

CENTIMETER-WAVE RADIO AND X-RAY EMISSION FROM THE SUN*

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The generation of solar radio waves on centimeter wavelengths appears to be closely associated with the production of X-rays during both quiet and disturbed periods of the Sun. The theory of solar X-rays shows that the temperature of the corona as deduced, among other methods, from radio observations can adequately account for the quiet X-radiation from the Sun. The dense hot regions (sources of slowly varying component on centimeter and decimeter waves) can be identified with the localized regions of X-radiation of increased intensity and of higher quantum energy and are consequently the sources of slowly varying X-radiation. Both the quiet and the slowly varying radio and X-ray emissions can be explained by thermal Bremsstrahlung mechanism. During solar flares bursts of centimeter-wave radio emission and X-rays of high and low energy occur simultaneously. The high energy X-ray bursts are due to non-thermal Bremsstrahlung, while the associated cm- λ radio bursts can be due to synchrotron radiation of the high-energy electrons. In this review, we shall discuss the various relationships existing between solar radio emission and X-radiation.

An Outline of the Theory of Solar X-Rays

The radiation of the sun in the wavelength range of X-rays arises due to the high temperatures of the emitting layers in the solar atmosphere namely the corona, the region of transition between the corona and the chromosphere and the dense hot regions. The flux of X-radiation is dependent upon the electron density, the relative abundance of elements and the temperature of the emissive regions. If a state of ionization equilibrium is assumed, there must be a balance between the rate of ionization by electron impacts and radiative recombination. On the basis of ionization equilibrium, several authors have calculated the X-ray intensity to be expected. On the assumptions of ionization equilibrium and a uniform temperature distribution, the electron temperature in the corona can be determined from the ratio of the intensities of the green and red coronal lines. The temperature thus determined is of the order of 10^6 K or higher (ELWERT, 1961). Doppler profiles of coronal emission lines indicate higher temperatures in the corona, but the temperatures determined from the line

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profiles should be considered as upper limits, since the lines can be broadened by turbulent motions. Observations by BILLINGS (1959) of line widths (a) of the green line (5303 Å Fe XIV) and the red line (6374 Å Fe X), and (b) of the yellow line

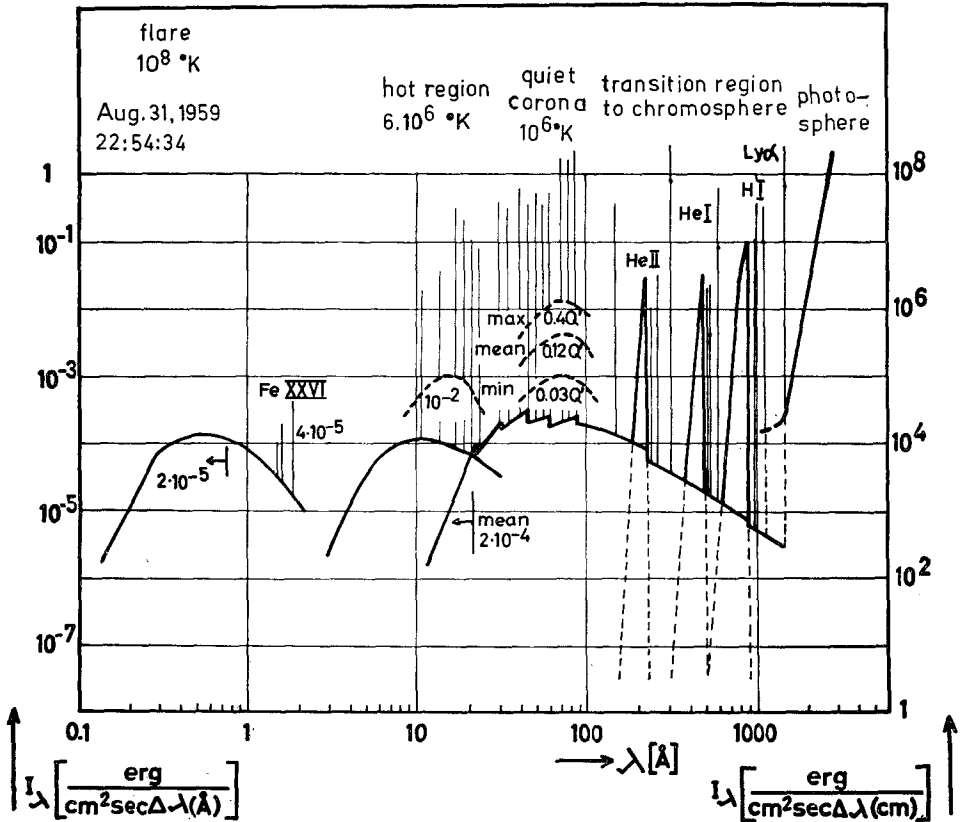


Fig. 1. The X-ray spectrum of the sun. The radiation of the quiet Corona and the transition region exists permanently, whereas the X-ray emission of hot regions appears only with the appearance of such regions on the disc. The X-radiation below 1 Å during flares disappears after a few minutes. An uncertainty factor in the computation of the line intensity arises from the excitation cross-sections and is denoted by Q' . The dashed curves between 40 and 100 Å represent the total line emission in this wavelength range (After ELWERT, 1961).

(5694 Å Ca XV) in coronal condensations yield temperatures of about (a) 2.4×10^6 K and (b) 3.5×10^6 K respectively. Also, the radio observations indicate temperatures of a few million degrees Kelvin in the corona. If one calculates the emission spectrum for such high temperatures, then the computed radiation falls in the soft X-ray region corresponding to quantum energies of a few hundreds of electron volts. The emission spectrum is found to be composed of a continuous background on which are superimposed many discrete emission lines.

The continuous radiation is accounted for by free-free transitions or Bremsstrahlung, recombinations and line emissions. The power radiated by Bremsstrahlung per cm^3 and second is given, according to ELWERT (1961) by

$$I = N_i N_e 7.10^{-41} \left(\frac{10^6}{T_e} \right)^{\frac{1}{2}} e^{-\frac{h\nu}{kT_e}} \bar{g} \text{ dverg/cm}^3 \text{ sec},$$

where N_e and N_i are the electron and ion density respectively, \bar{g} is the Gaunt factor which was first used in the calculation of X-ray emission by KAZAČEVSKAJA and IVANOV-HOLODNYI (1959). According to ELWERT (1961) the intensity of continuous radiation is not significantly changed through the use of the Gaunt factor which is of the order of 1. Below the Lyman- α limit ($\lambda < 912 \text{ \AA}$) part of the continuum is produced by free-bound transitions of hydrogen. An additional contribution comes from the recombination in the He II continuum below 304 \AA . At shorter wavelengths, continuous radiation is emitted by recombination of electrons and heavy ions (FRIEDMAN, 1959b).

According to ELWERT's calculations (1959), the recombination intensities are proportional to the product $N_e N_i$ or N_e^2 . ELWERT considered the ions as hydrogen-like, assumed an isothermal corona, and used the Baumbach model of electron density distribution with height. In the region concerned, the electron densities range from 10^9 to 10^6 cm^{-3} .

The computation of the line emission consists of (1) investigating the energy-level schemes of highly ionized atoms to determine the possible emission wavelengths, (2) determining the probability of recombination into excited states followed by line emission, and (3) determining the probability of direct excitation by electron impact. Although some of the line emissions follow recombinations into excited states, the process of electron impact excitation is the most important, and maximum intensity occurs around 80 \AA for 7.10^{50} K and around 60 \AA for 10^{60} K .

ELWERT (1961) has calculated the intensities of X-rays emitted within the normal corona, the transition region (lying between 4 000 and 14 000 km above the photosphere) and the dense hot regions. In his calculations, ELWERT has assumed line emissions and free-bound and free-free emissions. His results are summarized in Figure 1. The emission lines appear to make a much more important contribution than the continuum. The radiation of the quiet corona and of the transition region exists permanently, whereas the emission of dense hot regions occurs only when such regions are present in the sun's atmosphere. The line emission and the continuous spectrum of such a region with a temperature of 6.10^{60} K and a value of the integral of the square of electron density corresponding to a coronal condensation of mean size, is also shown in Figure 1. ELWERT compared his theoretical results with the rocket measurements of FRIEDMAN *et al.* (1952) under quiet conditions and found that for wavelengths above 20 \AA , the theory of continuous radiation of the quiet corona at 10^{60} K can account for most of the observed X-rays. For X-rays below 20 \AA , the radiation from dense hot regions is much more important than due to the quiet corona. The relative intensity distribution of X-rays across the solar disc can also be

calculated. Since the X-ray fluxes are proportional to the integral over N_e^2 along the line of sight, a limb brightening results. Using WALDMEIER's model for the electron density distribution of an oblate corona and considering line absorption, ELWERT (1961) obtained the intensity distribution as shown in Figure 2. The center-to-limb variation of solar X-radiation, showing enhanced limb-brightening was also computed by ŠKLOVSKI (1950). The total remaining intensity during the totality of an eclipse should then be a function of the ratio of the apparent radii of the moon and the sun.

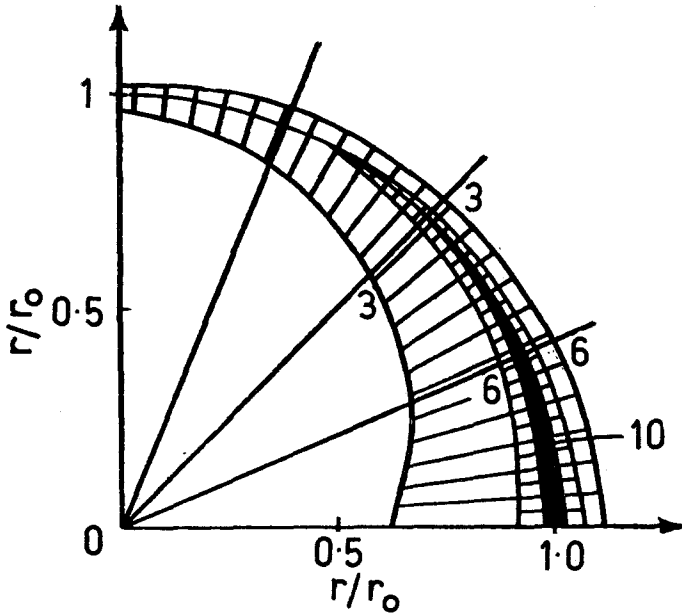


Fig. 2. Intensity distribution of the X-radiation across the disk of the sun. The figure shows relative intensities; r_0 is the radius of the photospheric disk. (After ELWERT, 1961).

The limb brightening has actually been observed by FRIEDMAN (1959a) and the residual intensity of X-rays observed during a total eclipse agreed with the theoretical calculations.

Centimeter-Wave Bright Regions and X-Rays

Interferometric measurements over a wide range of wavelengths between 3 and 21 cm show that the bright regions (responsible for slowly varying component of solar radiation) having electron density of about 10–20 times the density in the innermost corona have brightness temperatures of 2 to 5 million degrees. Also, as has already been mentioned, measurements of the yellow coronal line indicate hot regions of temperatures about 4 million degrees. The existence of such high temperatures in localized bright regions leads naturally to the emission of X-rays. If one calculates the intensity of X-rays emitted from these hot regions with a temperature of 6.10^6 K,

the total flux below 20 \AA , (both continuous and line emission) is found to be of the order of $10^{-2} \text{ erg/cm}^2 \text{ sec}$. Assuming a temperature of 3.10^{6° K , the maximum intensity would be at about 20 \AA . The electron density, the size and the temperature of the regions may, however, vary from one region to the other; also several bright regions may be simultaneously present. In any case, the X-ray fluxes observed by FRIEDMAN between 10 and 30 \AA are of the order of $10^{-2} \text{ erg/cm}^2 \text{ sec}$. Thus, the solar X-radiation has also a slowly varying component originating in localized hot regions which are

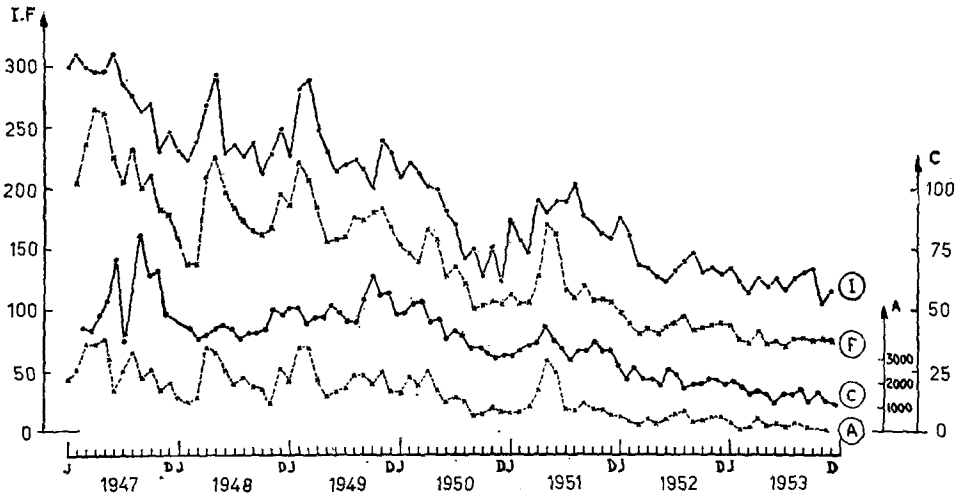


Fig. 3. Variations of the ionospheric index I ; $10.7 \text{ cm-}\lambda$ flux density F ; intensity of the green coronal line C and sunspot area A over the years 1947–1953. (After DENISSE and KUNDU, 1957).

identified with the sources of slowly varying component on centimeter and decimeter waves. This identification is supported by the following two relationships.

I. RELATIONSHIP USING IONIZATION OF THE IONOSPHERIC E-LAYER

It is known that there is a general relation between the ionization of the E-layer of the ionosphere and the solar activity as indicated by the area or the number of sunspots present on the solar disc. However, between maximum and minimum of the solar cycle, the critical frequency of the E-layer varies only in a ratio of the order of 1.3 whereas the sunspots disappear completely during solar minimum.

At present it is known that the E-layer ionization is caused by solar X-radiation of wavelengths lying between 10 and 100 \AA . As discussed in the preceding sections, this radiation, if of thermal origin, can be generated in discrete regions of the solar corona, having temperatures greater than about 10^{6° K . On the other hand, the radio bright regions, also believed to be of thermal origin, have brightness temperatures greater than about 10^{6° K on wavelengths between 3 and 21 cm . These facts suggested a possible relationship between solar radio emission on centimeter and decimeter

wavelengths and solar X-radiation measured indirectly by the ionization of the E-layer of the ionosphere.

DENISSE and KUNDU (1957) pointed out that a good correlation exists between E-layer ionization and solar radio emission on decimeter waves. Their study was based upon observations of solar radio emission made by COVINGTON at Ottawa on 10.7 cm wavelength and measurements of E-layer critical frequency (f_0E) made at Freiburg and Puerto Rico. Studies of correlation between 10.7 cm- λ solar radio emission and E-layer ionization on both monthly and daily basis led them to suggest that the flux density of solar radiation on 10.7 cm wavelength can be used as a solar index for ionospheric studies; this index is as good as any other index (WOLF's sunspot number

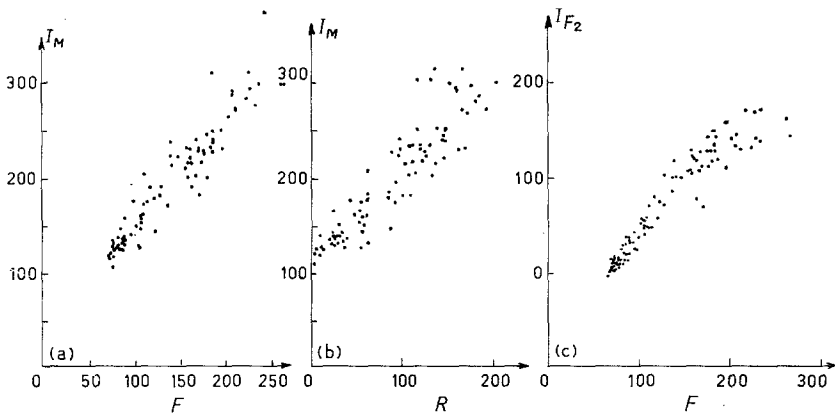


Fig. 4. Correlation diagrams of monthly mean values of solar and ionospheric indices: (a) E-layer ionization index I_M versus 10.7 cm- λ solar radiation F expressed in 10^{-22} w cm^{-2} (c/s) $^{-1}$. (b) I_M versus Zurich sunspot number R . (c) Ionization index of the F2 layer (I_{F2} - prepared by MINNIS) versus F . (After KUNDU and DENISSE, 1958).

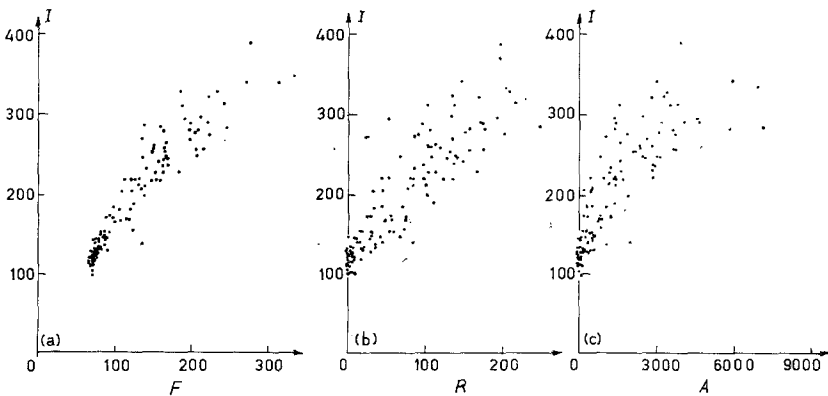


Fig. 5. Correlation diagrams of 5-day mean values of solar and ionospheric indices: (a) E-layer ionization index I versus 10.7 cm solar radiation F . (b) I versus Zurich sunspot number R . (c) I versus sunspot area A (After KUNDU and DENISSE, 1958).

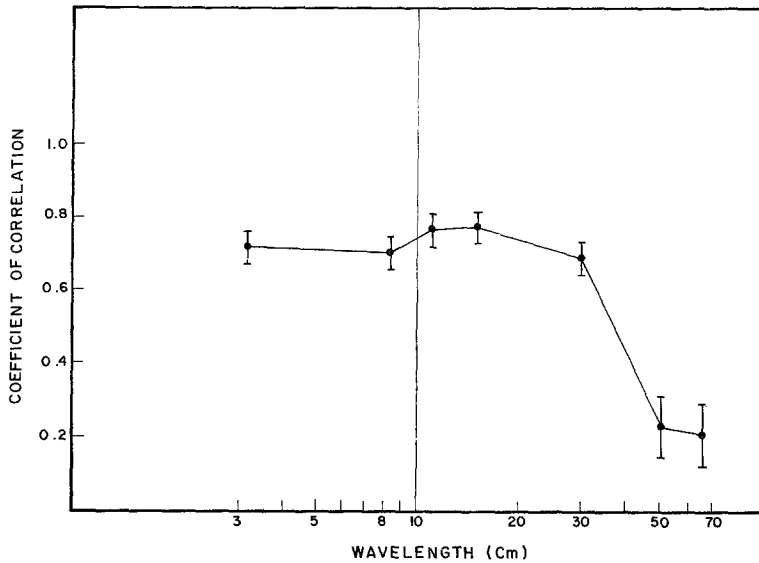


Fig. 6. Coefficient of correlation between 5-day mean values of the E-layer ionospheric index J_E and the flux density of solar radio emission as a function of wavelength. The short vertical lines at each wavelength represents the probable error. (After KUNDU, 1960).

and green coronal line) on a time scale of the order of a month or larger, and it is better than the others on a shorter time scale (KUNDU and DENISSE, 1958). These relationships are shown in Figures 3, 4 and 5.

In studying these relationships, the selection of 10.7 cm wavelength was made mainly for the reason that measurements of solar decimeter radio emission were available at this wavelength over a period of more than one solar cycle and were probably internally consistent with a relative accuracy of a few per cent (MEDD and COVINGTON, 1958). With the subsequent availability of equally precise measurements (TANAKA, 1955) of solar radio emission on other centimeter and decimeter wavelengths, KUNDU (1960) studied the relationship between E-layer ionization and solar radio emission over different wavelengths in the centimeter and decimeter regions.

It was found that solar radio emission at any wavelength in the range 3 to 30 cm is closely correlated with the E-layer ionization of the ionosphere. The coefficient of correlation between the flux density of solar radio emission (in units of $10^{-22} \text{ w m}^{-2} (\text{c/s})^{-1}$) and the E-layer ionization index ($f_0 E^4 / \cos z$) is quite high (about 0.8) at all wavelengths between 3 and 30 cm, but it is very low at longer wavelengths of 50 and 65 cm (Figure 6). This fact suggests that a major part of the solar X-radiation (X-rays between 10–100 Å) responsible for E-layer ionization originates in the solar atmosphere below the height of origin of about 50 cm solar radio emissions.

II. RELATIONSHIP USING DIRECT MEASUREMENT OF X-RAYS

A striking direct evidence of the high correlation between solar X-rays (8–20 Å) and

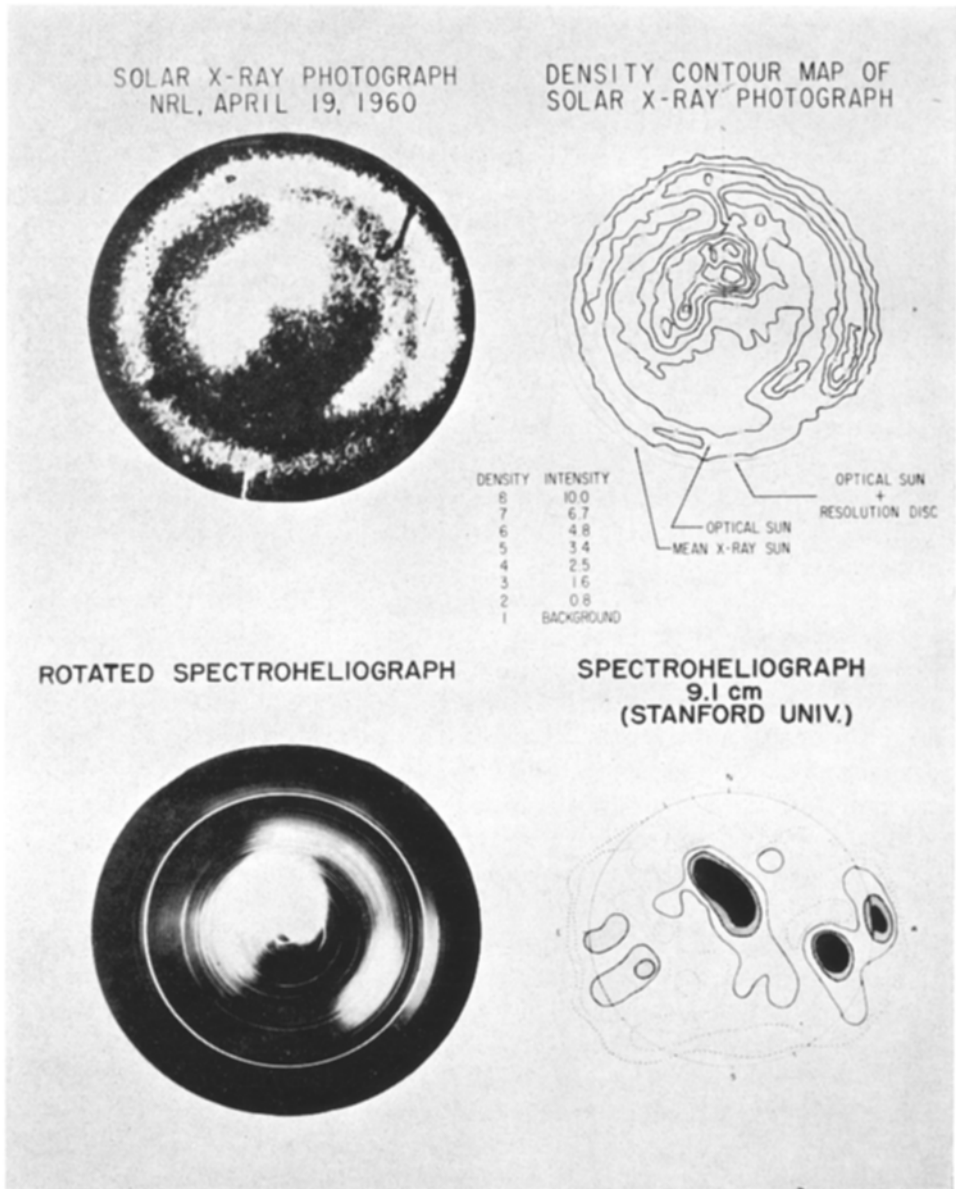


Fig. 7. The X-ray photograph of the sun obtained by the Naval Research Laboratory on April 19, 1960 with a pinhole camera flown in an Aerobee Rocket. The density contour map of the X-ray photograph and the Stanford radio heliogram of the sun on 9.1 cm- λ are also shown in the figure. The photograph of the radiospectro-heliogram with rotation introduced during exposure to match rotation of rocket X-ray camera is also shown for comparison (After FRIEDMAN, 1961).

the decimeter wavelength solar radio emission was shown by the rocket experiments of FRIEDMAN. In a rocket experiment performed during an eclipse, it was observed that the intensity of X-rays varied in parallel with the 10.7 cm- λ radiation (FRIEDMAN, 1959a). In another experiment, an X-ray photograph of the sun at wavelengths shorter than 60 Å was taken during a rocket flight (FRIEDMAN, 1961). This X-ray picture is shown in Figure 7. A comparison of this picture with the photograph taken in the CaK line on the same day shows a very good correlation when allowance is made for the rotation of the camera. Two bright plage areas on the W-limb, a plage appearing a day later on the E-limb and a bright plage in the N-E quadrant account for most of the X-ray emission. These discrete X-ray emitting regions also resemble the sources of the slowly varying component of radiation on centimeter and decimeter waves. When this X-ray picture of the sun is compared (Figure 7) with a high resolution map of the sun on centimeter waves (for example, the 9.1 cm- λ map of Stanford obtained with a pencil beam of about 2' arc), one finds a very close correspondence between regions of emission of X-rays and centimeter waves. All these observations point to a very close association between solar X-rays and solar radio emission on centimeter and decimeter waves.

Recently, FRIEDMAN and his associates of the Naval Research Laboratory have been observing solar X-rays in the wavelength range 2–8 Å by means of satellites (KREPLIN *et al.*, 1962). From the published data it appears that X-rays in this range are often observed without any visible flares or radio bursts. Their intensity is of the order of 10^{-3} ergs/cm² sec or less. These X-rays are probably to be associated with the bright regions on centimeter and decimeter waves, which can attain brightness temperatures of $2 - 3 \times 10^6$ K or more.

Bursts of Radio Emission and X-rays During Solar Flares

I. RELATIONSHIP USING IONOSPHERIC D-LAYER ABSORPTION (SID)

It has been observed by FRIEDMAN by means of rocket experiments that flare-time X-rays in the 2–10 Å range are the main components of radiation responsible for enhanced ionization in the D-region of the ionosphere (Sudden Ionospheric Disturbance or SID). ELWERT (1961) as well as FRIEDMAN (1959) have suggested that the presence of hot regions in the corona, having temperatures of the order of 10^7 ° K or higher can produce the required X-radiation. Evidence of such high temperatures is found in radio bursts. Consequently a study of solar burst radiation during sudden ionospheric disturbances (SID) is suggested.

Such studies of relationships between SID's and solar radio bursts were made by HACHENBERG and VOLLAND (1959), HACHENBERG and KRÜGER (1960) and HAKURA (1958). These authors established that sudden ionospheric disturbances are very closely associated with bursts in the centimeter wave region. They also found that the ionizing radiation responsible for excessive absorption in the D-region runs nearly parallel to that of the centimeter-wave burst radiation and in many cases their maxima coincide. The percent association between SID's and cm- λ bursts appears to increase

with the intensity of cm- λ burst intensity and maximum a loose connection between cm- λ burst intensity and absorption in the ionosphere seems possible. These relationships are illustrated by Figures 8 and 9. HACHENBERG and KRÜGER also found that the bursts not associated with SID are usually very weak in the cm- λ region and occur predominantly in the decimeter- and meter-wavelength regions. Furthermore, the SID-associated bursts have in many cases a sharp low-frequency cut-off – their intensity

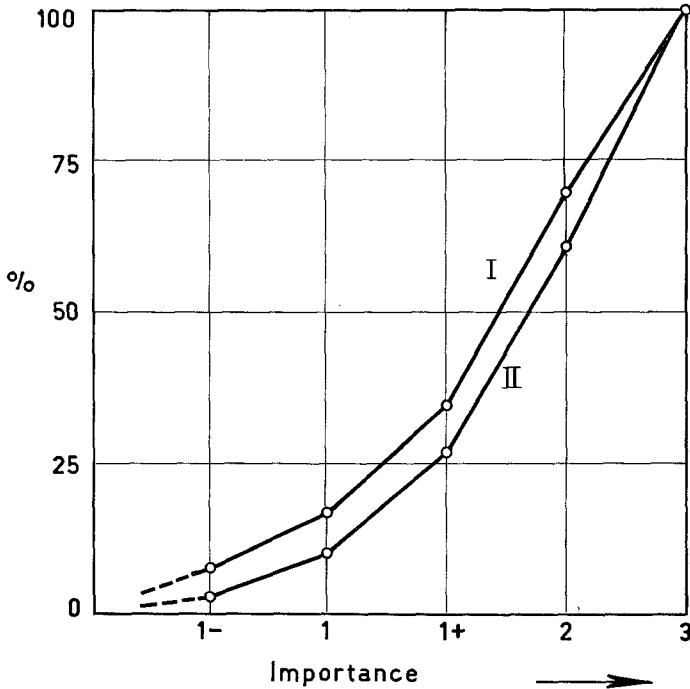


Fig. 8. Percentage of flares associated with cm- λ bursts (I) and SID (II), in the total number of flares of different importance. (After HACHENBERG and KRÜGER, 1960).

being very strong at 3 cm, weak at 10 cm and below the limit of detection at 15 and 20 cm wavelengths. This could be due to the fact that for a thermal source, the optical thickness, $\tau < 1$ for $\lambda > 20$ cm. The other possibility is that the bursts do not appear above $\lambda = 20$ cm only because the emitting plasma is lying below the level at which the refractive index $n = 0$ for $\lambda = 20$ cm; then the region of emission of the ionizing radiation must be less than about 10 000 km above the photosphere – i.e. the same region of emission as the short centimeter-wavelength bursts. In this connection, it should be remarked that from a study of limb flares and associated SID's, WARWICK and WOOD (1959) found that the occurrence of SID depends strongly on flare height and found a height of the order of 12 000 km for the SID producing ionization; however, they incorrectly interpreted their results in terms of Lyman- α radiation rather than X-radiation as the source of the radio fadeouts.

It is interesting to note that HAKURA (1958) independently found a close association between cm- λ bursts and SID's and observed that the power spectrum of the associated cm- λ bursts usually increases towards higher frequencies. Sometimes the power spectrum is flat. But a radio burst whose power spectrum increases towards lower frequencies is not usually followed by a pronounced SID.

A centimeter-wave burst is characterized by an initial rapid rise to a peak intensity and a rapid decline (the simple or impulsive burst); this is followed by a much slower decay, which is called the post-burst. Recently, KAWABATA (1960) has suggested, from a statistical study, that sudden ionospheric disturbances are closely related in frequency of occurrence and duration to post-burst increases of centimeter-wave burst radiation. Investigation of the spectrum of SID associated post-bursts shows that post-burst increases are caused by thermal emission from a hot plasma in the solar

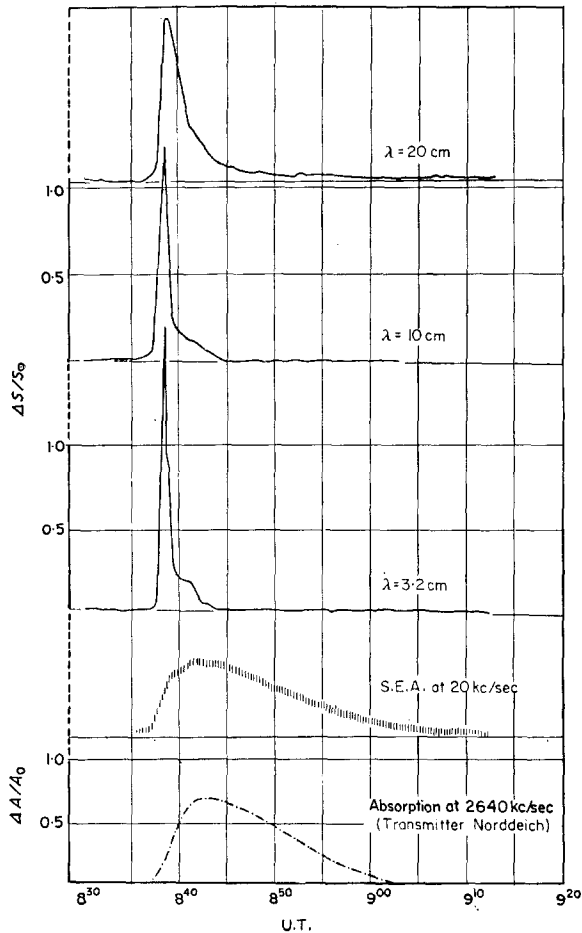


Fig. 9. The cm- λ radio burst of November 6, 1957 together with records of SEA and excessive absorption in the ionospheric D-layer (After HACHENBERG and KRÜGER, 1960).

corona. KAWABATA calculated its temperature to be as high as 10^7 to 10^8 K, assuming the size of the post-burst to be the same as that of the flare. He finds that such a hot plasma emits sufficient X-rays to explain the rocket observations of FRIEDMAN. KAWABATA extended ELWERT's calculations of intensities of X-rays emitted within

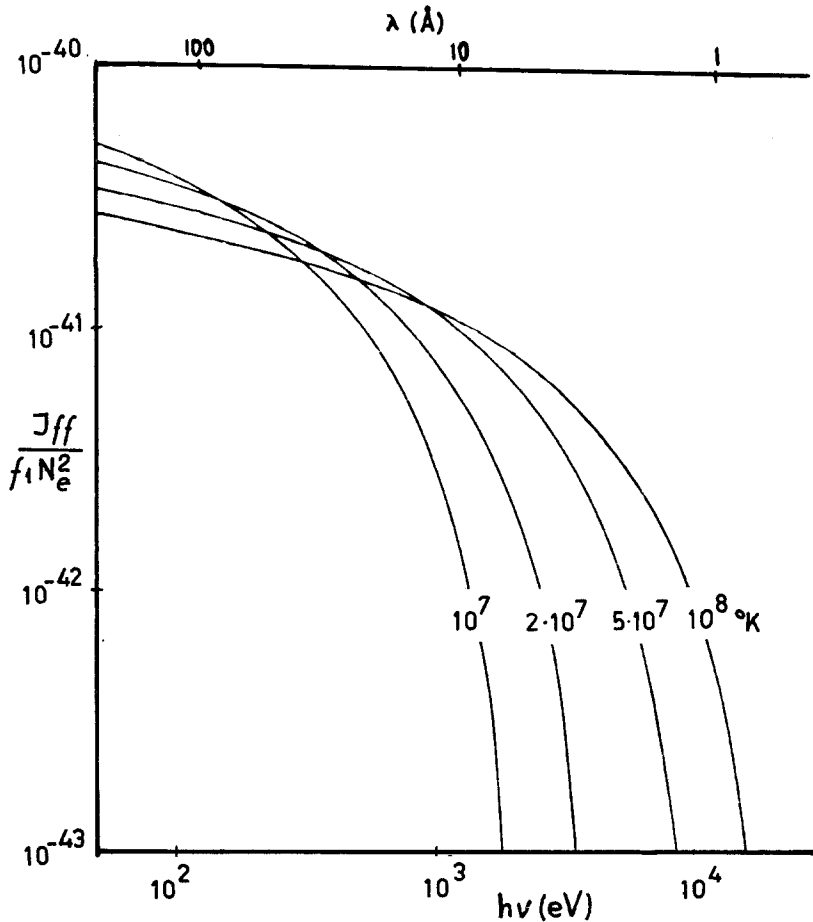


Fig. 10. Computed X-ray spectra of free-free emission. (After KAWABATA, 1960).

these hot regions. His results are summarized in Figures 10, 11 and 12. In these figures, J_{ff} and J_{fb} are the X-ray intensities in erg per cm^3 per second emitted by free-free and free-bound transition respectively; f_1 is the uncertainty factor in the cross-section for photo-recombination. J_L is the line emission in erg per cm^3 per sec and f_3 is the uncertainty factor in the cross-section for collisional excitation. N_e is the electron density per cm^3 .

KAWABATA finds that between 2 and 8 Å, X-rays are emitted mainly by the free-

bound transition of K-shell electrons of C, N, O and Ne for temperatures below 3×10^7 K, and by free-free transition for temperatures above 3×10^7 K. X-rays with energy above 20 keV are emitted mainly by free-bound transition of K-shell electrons of Fe. As regards the total intensity integrated over the whole frequency range, most of the radiation is emitted by free-free transition. KAWABATA estimated

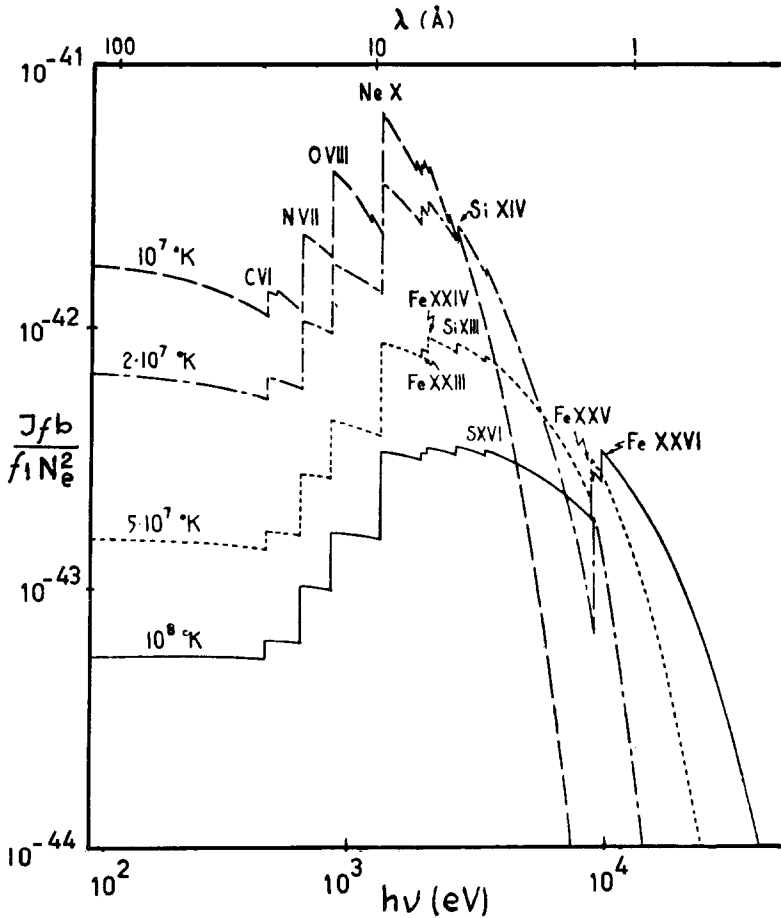


Fig. 11. Computed X-ray spectra of free-bound emission (After KAWABATA, 1960).

TABLE 1
X-ray Flux in $\text{erg cm}^{-2} \text{sec}^{-1}$

	10^7 °K	2×10^7 °K	3×10^7 °K	10^8 °K	Observed Values
> 20 keV	—	1.6×10^{-6}	2.9×10^{-4}	2.1×10^{-3}	2.3×10^{-5}
$2 - 8$ Å	2.1×10^{-2}	2.7×10^{-2}	4.6×10^{-2}	7×10^{-2}	10^{-2} —

$\int N_e^2 dV$ (V is the volume of the emissive region) to be about $3 \times 10^{49} \text{ cm}^{-3}$ from cm- λ post-burst increases and found that the observed X-ray fluxes on the earth agreed reasonably with his computed values, as shown in Table 1.

The following remarks may be appropriate with regard to KAWABATA's results. Firstly, many cm- λ bursts without any apparent post-burst increase are associated with SID, and the duration of a SID is to a large extent determined by the recombination coefficient of electrons in the D-region. Secondly, KAWABATA's estimate of the temperature of post-burst increases ($> 10^7$ K) made by using the same area

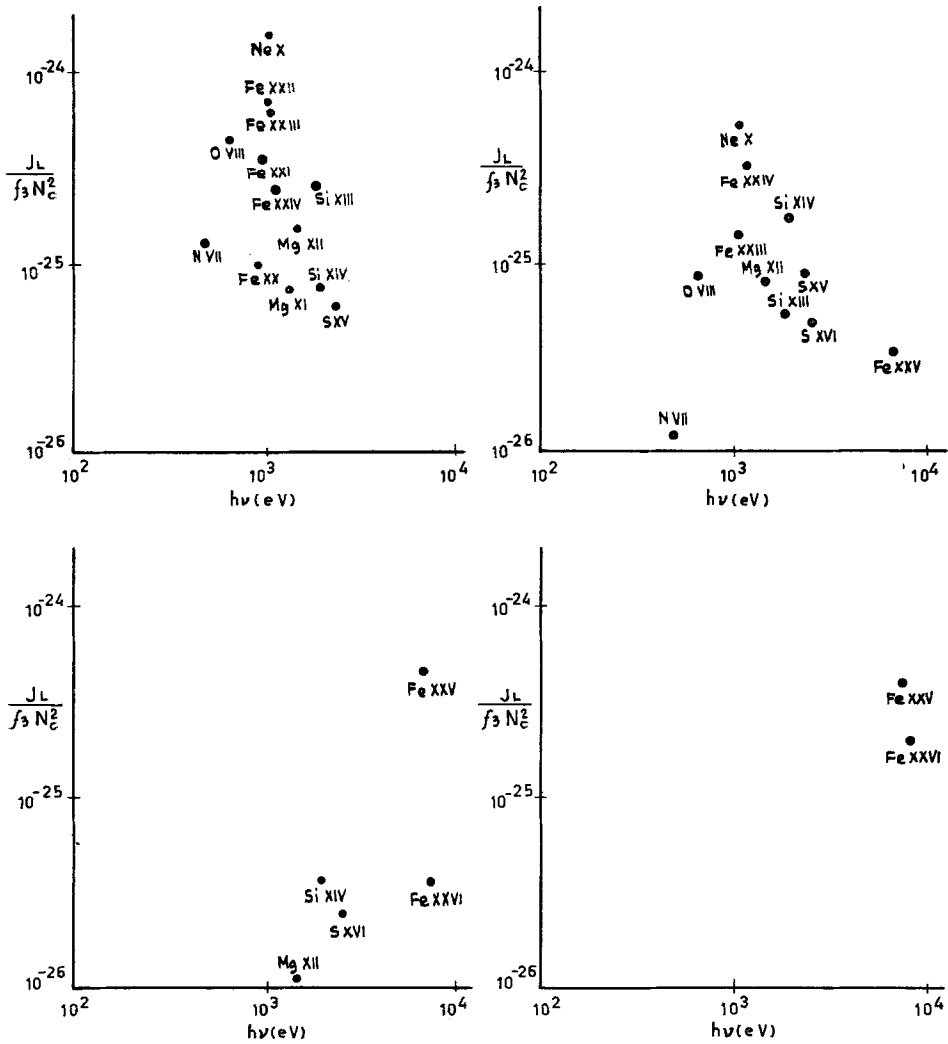


Fig. 12. Computed X-ray spectra of line emission (a) 10^7 °K, (b) 2×10^7 °K, (c) 5×10^7 °K, (d) 10^8 °K.

as that of the visible flare, is higher than the temperature of about 10^6 ° K determined by using the burst diameter of about 3' estimated from interferometric measurements (KUNDU, 1959). However, the brightness temperature of the cm- λ burst at its maximum can reach a value of 10^7 ° K or higher (corresponding burst diameter 2' or lower) and the calculations will then be valid. It is highly probable that X-rays in the 2-8 Å range

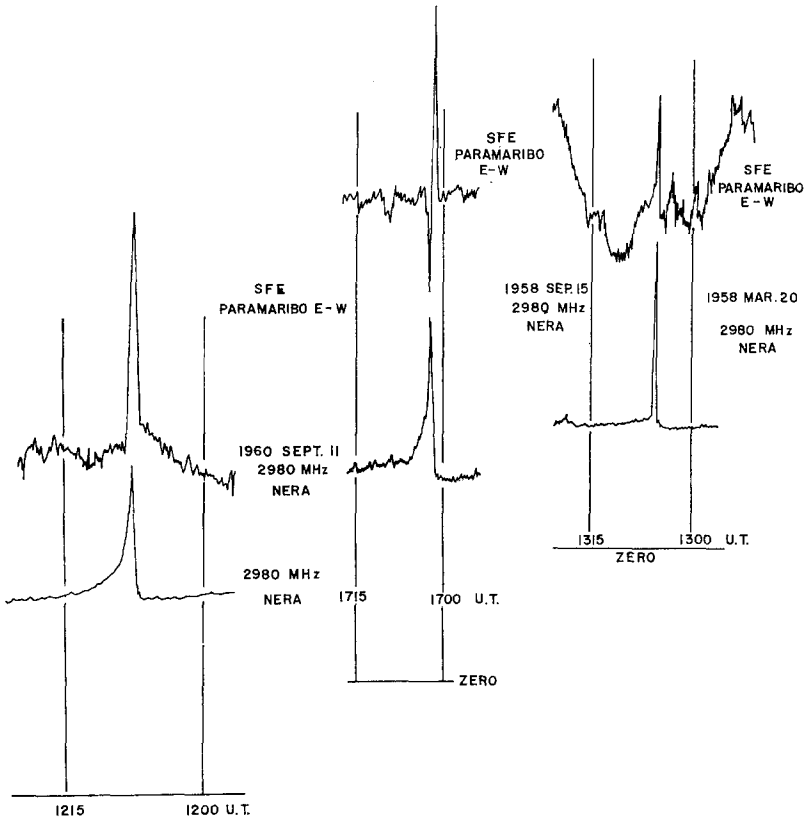


Fig. 13. Records of three geomagnetic crochets compared with the simultaneous 2980 Mc/s records of bursts associated with solar flares. (After FOKKER, 1962).

are caused by both thermal radiation of the plasma as well as by superthermal electrons giving rise to a non-thermal Bremsstrahlung X-radiation. The same electrons will probably cause cm- λ burst emission by thermal plus synchrotron radiation.

II. RELATIONSHIP USING GEOMAGNETIC CROCHETS

Another indirect evidence of high correlation of cm- λ bursts and X-ray bursts from the sun has recently been provided by FOKKER (1962). Fokker showed that there is a very good correspondence between the geomagnetic solar flare effects (crochets) as

indicated by the earth potential measurements at an equatorial station and the cm- λ bursts. The two phenomena start suddenly and practically simultaneously, as shown in Figure 13. The crochet-associated cm- λ bursts are impulsive in nature and the associated flares show an explosive phase at their onset (ELLISON, 1950; ELLISON *et al.*, 1960). It is believed that hard X-ray emissions of wavelengths $< 2 \text{ \AA}$ are responsible for producing geomagnetic crochets and consequently the above relationship suggests an intimate association of high energy X-ray bursts with cm- λ bursts. However, in order to establish unambiguously the high energy X-radiation as the cause of geomagnetic crochets, it is highly desirable to compare bursts of high energy X-rays

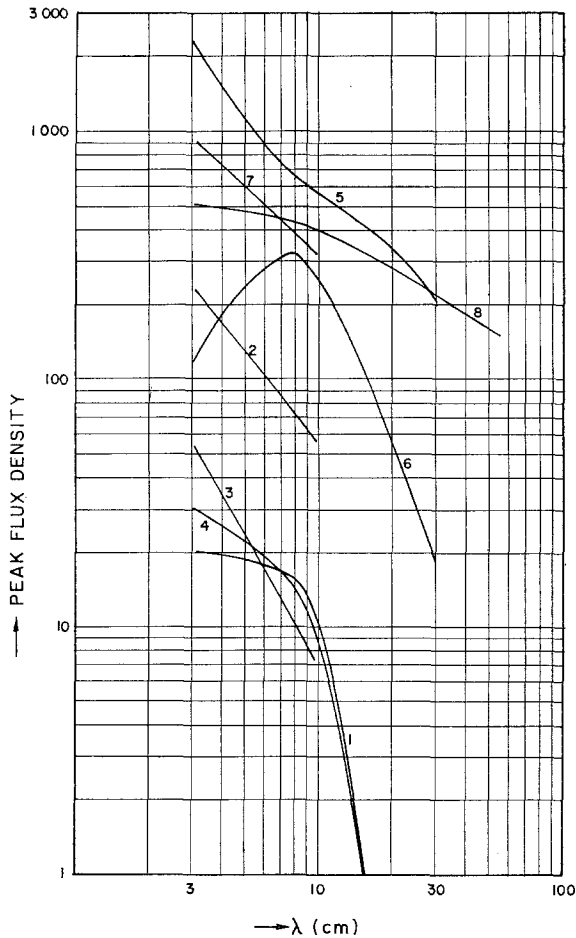


Fig. 14. The spectra of cm- λ bursts associated with the X-ray bursts observed by the NRL satellite in the range of wavelengths 2–8 \AA . The events of July 19, 1960 (1), July 20, 1960 (2), August 6, 1960 (1509 U.T.) (3), August 7, 1960 (0503 U.T.) (4), were not associated with any concurrent emission on meter waves. The remaining four events for which the cm- λ peak flux was higher, were associated with meter- λ bursts.

observed from rockets and satellites with geomagnetic or geoelectric records taken simultaneously at some equatorial stations.

III. RELATIONSHIP WITH LOW ENERGY X-RAYS (DIRECT MEASUREMENT)

As previously mentioned, FRIEDMAN and his colleagues at the Naval Research Laboratory have been measuring 2–8 Å X-rays by means of satellites. X-rays in this range are sometimes observed without any accompanying solar flare. The intensity of X-rays in this 2–8 Å range is weak (less than 10^{-3} ergs/cm²/sec), and these X-rays in nonflare conditions are attributed to localized regions identifiable with the radio bright regions on centimeter and decimeter wavelengths. The intensity of these X-rays increases greatly (by more than a factor of 2) during a solar flare. An analysis of the NRL satellite data of X-rays reveals that nearly all cases of increase of intensity of 2–8 Å X-rays are associated with cm-λ radio bursts. An exception is the event of July 24, 1960, when a significant increase of 2–8 Å X-ray flux (peak flux $\sim 5 \times 10^{-3}$ erg/cm²/sec) was observed in association with a large prominence on the limb (KREPLIN *et al.*, 1962). No significant increase of centimeter-wave radio emission (peak flux $< 5 \times 10^{-22}$ Wcm⁻² (c/s)⁻¹) was associated with this increase of X-ray flux. Neither was there any associated burst on meter waves. The cm-λ bursts associated with the X-ray bursts have a sharp low-frequency cut-off and bursts on meter waves are observed only when the cm-λ burst intensity is very high. Some typical spectra of cm-λ bursts associated with the 2–8 Å flare X-rays are shown in Figure 14. These spectra will be discussed in the next section in connection with high energy X-rays (> 20 kev).

IV. RELATIONSHIP WITH HIGH ENERGY X-RAYS (DIRECT MEASUREMENT)

High energy (> 20 kev or < 0.6 Å) solar X-ray emission during flares has been measured directly with the help of rockets and balloons by various workers (CHUBB *et al.*, 1960; PETERSON and WINCKLER, 1959; WINCKLER *et al.*, 1961; VETTE and CASAL, 1961; KREPLIN *et al.*, 1962). Thus, PETERSON and WINCKLER (1959) reported a short lived burst (≈ 18 sec duration) of radiation in the 200–500 kev region, occurring simultaneously with the flash phase of a solar flare. CHUBB, FRIEDMAN and KREPLIN (1960) found three cases of less energetic emission (20 \sim 80 kev) during flares of importance 2+ or 3. X-rays were observed at altitudes below 43 km in the two stronger flares. Figure 15 shows a plot of the number of X-ray quanta as a function of energy, measured from pulses produced in a scintillation spectrometer during the importance 2+ flare of August 31, 1959. The X-ray flux persisted throughout the 6 minutes duration of rocket measurement, but the two distributions at two different times show that a definite softening of the spectrum occurred during the period of observation (Figure 15). The total energy emitted in the high energy X-ray tail, about 4.5×10^{-6} ergs/cm²/sec for $E > 20$ kev, is only a small portion of the total X-ray emission accompanying a flare. No X-rays of $E > 20$ kev were observed by CHUBB, FRIEDMAN and KREPLIN in the firings conducted for background data in the absence of flares. The observation of X-rays in the quantum energy range 20–80 kev

TABLE 2
X-RAY EVENTS AND ASSOCIATED SOLAR RADIO BURSTS

Date	X-Ray			Cm- λ Burst			Flare			Meter- λ Burst	
	Time of Obs. (U.T.)	Energy kev	Time of Max. Count	Start End (U.T.)	Max. (U.T.)	P. Flux* Wavelengths cm	Start (U.T.)	Max. (U.T.)	Posn. Imp.	Time Type U.T.	Start of SID
March 20, 1958	1304.5-05	200-500	1304.6	1304-1309	1304.7	> 850	3, 10, 15, 21	3105 E	N23E29/2	No Event	1302
Aug. 24, 1959	2247	80	-	2237 > 2320	Indet.	> 150	10	2233 2239	N18E28/2+	No Event	2240
Aug. 31, 1959	2253	10-70	-	2236-2326	2248.8	77	3, 8, 15, 30	2235 2252	S08W46/2+	No Event	2242
Sept. 1, 1959	1700	80	-	1657.5-1713.5	1706	85	10, 15	1656 1707	S11W53/2+	No Event	1655
Aug. 11, 1960	1928-32	30	1927-28	1923.5-2000	1928	1100	10, 55	1924 1928	N22E27/3+	III 1925.9-28.8 II 1929 - 43.2 IV 1926 - 36	1925
Oct. 12, 1960	1730	20-80	1730	1725-1731	1726.5	29	10	1722 1728	S18W61/1	III 1725 - 30	1729
Oct. 12, 1960	1747-50	20-20	1748	1745.5-1752.5	1748	83	10, 55	1745 1749	N10W23/1	III 1745.5-47 II 1752 - 1802 IV 1753 - 1800	1744
Sept. 28, 1961	2214-22	20	2217	2213-2400	2217.5	1.8×10^8	3, 8, 15, 30, 55	2202 2224	N15E29/3+	III 2213.5-2220 II 2217.4-2231 IV 2212 - 2249	2211

during three flares accompanied by SID's led FRIEDMAN and his colleagues to suggest that the presence of such X-rays was characteristic of the flare process. The 20–80 keV X-rays appeared as an extension of the high intensity flux of 2–10 Å X-rays, which are the main components responsible for flare time enhanced D-layer ionization (SID).

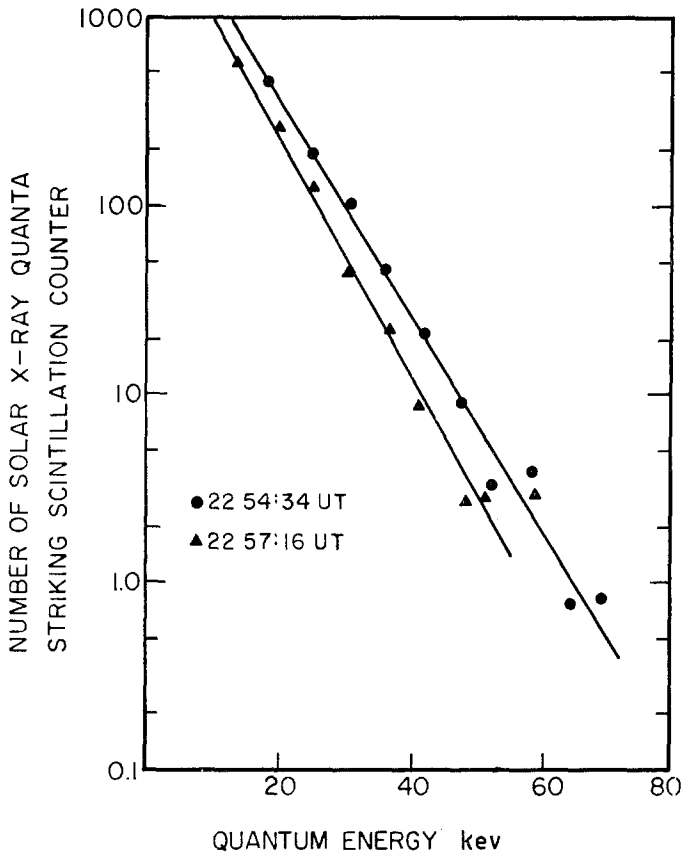


Fig. 15. Number of solar X-ray quanta striking scintillation counter as function of quantum energy at two times during the flare of August 31, 1959. (After CHUBB, FRIEDMAN and KREPLIN, (1960).

As discussed earlier, KAWABATA (1960) and ELWERT (1961) have theoretically computed the intensity of X-rays by thermal emission from very hot regions and have shown that the effective temperature of centimeter-wave bursts ($10^7 - 10^8$ K) is sufficient to explain the X-rays observed by FRIEDMAN during rocket flights. ELWERT also considered the non-thermal mechanism. According to DE JAGER (1960), such high energy X-rays cannot be explained by thermal radiation of the corona. The quiet corona, with an average kinetic temperature of 1.5×10^6 K, emits radiation with wavelengths > 10 Å. The radio bright regions may attain higher temperatures, but hardly exceed 10^7 K. For shorter wavelengths no appreciable thermal radiation

can be expected since (a) the ions that are able to emit radiation of that energy are not sufficiently abundant in the sun, and (b) temperatures of 10^7 ° K or higher have never been observed on the sun under quiet conditions. Nuclear radiation should also be excluded since the measured frequency is too high and density in the outer layers of the sun is too small to yield a sufficient intensity of high energy radiation. PETERSON and WINCKLER (1959) first proposed a non-thermal mechanism for the production of X-rays and suggested that high energy X-rays originate as Bremsstrahlung due to the

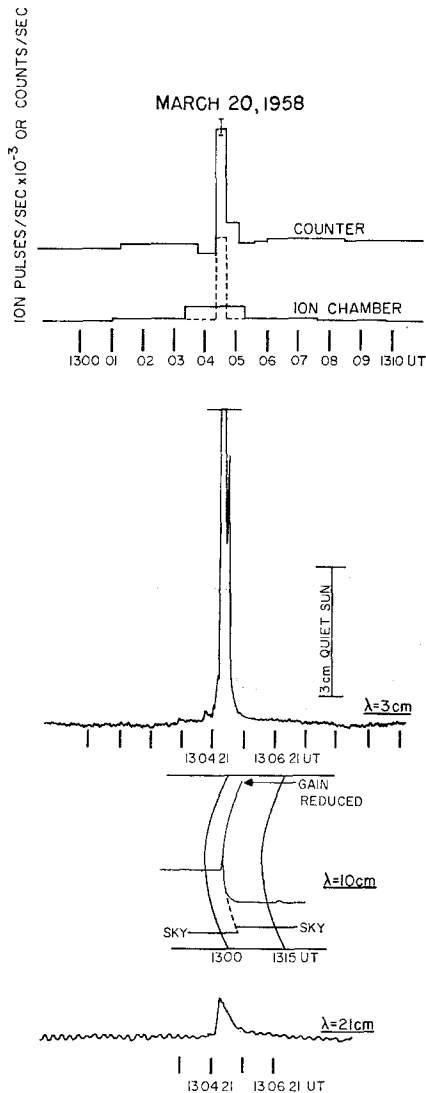


Fig. 16. The gamma-ray burst of March 20, 1957 observed by PETERSON and WINCKLER (1959), and the associated bursts on 3, 10 and 21 cm-wavelengths.

braking of high velocity electron jets in the flare or in the photosphere. In the development of this concept DE JAGER (1960) predicted a close association between meter-wave type III bursts (fast frequency drifting bursts) and flare X-rays. DE JAGER implied

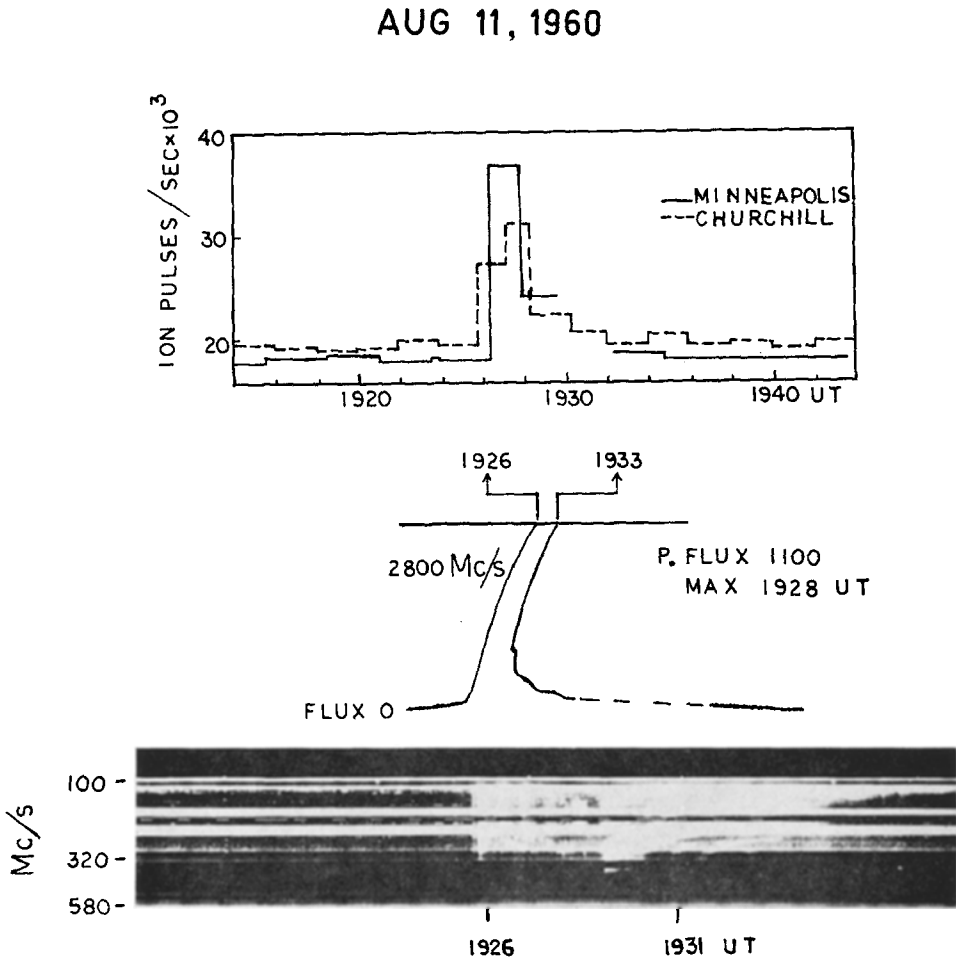


Fig. 17. Record of the X-ray event of August 11, 1960, together with the records of solar radio bursts on 2800 Mc/s of Ottawa and in the 100–580 Mc/s range of Michigan (After KUNDU, 1961).

that while high energy X-rays will be produced by the braking of energetic electrons in the dense flare region or in the photosphere, it is possible that some of the electrons generated will not brake and will excite type III bursts on their passage through the corona. This prediction appeared to be confirmed by the subsequent observations of WINCKLER *et al.* (1961).

In view of the apparent difference of opinion regarding the production of flare X-rays and the associated solar radio bursts (i.e., cm- or m- λ bursts), KUNDU (1961)

examined the solar radio bursts observed in different meter- and centimeter-wave frequency ranges, simultaneously with the X-rays directly measured by balloons and rockets. The details of the observed X-rays and the associated radio bursts are listed in Table 2.

It appears from this table that during all eight cases of flare X-rays observed by

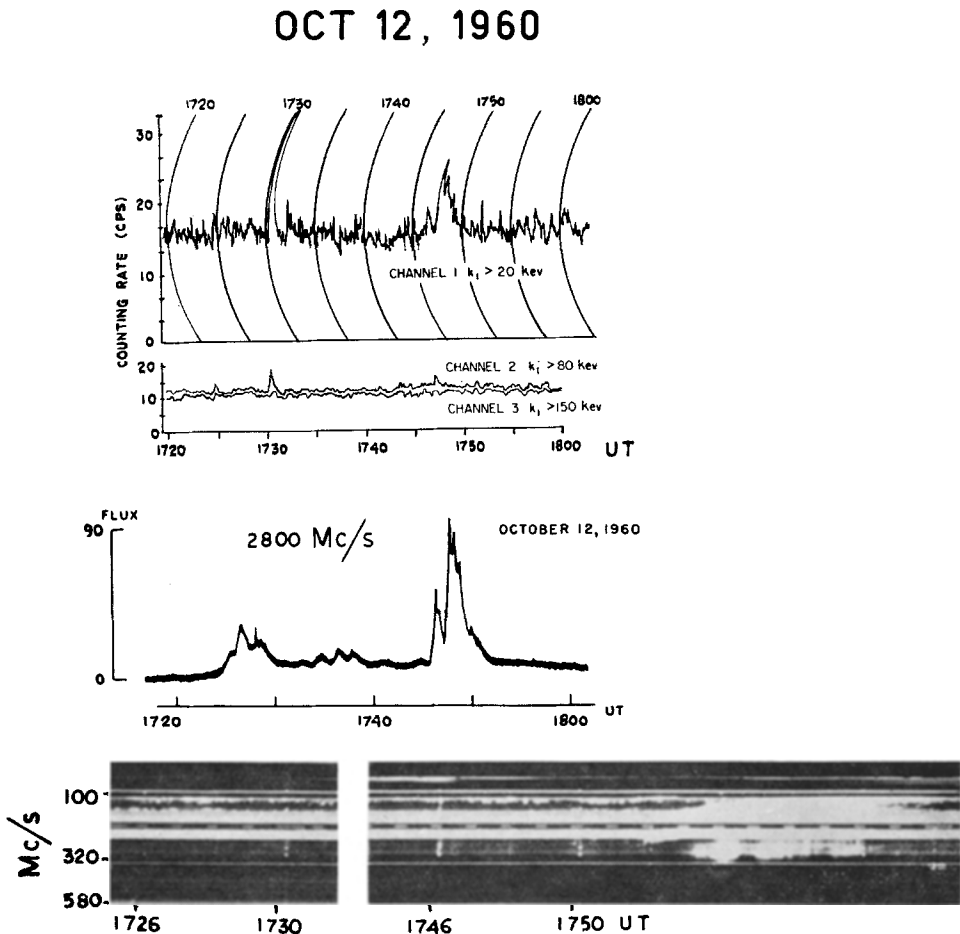


Fig. 18. Same as Figure 17 for October 12, 1960 (After KUNDU, 1961).

balloons and rockets, there were simultaneous centimeter-wave bursts, whereas during only four cases were there meter wave bursts. In only two (August 11, 1960 and September 28, 1961) of these four cases, there were strong groups of type III bursts simultaneously with X-rays; in the other two cases there were a few weak isolated type III bursts at the time of X-rays and it is questionable if the association of these type III bursts with the observed X-rays (whose duration is much longer) is significant.

In three of the four cases the type III bursts were followed by type II and type IV bursts during which time X-rays were no longer observed. In four of the five cases where X-ray maxima were observed, the time of maxima agreed almost precisely with the peaks of centimeter-wave emission. In the fifth case, the maximum occurred

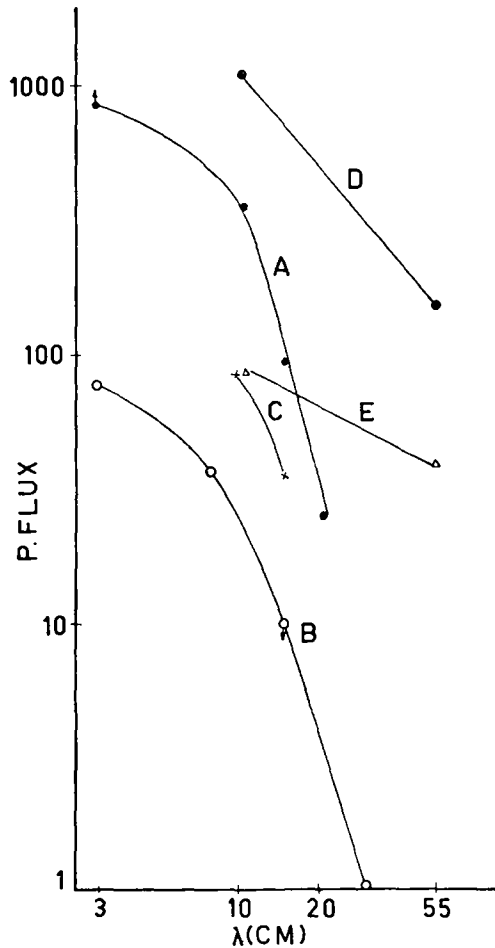


Fig. 19. The spectra of cm- λ bursts associated with high energy X-ray events. The curves marked A, B, C, D, and E correspond to the X-ray events of March 20, 1958; August 31, 1959; September 1, 1959; August 11, 1960; and October 12, 1960; respectively. The first three events are not associated with any bursts on meter waves. The peak flux of cm- λ bursts are expressed in units of $10^{-22} \text{ w m}^{-2} (\text{c/s})^{-1}$ (After KUNDU, 1961).

during the 6 minutes duration of the cm- λ burst. Figures 16, 17 and 18 show some X-ray events simultaneously with the solar radio bursts on 2800 Mc/s (Ottawa) and in the 100-580 Mc/s range (Michigan). It is seen that the second X-ray event of October 12, 1960 agrees even in fine structure detail, involving four peaks, with the

centimeter-wave burst and the ratio of X-ray and cm- λ intensities is nearly constant.

The centimeter-wave bursts associated with flare X-rays are characterized by a sharp rise time and a short impulsive phase; in one rare case (Mrach 20, 1958) (Figure 16) the burst source had a very large angular size (about 4' and 8' on 3 cm and 21 cm respectively) as compared with 2' and 4' for average bursts (DENISSE, 1959) (KUNDU and HADDOCK, 1961). Also, the spectra of the X-ray associated cm- λ bursts show a rather sharp low frequency cut-off, except when they are associated with bursts on meter waves (Figure 19). If we assume a burst size of about 2' on 3 cm, in agreement with interferometric observations (KUNDU, 1959) we find a brightness temperature of about 10^6 – 10^7 ° K for the X-ray associated cm- λ bursts which are not accompanied by any burst on meter waves. One possible way of explaining these temperatures and the spectra of the cm- λ bursts is by thermal radiation from an isothermal plasma whose optical thickness at centimeter wavelengths is greater than unity over the long wavelength end of wavelengths between 3 and 30 cm. The spectra of the three cm- λ bursts associated with meter-wave type III (followed by types II and IV) bursts do not show any sharp low-frequency cut-off (Figure 19). These cm- λ bursts are usually more intense and have higher temperatures (10^7 – 10^8 ° K) than in the previous cases. Such high temperatures of the centimeter-wave continuum bursts are probably due to an additional component of synchrotron radiation of electrons generated during the flare.

The above discussion shows that solar flare X-ray bursts are intimately associated with centimeter-wave bursts from the sun, while the relation with type III bursts is much weaker. This result provides strong evidence that flare X-rays of energy greater than 20 keV are generated not in the higher levels of the corona, but rather in the region of origin of emission of centimeter-wave bursts, i.e., within about 10 000–20 000 kms above the photosphere as determined by interferometric and eclipse observations.

Recently, ANDERSON and WINCKLER (1962) described the high energy (> 20 keV) X-ray burst observed on September 28, 1961 by means of high-altitude balloons and suggested that the same electrons producing Bremsstrahlung X-rays in the lower levels of the chromosphere also produce type III bursts at much higher levels in the corona. They reported, in agreement with the observations of KUNDU (1961), a remarkable coincidence in time of the cm- λ burst with the precursor and main peak of the X-ray burst, but they also contended that three groups of type III bursts occurred at or near the time of discontinuities in the decay of the X-ray burst. They associated these type III burst groups with the leading edges of three energetic electron pulses whose Bremsstrahlung at lower levels constituted the X-ray burst. The three electron pulses were identified by them with three separate passes of the same electron bunch along magnetic lines of force, the electron bunch having been repeatedly reflected at two ends of a converging magnetic tube. ANDERSON and WINCKLER (1962) implied that the energetic electrons were contained and guided by some filamentary structure to greater heights ($\approx 10^5$ km above the photosphere) in the corona where they produced type III bursts. The following arguments may be presented against

this hypothesis of the production of X-ray and type III bursts by the same electron streams.

1. It has been shown above that high energy X-rays bursts are associated with cm- λ bursts in 100 % cases, whereas the association with type III bursts is much weaker (about 25%). The cm- λ maxima always coincide almost precisely with the X-ray maxima. Sometimes there is agreement even in fine structure detail between the cm- λ and X-ray bursts.

2. It is very difficult for the same electrons producing Bremsstrahlung X-rays to excite type III bursts for the reason that these electrons after being "braked" in regions of small mean free path will not have sufficient energy left to excite the type III plasma oscillations (DE JAGER and KUNDU, 1962).

3. If the same electron bunch produces type III bursts in the corona and then Bremsstrahlung X-rays at lower chromospheric levels as suggested by ANDERSON and WINCKLER (1962), then one should be able to observe type III bursts of reverse drift whenever the electron bunch is moving from higher to lower levels in the solar atmosphere. There is no evidence of reverse-drift bursts at any time during the X-ray burst of September 28, 1961 observed and studied by ANDERSON and WINCKLER (1962).

From the above discussions it follows that the same electron streams are unlikely to produce high energy X-rays by Bremsstrahlung at lower levels in the chromosphere and still produce type III bursts at higher levels in the corona. On the other hand, it is highly likely that the electrons producing cm- λ bursts by synchrotron radiation flow into the lower chromosphere through the cm- λ radio source from above the chromosphere and produce high energy X-ray bursts by Bremsstrahlung. One occasionally observes meter- λ type III bursts with X-rays, particularly when the cm- λ burst is very intense. In such cases, in addition to the electrons flowing from the cm- λ source (hot plasma) into the lower chromosphere to generate Bremsstrahlung X-rays, there are other electrons which are accelerated upwards, possibly as a consequence of an irregular flare structure, and go through the corona, without being "braked". These "unbraked" electrons may excite type III bursts at higher levels in the corona.

V. OPTICAL FLARES AND HIGH ENERGY X-RAYS

The gamma-ray burst of March 20, 1958 (Fig. 16) was associated with an optical flare (importance 2+) coincident in time with the burst. The flare was very bright and localized, and it started at 1304 U.T. on top of another flare which was already in progress. The flare showed a very rapid rise to its maximum and it lasted for a period much longer than the duration of the X-ray burst. This flare was also associated with a geomagnetic crochet (Fig. 13).

The X-ray burst of August 11, 1960 was associated with a flare (importance 2+) whose period of rapid rise to maximum coincided with that of the X-ray burst. The X-ray event of October 12, 1960 was similarly associated with a flare (importance 1) whose brightness rose very rapidly to its maximum. These flares observed by Lockheed Solar Observatory are illustrated in Figures 20 and 21.

It appears that the flares associated with high energy X-rays are characterized by a

very short time (of the order of 1–2 minutes) for their rise to maximum brightness. Such flares with characteristically short time scales have been called by ATHAY and MORETON (1961) as flares with “explosive phase”. The “explosive phase” is identical to the “flash phase” described initially by ELLISON (1950). It appears to be the characteristic of all flares exhibiting an “explosive phase” to be associated with high energy

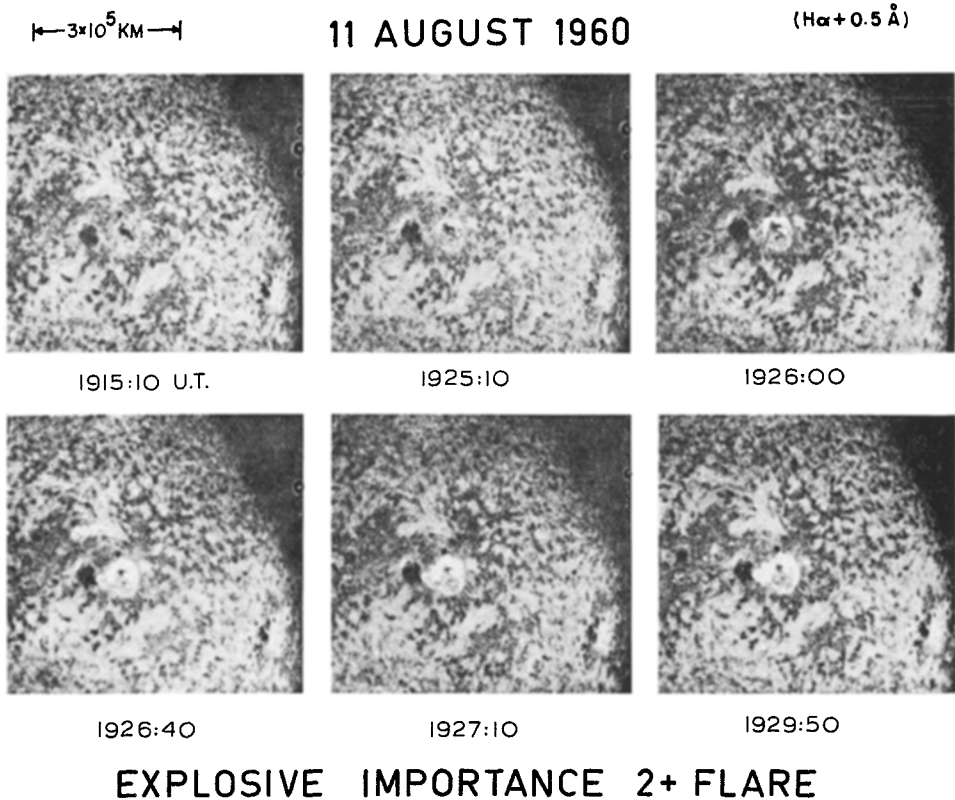


Fig. 20. $\text{H}\alpha$ photograph of the flare with ‘explosive phase’ of August 11, 1960 (Courtesy of Lockheed Solar Observatory).

X-rays. This is further supported by the fact that the occurrence of an “explosive phase” at the onset of a flare favors the production of a geomagnetic crochet which provides an indirect evidence of the production of high energy X-rays from solar flares.

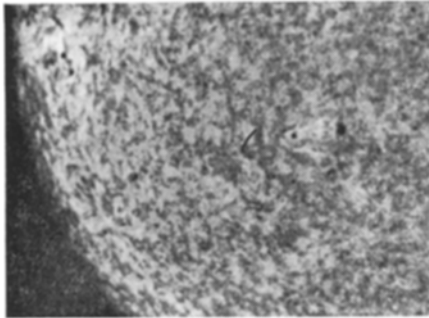
VI. ACCELERATING MECHANISM AND GENERATION OF HIGH ENERGY X-RAYS

From what has been discussed above, it appears that the same electrons produce centimeter-wave radio burst emission as well as X-ray emission. In both cases, acceleration of electrons is involved. According to TAKAKURA (1961) the following mechanism may be relevant in this connection.

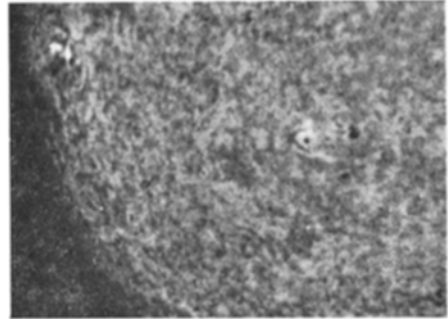
Due to the strong sunspot magnetic field, the velocity v_m of Alfvén waves along the magnetic lines of force is very high: v_m as a function of height in a model solar atmosphere is shown in Figure 22.

It appears that thermal electrons can easily get relativistic velocities (0.6–0.8 times the velocity of light) after several head-on collisions with oppositely moving wave-

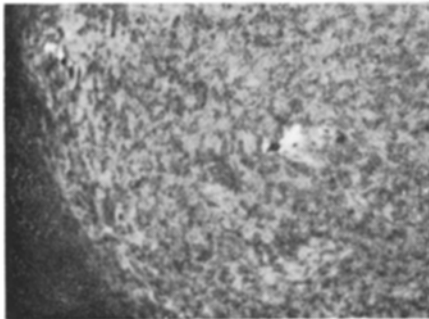
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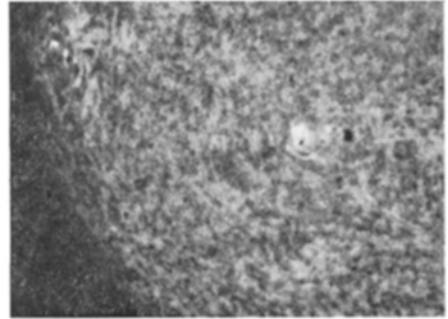
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Fig. 21. $H\alpha$ photograph of the flare with 'explosive phase' of October 12, 1960 (Courtesy of Lockheed Solar Observatory).

fronts of the Alfvén waves. However, a reflection of the electrons from the wave front increases the v_{\parallel} only (velocity component parallel to the magnetic lines of force) so that the helical pitch angle ϑ

$$\left(\tan \theta = \frac{v_{\perp}}{v_{\parallel}} \right)$$

becomes so small that no further reflection occurs. In order that the accelerations

continue up to relativistic velocities, redistribution of the electron velocities must be made. This redistribution can occur by coulomb collision with ambient thermal electrons well before a large fraction of the initial energy is lost. The ratio between the deflection time t_D (SPITZER, 1956) and energy exchange time t_E is of the order of 0.1 when the velocity of accelerated electrons is greater than about three times that of

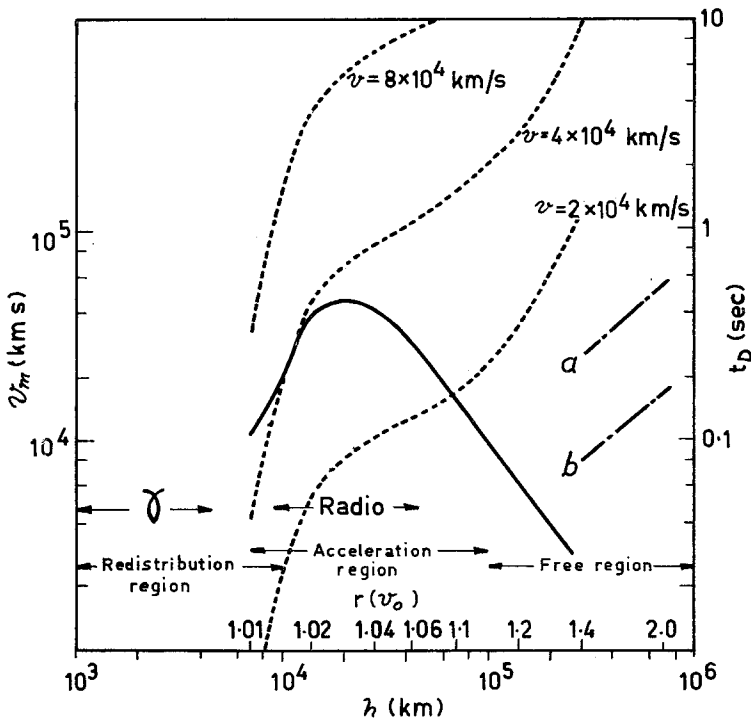


Fig. 22. Alfvén wave velocity v_m and deflection time t_D plotted against height above the photosphere in kms. Distances r from the center of the sun are also given on the abscissa in units of r_o (radius of the photosphere). Solid curve: v_m calculated on the assumption of a magnetic field of 2000 Gauss at the photosphere, and ten times the normal electron density. Dash-dotted curves: v_m calculated with a magnetic field of 50 Gauss in this region for (a) normal electron density, and (b) ten times the normal electron density. Dashed curves: t_D for given values of v shown on the curves (After TAKAKURA, 1961).

thermal electrons. Thus the velocity redistribution of accelerated electrons allows the particles to be accelerated without limit. As shown in Figure 22, the redistribution is effective in the upper chromosphere where t_D is short, while the accelerations are effective in the lower corona (10^4 – 10^5 km) where v_m is high. Since the electrons spend most of their time in regions where the field is largest and the pitch angle is the greatest, they tend to accumulate in the corona above the sunspots. This is consistent with the positions of cm- λ bursts. Electrons with small pitch angle which are not mirrored in the corona penetrate into the chromosphere and in regions below

5 000 km above the photosphere lose their energy through collisions with neutral hydrogen atoms. Such collisions result in Bremsstrahlung radiation at X-ray wavelengths. Thus in the picture the source of the cm- λ bursts lies above that of the X-rays (Fig. 23).

Recently, WENTZEL (1963) presented two different mechanisms of Fermi acceleration of electrons by hydromagnetic shocks. He showed that the mechanism of acceleration between approaching shocks is efficient even for moderate shock strengths. Further, he showed that efficient acceleration could occur ahead of a shock moving into stronger magnetic fields. With the gradual acceleration of the particle and its consequent penetration into stronger fields, the shock field becomes stronger and the particle remains trapped. WENTZEL established two conditions of acceleration: (1) the

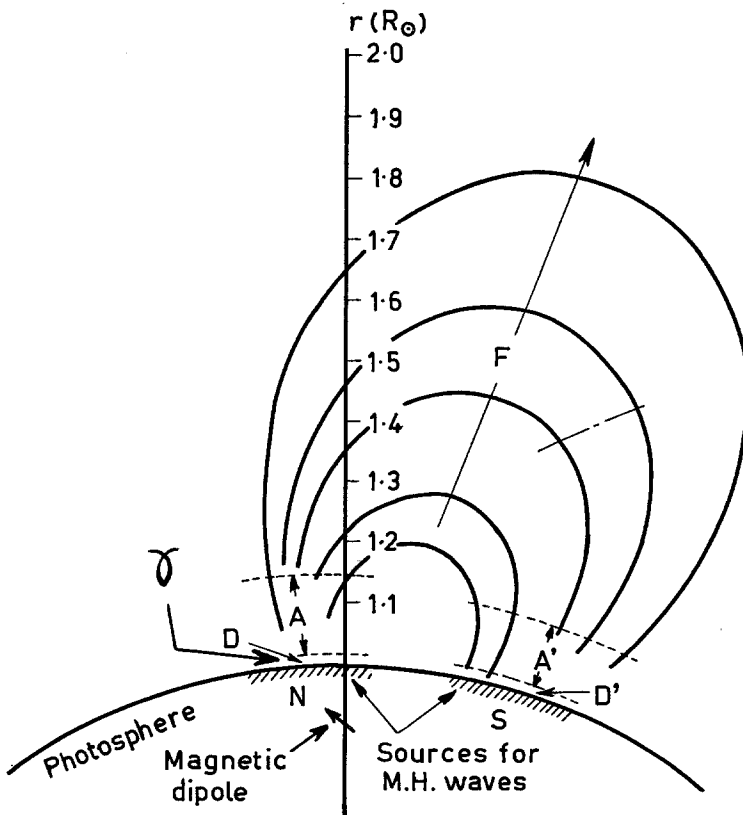


Fig. 23. A schematic diagram of a sunspot magnetic field in which accelerations of electrons could occur. In order that the magnetic field of the preceding spot (N) be greater than that of the following spot (S) the field of an oblique magnetic dipole situated at $0.1 r_0$ below the photosphere is considered. A, A': Acceleration regions; A is also the source of cm- λ burst; D, D': Redistribution regions; γ : Hard X-ray or γ -ray source; F: Free Region; Accelerated electrons move back and forth along the magnetic lines between their mirror points. The sources of Alfvén waves are considered to be just under the photosphere below the N and S spots (After TAKAKURA, 1961).

particle should move faster than the shock, and (2) the collisions with other particles should be negligible.

It should be remarked that in TAKAKURA's mechanism, the thermal electrons cannot be accelerated by the Alfvén waves unless they have velocities comparable to the wave velocity. Thus, the electrons lying at the mean thermal velocity are not accelerated. Further, there is a maximum velocity to which the electrons can be accelerated. This limit is set by the requirement that the electrons' Larmor radius or the distance travelled into the shock during one Larmor period cannot exceed the shock thickness, otherwise the magnetic moment is no longer constant and no further acceleration occurs according to this mechanism. Since in an ionized gas of low density, the shock thickness is of the order of the proton Larmor radius, the electron can be accelerated to a velocity approximately 1800 times that of the mean thermal proton velocity. This is what sets the upper limit in WENTZEL's mechanism which is not basically different from TAKAKURA's in this respect. Particles can be scattered by the shocks and they have their pitch angle redistributed by this mechanism as well as by collisions, in order that repeated Fermi acceleration is possible.

However, it is known that some cm- λ bursts, particularly those unaccompanied by bursts in the meter- λ region, can also be accounted for by thermal radiation. Other cm- λ bursts – those associated with meter- λ bursts – are explained by synchrotron or by synchrotron plus thermal radiation. Both low energy X-rays (2–8 Å) and cm- λ burst radiation can be emitted by Bremsstrahlung by the same non-relativistic electrons during most of the lifetime of the cm- λ bursts. Only at peaks of cm- λ bursts or for short impulsive bursts, relativistic electrons (at the tail of the Maxwellian distribution) come into play – producing enhanced cm- λ burst emission by synchrotron mechanism and X-rays of higher energy (> 20 keV) by non-thermal Bremsstrahlung.

We have seen that high-energy X-ray associated cm- λ bursts of weak intensity are not accompanied by electrons exciting type III bursts on their passage through the corona. It is likely that for such weak cm- λ bursts the electron velocities are small – probably less than 60 000 km/sec. It is known that for charged particles with $v = 6 \times 10^4$ km/sec the mean-free path L in the corona is approximately equal to the scale height of the corona (= 50 000 km). Since L decreases very rapidly with decreasing velocities all electrons with velocities smaller than 6×10^4 km/sec are too rapidly stopped and do not show up as type III bursts. The alternate explanation is that the electrons do not escape into the middle corona and lose all their energy in the chromosphere.

Conclusion

Solar radio emission on centimeter wavelengths is found to be very closely associated with the solar X-radiation during both quiet and disturbed periods of the sun. The brightness distributions of the sun on radio (centimeter) and X-ray wavelengths appear to be qualitatively similar. The radio bright regions – sources of slowly varying component – on centimeter and decimeter wavelengths seem to be associated with the localized regions of enhanced X-radiation and are probably to be identified with the

sources of slowly varying X-radiation. The strong correlation existing between X-radiation and radio emission on wavelengths shorter than about 30 cm and the absence of any correlation on longer wavelengths suggest that the X-rays originate in the same levels of the solar atmosphere (i.e. the chromosphere) as the emission of centimeter wavelengths. Both the quiet and slowly varying radio and X-ray emissions can be explained by thermal Bremsstrahlung mechanism.

During solar flares, bursts of centimeter-wave radio emission are accompanied by bursts of X-radiation of both high (> 20 kev) and low energy (< 20 kev). The intensity of the high energy X-radiation is only a small fraction of that of lower energy, which is mainly responsible for flare-time enhanced D-layer ionization (SID). Type III bursts on meter wavelengths, which provide indications of the passage of electron streams through the corona do not appear to be associated with high energy X-ray bursts in any significant manner. On the other hand, there is a one to one correspondence between the occurrences of cm- λ and X-ray bursts. The cm- λ maxima always coincide almost precisely with the X-ray maxima and sometimes there is agreement even in fine structure detail between the cm- λ and X-ray bursts. It appears that the energetic electrons (as a result of acceleration in the flare region) producing centimeter-wave bursts by synchrotron radiation flow into the lower chromosphere and produce high energy X-ray bursts through collisions with neutral hydrogen atoms (non-thermal Bremsstrahlung). The occasional occurrence of meter-wave type III bursts at higher altitudes in the corona in association with high energy X-ray bursts is probably due to the fact that some of the electrons produced during the flare are accelerated upwards, possibly as a consequence of an irregular flare structure, and move up through the corona, without being "braked". These "unbraked" electrons exciting type III bursts at higher levels in the corona do not seem to play any significant role in the production of high energy X-rays.

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