 0 \times 10^{-2}$	0502	0520	0530
	SOLRAD 9	0555	0600	0630	$5 \cdot 0 \times 10^{-3}$	0557	..	0620
	do.	0650	0700	0715	$4 \cdot 5 \times 10^{-3}$	0702	..	0708
	do.	0715	0725	0740	$4 \cdot 5 \times 10^{-3}$	0730	..	0740
	do.	0828	0835	0845	$5 \cdot 0 \times 10^{-3}$	0835	..	0845
29–10–1968	Exp. 35	0330	0400	U	$6 \cdot 2 \times 10^{-3}$	0330	U	0400
	do.	0407	0421	0500	$7 \cdot 2 \times 10^{-3}$	0415	..	0430
	do.	0545	0600	0630 U	$7 \cdot 5 \times 10^{-3}$	0552	0600	0630
	do.	C	C	C		0730	0748	U
	do.	0858	0915	C	2×10^{-2}	0900	0915	..
	do.	1000	..	1008	1×10^{-2}	100	1004	1015
1–11–1968	Exp. 35	0545	0557	0620	7×10^{-3}	0545	..	0557
	do.	0627	0640	0645	5×10^{-3}	..	0622	0630
	do.	0825 U	0910	1200	5×10^{-2}	0814	0900	1200
2–11–1968	Exp. 35	C	C	C	..	0330	0338	0355
	do.	0600	0610	0637	7×10^{-3}	0600	0610	0655
	do.	0915	1002	1200	1×10^{-1}	0915	1000	1045
3–11–1968	Exp. 35	0530	0537	0600	$5 \cdot 4 \times 10^{-3}$	0530	×	0537
	do.	0708	0715	0730	$7 \cdot 0 \times 10^{-3}$	0712	0722	0800

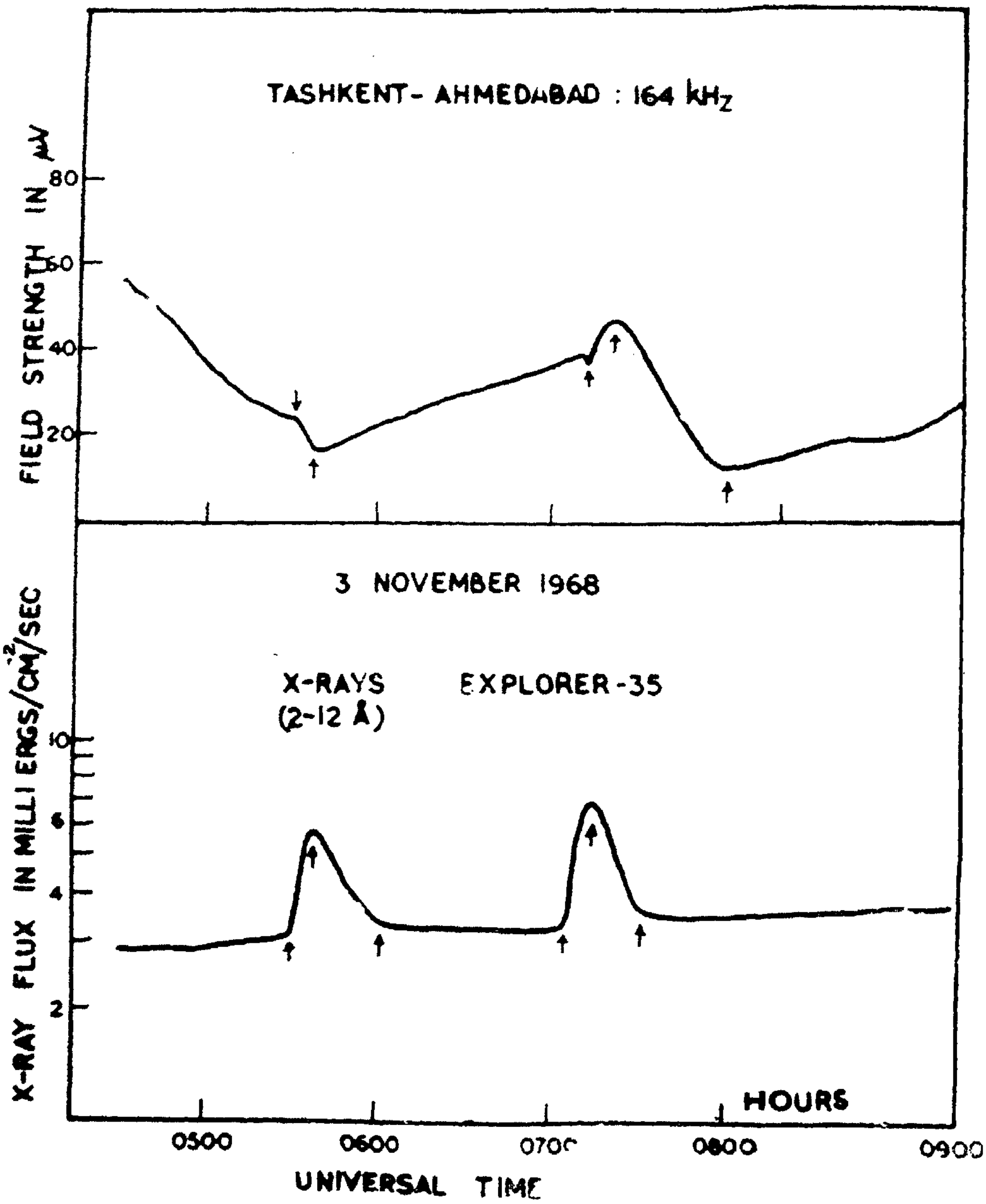

FIG. 1. Variation of the amplitude of 164 kHz radio waves and X-ray fluxes (2–12 Å) during the flares on 3 November 1968.

Figure 2 shows the big flare of November 2, 1968. The simultaneous changes in the field intensity of 164 kHz radio waves can be seen at every stage of the changes of X-ray spectrum. The X-ray flux started increasing at 0915 and the rate of rise decreased at 0945 hr. From 0945 hr to 0952 hr the flux showed only a slight increase. The X-ray flux thereafter increased sharply, reaching a maximum at 1000 hr, showing the changeover point very clearly at 0952 hr (Type A). The fast recovery of the X-ray flux after

1000 hr U.T. can be seen from the figure. The corresponding 164 kHz radio intensity started decreasing at 0915 hr reaching a minimum at 0945 hr. From 0945 hr to 0952 hr the intensity showed an enhancement of about 40 microvolts. This pertains to the slow rising part of the X-ray flux at the same time. The field intensity then reaches a maximum at 1000 hr, coinciding with the time of maximum of the X-ray flux. The changeover point at 0952 hr is also clear from these records. After 1000 hr, the time sequence in the

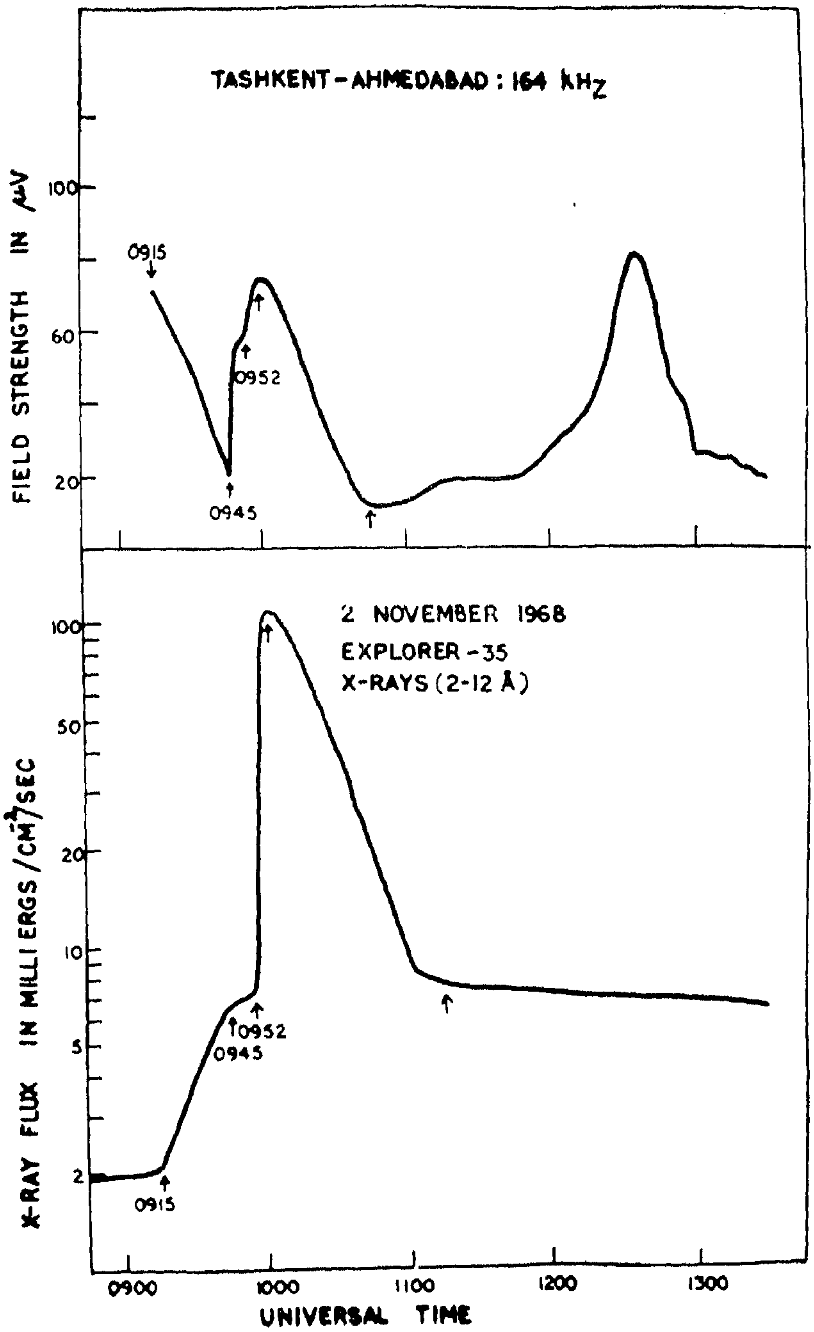

FIG. 2. Variation of the amplitude of 164 kHz radio waves and X-ray fluxes (2–12 Å) during a big flare on 2 November 1968.

recoveries of 164 kHz intensity and X-ray flux are somewhat different. Up to the time of the peak of the flare the variations of signal-intensity and X-ray fluxes were very nearly simultaneous. Even small details of the changes in X-ray flux are reflected in the sudden deviations of the signal strength. The second peak in field-strength at 1245 hr U.T. is not a flare effect but is a normal sunset effect.

Figure 3 shows the occurrence of a complex of 6 flares during the period 0700 to 1400 hr U.T. on 28 October 1968. The remarkable point to be

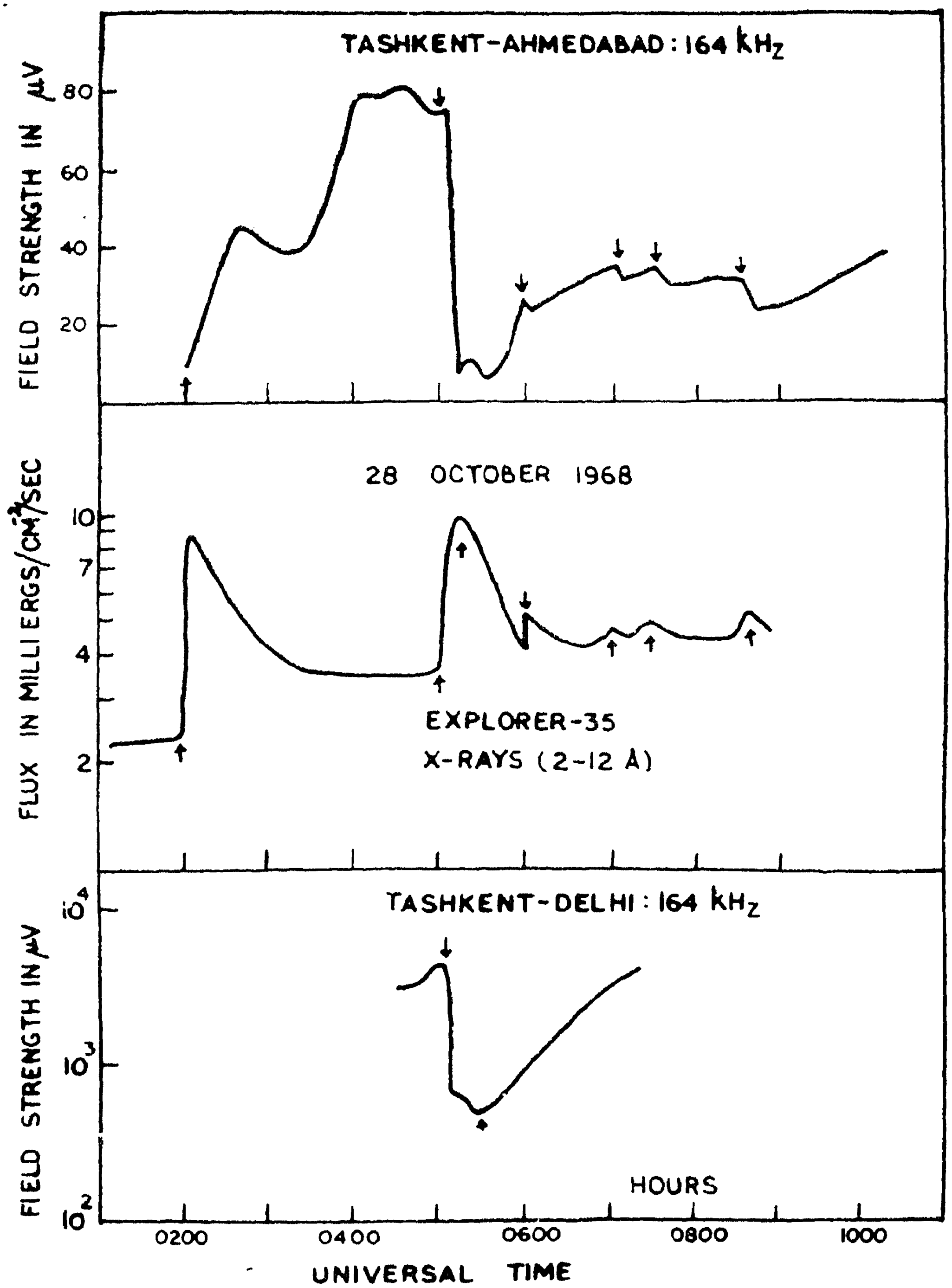

FIG. 3. Field-strength changes of 164 kHz radio waves observed at Ahmedabad and at Delhi during the occurrence of a complex of X-ray flares on 28 October 1968.

noticed is that even e small X-ray fiuxes of average peak flux of $4 \cdot 5 \times 10^{-3}$ ergs/(cm^2 sec.) have been able to produce effects in the radio intensity at Ahmedabad in the form of small decreases. The Tashkent signal received at Delhi (1000 km from the transmitter) shows sudden changes due to the big flare at 0500 hr U.T. but does not show any change of the subsequent small flares. The absence of any effect of the small flare at 0600 hr at Delhi may be noted. Figure 4 shows the simultaneous records of 164 kHz field strength received at Ahmedabad and at Poona (2100 and 2500 Km from

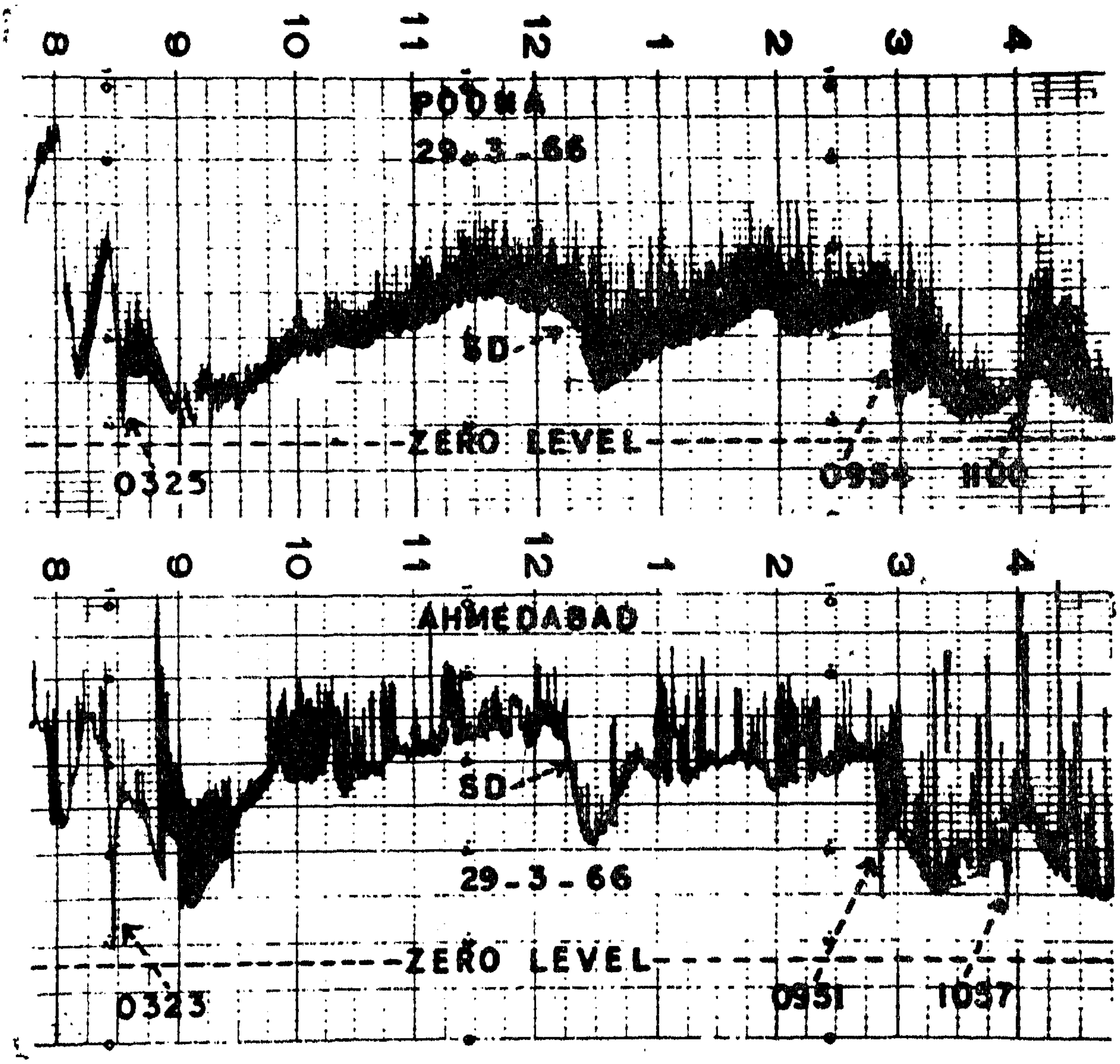

FIG. 4. Simultaneous observations of flare effects in the 164 kHz radio intensity at Ahmedabad and at Poona on 29 March 1966.

Tashkent) on 29 March 1966. It will be seen that the flares at 0325 hr, 0715, 0954 and 1100 hrs U.T. produced similar impressions at both the stations, Coming back to Fig, 3, it appears that the smaller flares do not produce an effect at short distances, but show up in the records at longer distances. Since the height of reflection of LF radio waves depends on the transmitter-receiver distance, it will be an important factor in determining the effect of X-rays in the intensity of the field-strength. Tashkent–Ahmedabad or Tashkent–Poona paths for 164 kHz radio waves seem to be well suited for observing the weaker X-ray flares.

Figure 5 shows a multiple flare on 27 October 1968. The X-ray flux started increasing at 1102 hr; the effect on the radio intensity was seen at

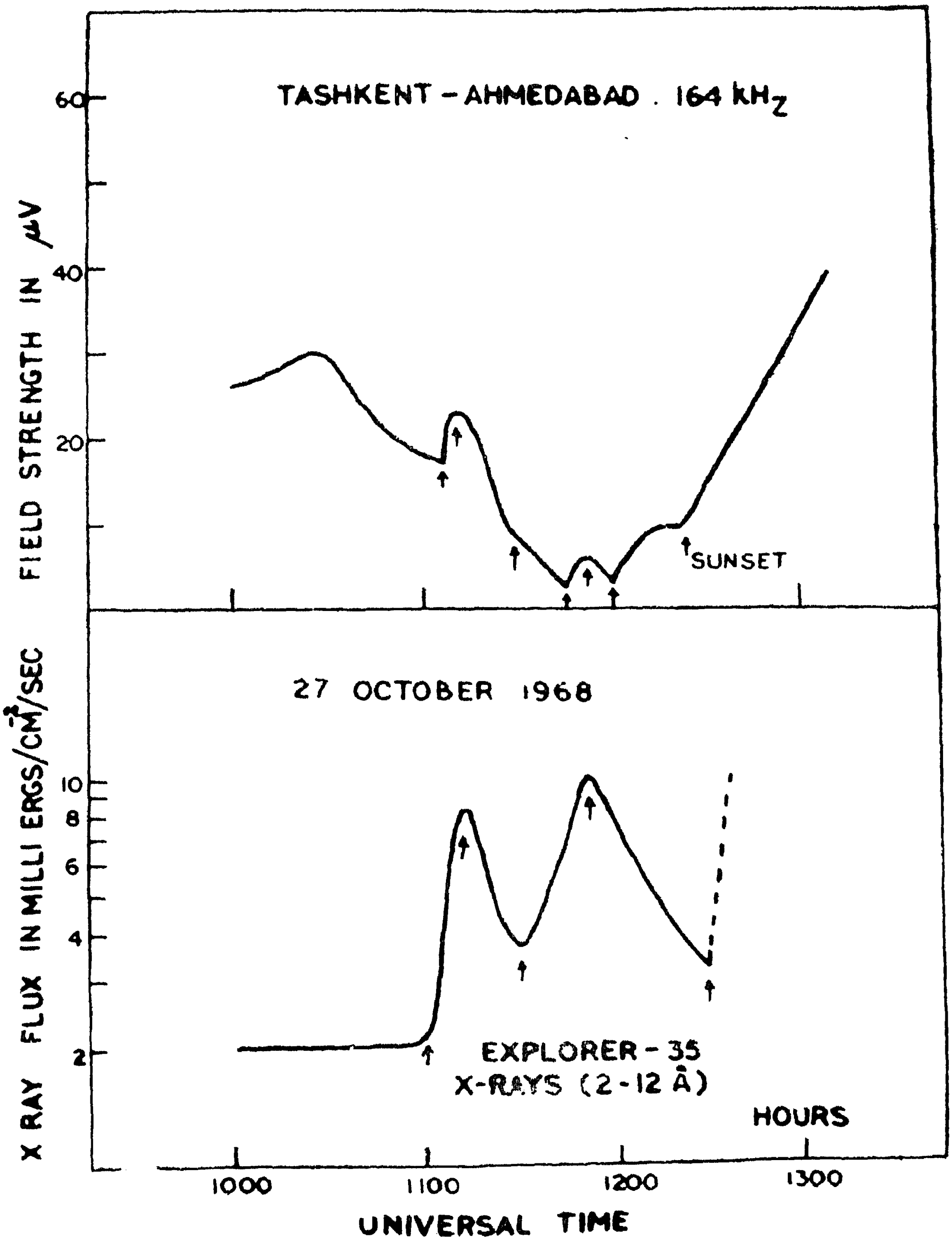

FIG. 5. Changes in the field-strengths of 164 kHz radio waves observed during two overlapping X-ray flares of 27 October 1968.

1108 hr when the X-ray flux reached a value of $4 \cdot 5 \times 10^{-3}$ erg/(cm^2 sec). Before the first flare ended, another started at 1130 hr and this showed up in the signal by a change in the slope of the recovery stage. The peak corresponding to the second X-ray flare was quite small in the field-strength record, presumably because of the high absorption due to the ionisation produced by the first flare.

4. Types of Changes in Signal Strength Observed at Ahmedabad Due to the Solar Flares and Their Diurnal and Seasonal Variations

Shirke and Alurkar (1963) analysed the records of field-strengths of transmissions from Tashkent on 164 kHz due to a large number of flares observed at Ahmedabad, and classified them into three types:

Type A: Sudden enhancement of intensity followed by decline to a minimum and gradual recovery. These are most frequent in summer (May to September) and particularly at times when the sun is high.

Type B: Initial sharp dip in intensity before the enhancement followed by decline to a minimum and recovery as in Type A. These are most frequent in October to April and in morning and evening hours.

Type C: Disturbances with a fall in the intensity gradual or rapid, followed by a slow rise. An example can be seen at 05 hr U.T. in the record of 28 October 1968 (Fig. 3).

An analysis of the LF disturbances recorded at Ahmedabad in 1969 due to X-ray flares recorded in satellites showed that 50 to 80% of the flares in the equinoctial months affected the LF field-strengths, but only 10 to 20% of the flares produced measurable effects in the months May to September (Fig. 6).

5. In order to find an explanation for the differences in response to different flares and to flares in different seasons, the peak X-ray fluxes in the wavelength bands 1–8 Å and 1–3 Å in the period January to August 1971 were compared with the types of disturbances which they produced. Figure 7 (*a*) shows the relation between X-ray photon flux ϕ (1–8 Å) and the hardness factor ϕ (1–3 Å)/ϕ (1–8 Å) corresponding to the three types of

disturbance. Figure 7 (*b*) is a similar diagram showing the relation between ϕ (1–3 Å) and ϕ (1–3 Å)/ϕ (1–8 Å). It will be noticed that the hardness factor required for a Type A disturbance is greater than that required for a Type B disturbance and that a Type C disturbance can be produced by even a smaller hardness ratio than that for Type B.

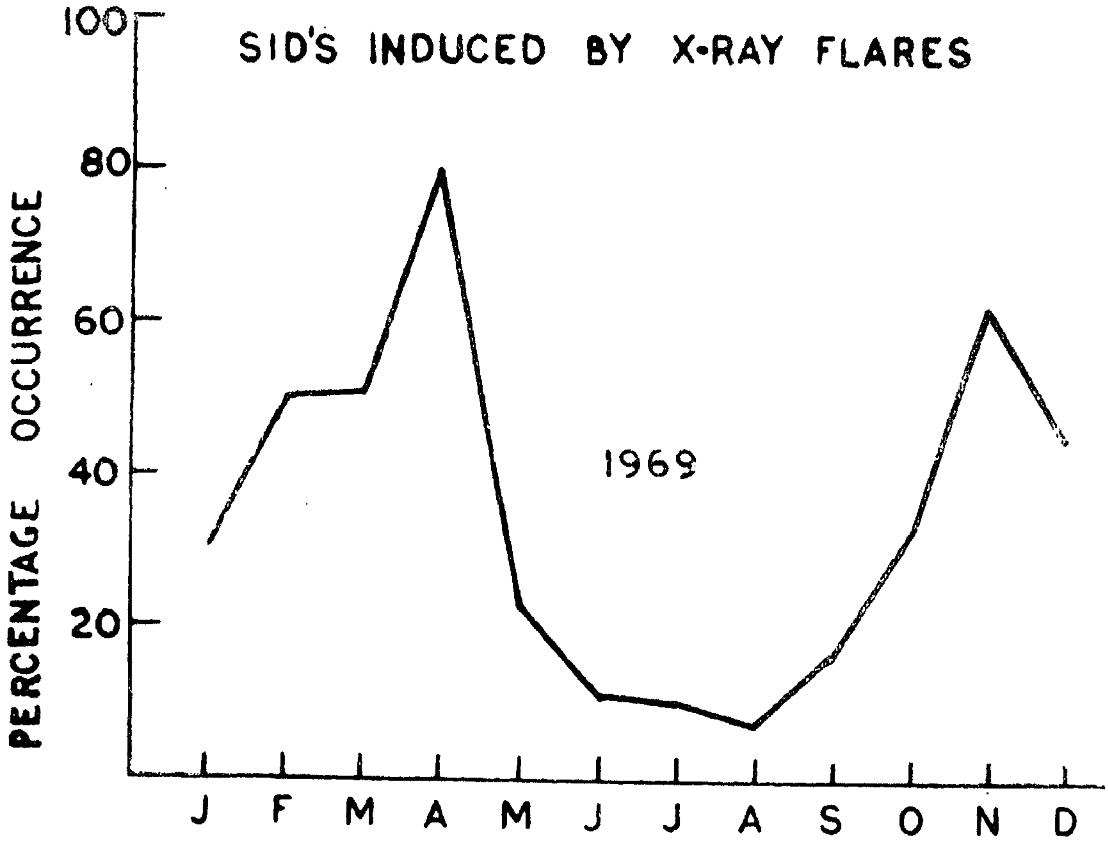

FIG. 6. Percentage of X-ray flares observed in each month in satellites in 1969 which produced measurable effects on 164 kHz radio amplitudes at Ahmedabad.

6. The difference in behaviour can be understood if we remember that long-distance reflection of LF radio waves depends on the distribution of electron density in the daytime D-region below about 85 km, and that the harder X-rays penetrate to greater depths in the atmosphere. It is known that in general, there are two reflecting regions, one between 82 and 87 km (D_2) above which the electron density increases rapidly with height, and another lower region at 70–75 km (D_1) (Lauter, 1966). Between D_1 and D_2, the rate of increase of electron density with height is comparatively small. In the summer months and at small zenith angles of the sun, D_1 has sufficient electron density to reflect 164 kHz, and the effect of a flare is to increase the electron density at the lower level and thus increase the

field-strength. In winter and equinoxes and particularly when the zenith distance of the sun is large, the lower D_1 layer is weak and reflection takes place from the higher level D_2. When there is a burst of hard X-rays, there is increased ionization below D_2 and even down to D_1, and consequent *temporary* increased absorption. This leads to a Type B response. The initial dip depends on the zenith distance of the sun. It is weak or absent when the sun is high, and the dip is greater the greater the zenith

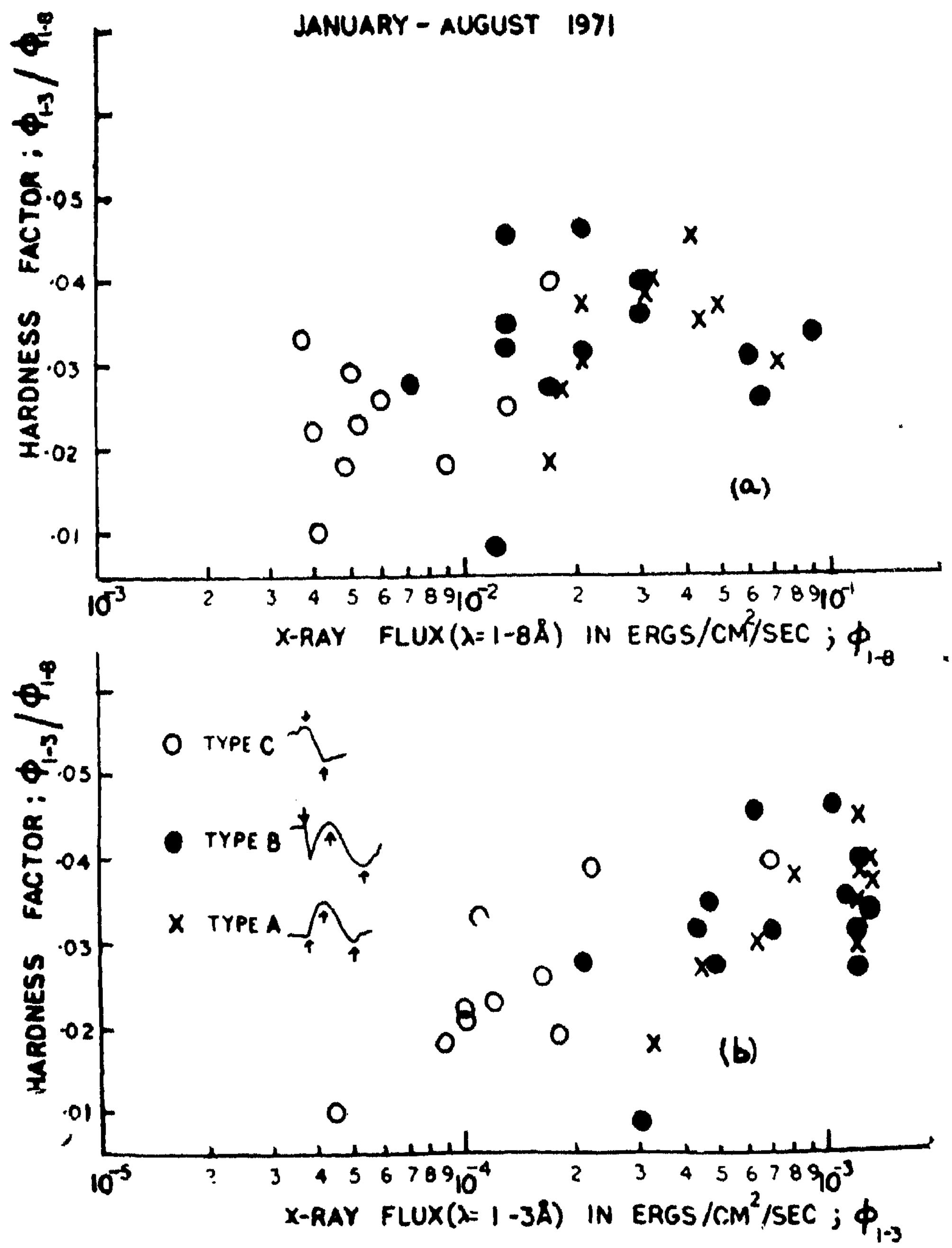

FIG. 7. Distribution of the three types of effect observed in the 164 kHz radio intensity a Ahmedabad in relation to the maximum hardness factor ϕ (1–3Å)/ϕ(1–8 Å) in the X-ray flares during January-August, 1971.

distance of the sun. When the hardness of the X-rays is small or the solar zenith distance is large, the reflection continues to take place from D_2 and there is only a temporary increase in ionization below D_2 leading to a C type absorption.

7. CONCLUSION

The comparison of X-ray flares observed in satellites and their manifestation in the field-strength records of 164 kHz radio waves received at Ahmedabad from Tashkent show that almost all the flares between 0200–1200 hr U.T. during the period 27 October to 3 November, 1968, were able to influence the signal intensity. The starting time and peak time of the X-ray flare and the sudden changes in 164 kHz radio signal agreed within a few minutes. The flare effect on the signal strength persists for a longer time than the flare itself.

The effects of even small X-ray flares on 164 kHz field-strength can be seen at Ahmedabad and Poona whereas only bigger flares show up at Delhi often with a pronounced initial dip. This suggests that the distance between the transmitter and receiver plays an important role in the observable effects on LF propagation; the longer the distance, the better is the effect observed. The details of the X-ray flux variations during a flare and the associated changes in radio signal intensities (164 kHz) at Ahmedabad and Delhi are under further study.

ACKNOWLEDGEMENTS

Our thanks are due to Prof. R. G. Rastogi for his interest in the work. One of the authors (S. C. C.) was the recipient of a Research Scholarship from the Department of Atomic Energy.

REFERENCES

Alurkar, S. K. .. *Ph.D. Thesis*, (Gujarat University), 1963.

Ananthakrishnan, S. .. *Ibid.*, 1967.

———. .. *Brazilian Journal of Physics*, 1971.

Chakravarty, S. C. .. Unpublished, 1971.

Chubb, T. A., Friedman, H. and Kreplin, R. W. *J. Geophys. Res.*, 1960, **65**, 1831.

Friedman, H., Chubb, T. A., Kupperian, J. E., Jr., Kreplin, R. W. and Linsay, J. C. *Annales de Geophys.*, 1958, **14**, 232.

Kreplin, R. W., Chubb, T. A. and Friedman, H. .. *J. Geophys. Res.*, 1962, **67**, 2231.

Kreplin, R. W. .. Solar X-ray data for three 1968 flares; *NSSDC*, 1971, pp. 70–75.

Lauter, E. A. .. *Space Res.*, *VII*, 1966, **1**, 212.

Shirke, J. S. and Alurkar, S. K. *Proc. Ind. Acad. Sci.*, 1963, **57A**, 49.

Somayajulu, Y. V. and Aikin, A. C. *Aeronomy Report No. 32.* University of Illinois, 1969, p. 373.