SOLAR SOFT X-RAYS AND SOLAR ACTIVITY

I: *Relationships between Reported Flares and Radio Bursts, and X-Ray Bursts*

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(Received 15 January, 1969)

Abstract. Soft solar X-rays ($8 \leqslant \lambda \leqslant 12$ Å) were observed from OSO-III. An analysis of the X-ray enhancements associated with 165 solar flares revealed that there is a tendency for a weak soft X-ray enhancement to precede the cm-λ burst and Hα flare. The peak soft X-ray flux follows the cm-λ peak by about 4 min, on the average. Additionally, it was found that flare-rich active centers tend to produce flares which are stronger X-ray and cm-λ emitters than are flares which take place in flare-poor active centers.

1. Introduction

The association between optical, radio and X-ray emission from solar flares has been scrutinized recently by several observers. DONNELLY (1968) compared the timing of soft X-ray bursts with the onset and maximum of the Hα flare and with the accompanying microwave burst, concluding that there is a tendency of the soft X-ray flux to be enhanced prior to the detectable onset of other phenomena. In his study, Donnelly used preliminary data furnished by several experimenters. NEUPERT (1968) compared flux curves at 1.87 Å obtained on OSO-III with radio flux-density records (2695 and 2700 MHz) for three flare events. The maximum rate of solar line emission at 1.87 Å (Fe XXV?) occurred $\frac{1}{2}$–10 min after the peak microwave emission, while little or no change in flux from lower stages of ionization (Fe IX–Fe XVI) took place. The data are consistent with a model in which X-ray emission is produced by thermalization of the fast electrons which give rise to the impulsive radio burst.

The McMath-Hulbert Observatory has on OSO-III a soft X-ray ion chamber. In this communication we propose to describe, for 165 flare events observed by that instrument between March 9 and December 31, 1967, the statistical relations between timing of Hα, X-ray and cm-λ events accompanying flare phenomena. The relationships which are found are discussed in terms of a schematic model for X-ray production prior to and during flares.

2. Observations

Soft solar X-rays between 8 and 12 Å were observed from the wheel of the OSO-III satellite with an ion chamber having an aluminium foil window and nitrogen gas filling (see ACTON *et al.*, 1963). X-ray fluxes, calculated assuming a black-body energy distribution at $T = 2 \times 10^6$ K, were observed once each rotation of the wheel (1.7-sec period) and measured in discrete steps. Up to $E(8, 12) \cong 0.0044$ ergs cm^{-2} sec^{-1}, the interval between steps is about 0.000035 ergs cm^{-2} sec^{-1}. Above $E(8, 12) \cong$

Solar Physics **8** (1969) 348–368; © *D. Reidel Publishing Company, Dordrecht-Holland*

$\cong 0.0044$ ergs cm^{-2} sec^{-1}, the interval between steps is about 0.00095 ergs cm^{-2} sec^{-1}. The instrument saturates at $E(8,12) \cong 0.12$ ergs cm^{-2} sec^{-1}. Graphs of X-ray flux vs. time, prepared by a computer, were made by time-averaging 6.8 sec of data for each point that was plotted, not for reasons of signal noise but purely for economy of presentation. There is no evidence that the process of time-averaging has caused loss of significant information. Because the flow of X-ray data is interrupted periodically by satellite night and by tape-recorder playback, and its quality is sometimes degraded by particle interference, we often do not observe a complete X-ray flux curve for flares.

In the present investigation the data were organized around the Hα flare event as argument of entry, and cover the period March 9, 1967 through December 31, 1967. While we have examined flare-patrol films and in some instances have made intensity measures from them (Figure 1), our work here is concerned primarily with comparing our data to reports of optical and radio events. The discusssion of photometric flare light curves is left to a subsequent paper.

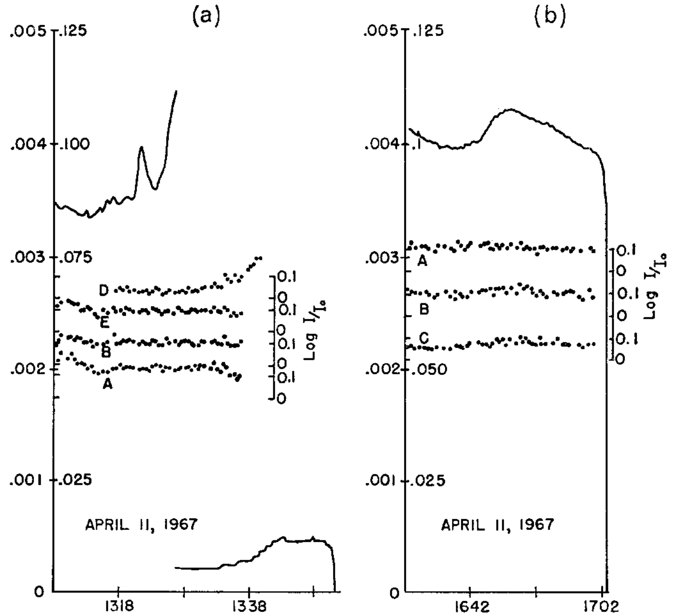

Fig. 1. – (a) Importance-1b flare (N22 W24) of April 11, 1967. Abscissa: Universal Time in hours and minutes. The solid curves are X-ray fluxes. Note change of ordinate scale at 13^h26^m. Left-most ordinate scale is for high-sensitivity operation (prior to 13^h26^m) and the additional ordinate scale is for low-sensitivity operation. Units are $E(8, 12)$ ergs cm^{-2} sec^{-1}, at earth, in band-pass 8–12 Å. Dots are intensity measures made in 4 parts of the region on Hα filtroheliographic flare patrol films, expressed in $\log_{10} I/I_0$ (right ordinate scale). I_0 is the intensity of the Hα image at the center of the disk. Only the initial flare phases were studied photometrically. Satellite sunset occurs at 13^h53^m. – (b) Non-flare brightening in the same region (N22 W24) on April 11, 1967. X-ray detector operation in high-sensitivity range only. Parts B and C of the region brightened perceptibly beginning at about 16^h42^m. Satellite sunset at 17^h03^m.

We have attempted to limit the flare sample to single flares of importance 1 or greater. Since not all flare reports are equally reliable (DODSON and HEDEMAN, 1968), we have selected only those flares observed at 3 or more stations which were called importance 1 or greater in the *Quarterly Bulletin of Solar Activity* (QB). Additionally, when it appeared that the X-ray or radio data might be confused by the occurrence of two or more flares close together in time, the events were ignored. After this culling process we are left with 165 events for which we have at least partial X-ray information.

Radio-burst reports have been taken from the *ESSA Solar-Geophysical Data Bulletin* (SGDB) and from the monthly compilations by Toyokawa and Hiraiso. As a result there is a 6-hour gap in the Universal Time distribution of our radio data, and there are fewer flares for which reports of related radio bursts were available than there are flares for which X-ray data were available.

The time-accuracy of the graphs of X-ray flux vs. time is limited only by the time-averaging mentioned earlier. In carrying out this investigation, we have read off relevant times to the nearest half-minute, since a greater precision is not warranted by the comparisons that were made.

3. Discussion of the Observations

A. X-RAY ENHANCEMENT AMPLITUDE: DEPENDENCE UPON FLARE IMPORTANCE AND UPON CM-WAVE RADIO BURST AMPLITUDE

Several observers have previously noted the wide variation of amplitude of X-ray enhancement associated with flares of a given importance (e.g. UNDERWOOD, 1968) which we have found in our data. In general there is a loose relationship of X-ray amplitude with flare importance and brilliance, but there also is a good deal of overlap of this relationship between the different flare categories. Our data additionally point towards a dependence of flux enhancement upon the flare-richness of regions in which flares take place.

In Figure 2 we have plotted the amplitude of soft X-ray bursts for flares of different importance and brilliance categories. There is a further subdivision of the material into flares occurring in regions which were prolific flare-producers and those which occurred in relatively inactive regions. There is a clear tendency for the X-ray amplitude to increase from low values for faint importance-1 flares to higher values for flares of greater brilliance and importance. Among all importance-1 flares, though, that amplitude spans more than 2 orders of magnitude. Among all importance-2 flares, the span of amplitudes is greater than a factor of 10.

While one of us (TESKE, 1969) previously claimed that all flares of importance $\geqslant 1$, and probably all subflares as well, are accompanied by at least a small soft X-ray enhancement, our flare sample here contains one event (the lowest data point in Figure 2) which apparently was not accompanied by soft X-rays. The flare was observed by three stations at N21 E80 on June 9, 1967, and was called importance 1 by two of them. It is of interest that the plage region in which it occurred (number 8843) was an old region which had had a small spot group in it for two days during

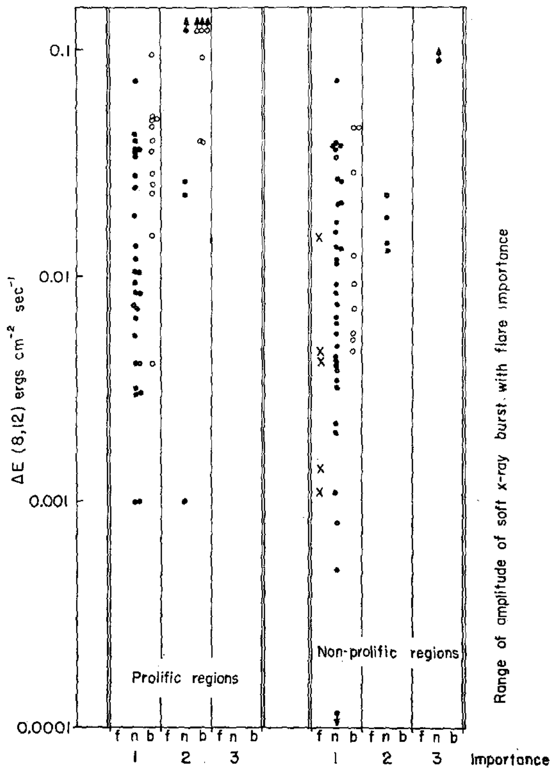

Fig. 2. Soft X-ray flux enhancements observed in flares of importance $\geqslant 1$, divided according to flare importance and brilliance and further divided as to whether the flares occurred, in our estimation, in flare-rich or flare-poor active centers.

its previous disk passage, and had no spots in it during the disk passage when the flare took place. Another importance-1n flare in the same region on June 11 was however accompanied by a detectable but small increase in soft X-rays ($\Delta E(8, 12) = 0.0011$).

In preparing Figure 2, we designated plage regions 8740, 8818, 8905, 8942, 9034 and 9115 as 'prolific' flare-producers, and plotted X-ray amplitudes for flares occurring in them separately from data which refer to 'non-prolific' regions. (Plage regions 8791, 8907, 9004, 9047 and 9128 were left out of both categories, being considered as moderately flare-rich regions.) Table I summarizes our results for flares of importance 1. This separation of data suggests that flares of importance 1 occurring in flare-rich regions tend to be better soft X-ray emitters than those flares seen to occur in relatively inactive regions. A similar relationship could probably be obtained if we used, for example, the radio brightness of regions as obtained by the Stanford observers, or some other suitable index for the general level of activity in individual regions, as independent variable. In particular, flare-rich regions are generally those with strong and complex magnetic fields.

TABLE I

Soft X-ray burst amplitude dependence upon flare-richness of plage regions, all flares of importance 1 only

	Percentage of flares investigated		
X-ray amplitude $\Delta E(8, 12)$	$\Delta E < 0.001$	$0.001 \leqslant \Delta E < 0.01$	$\Delta E \geqslant 0.01$
Prolific regions	0	38 %	62 %
Non-prolific regions	6 %	52 %	42 %

Median X-ray burst amplitude, all flares of imp 1	
Prolific regions:	Median $\Delta E = 0.017$ ergs cm^{-2} sec^{-1}
Non-prolific regions:	Median $\Delta E = 0.0074$ ergs cm^{-2} sec^{-1}

Median X-ray burst amplitude, imp 1n only	
Prolific regions:	Median $\Delta E = 0.01$ ergs cm^{-2} sec^{-1}
Non-prolific regions:	Median $\Delta E = 0.0085$ ergs cm^{-2} sec^{-1}

The great range of amplitude of X-ray bursts for flares of a given importance is qualitatively like the range found by Dodson *et al.* (1954) for the amplitudes of 2800 MHz bursts associated with Hα flares. We have previously compared 2800 MHz burst amplitude with soft X-ray burst amplitude (Teske, 1969) and have shown that there is a strong tendency for the two to be correlated. There is, however, a large and real dispersion. We have in Figure 3 again compared 2800 MHz burst amplitude with X-ray burst amplitude, this time using only flares from the sample under study here. Distinguishing now between events occurring in 'prolific' and 'non-prolific' regions, we find that flares in 'non-prolific' regions are also poor emitters at 10.7 cm (Figure 3).

B. Time-relations between Hα flares and X-ray bursts

In examining flare reports in connection with our X-ray data, we have focussed upon start-times and times of maxima. Designation of these times by the individual flare observers is difficult at best; the reported times are often matters of the observer's judgment (Dodson and Hedeman, 1964). In the case of the X-ray flux curves, times of start and maximum may be designated more objectively.

We have selected as starting time of the X-ray event that time when the flux curve first changes slope. Subsequent to this time there may be a monotonic flux increase or there may be fluctuations, during which the flux remains always above the pre-burst flux level. Since we are dealing with single flare events, however, the initial fluctuations, when they occur, are considered to be a part of a single comprehensive event (see Section 4A). Ending times are often as difficult to judge for X-ray events as for Hα events. We have therefore not studied them quantitatively at this time, but merely state that it is our impression that, for flares of importance $\geqslant 1$, the X-rays tend to outlast the reported end-time of a flare by a length of time dependent upon flare importance and brilliance (Teske, 1969).

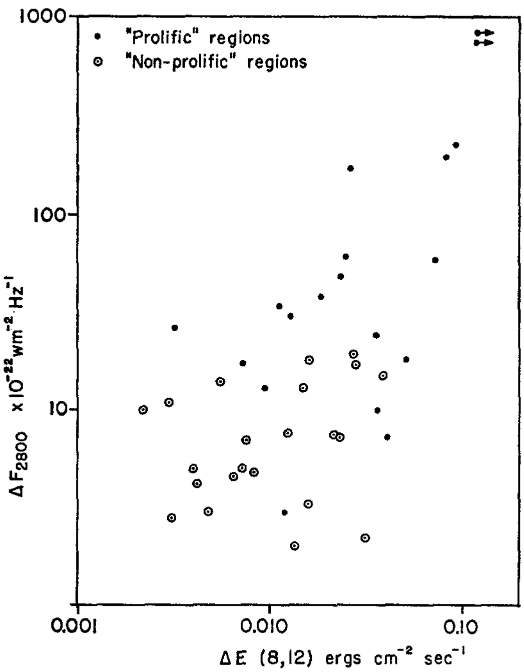

Fig. 3. Comparison for individual flares of associated enhancements of soft X-ray flux and 2800 MHz flux. Large dots and circled dots identify events in flare-rich and flare-poor regions.

1. *Starting Times*

At our disposal are starting times for Hα flares listed in both the *Quarterly Bulletin* and *Solar-Geophysical Data Bulletin.* We have, however, selected from the world-wide reports the earliest starting time recorded by a cinematographic or photographic station. Often a rapid initiation of the X-ray event is reflected by a small dispersion in Hα start-times as reported by the various observatories, while a slow X-ray rise is reflected by a wide dispersion of reported Hα start-times. The latter indicates an uncertainty among stations caused by a slow rise in Hα brightness. Thus the earliest reliable optical report is preferred in making the comparison attempted here, since something must have been taking place at that time on the sun. We cannot, of course, take into account possible clock errors at the various observing stations.

In Figure 4 we have diagrammed the start-time differences for flares within 60° (heliocentric) of the disk center, that is, for $\mu = \cos\theta > 0.5$, and for flares beyond 60° from the disk center ($\mu = \cos\theta < 0.5$). The diagram shows that: (i) there is probably a center-limb effect and (ii) the overall results depend strongly upon the sensitivity of the detector. Table II summarizes the information for starting times. In the table we also give confidence limits computed from a Fisher 't' test. Where too few data points have not permitted a reasonable application of the 't' test, no information is given.

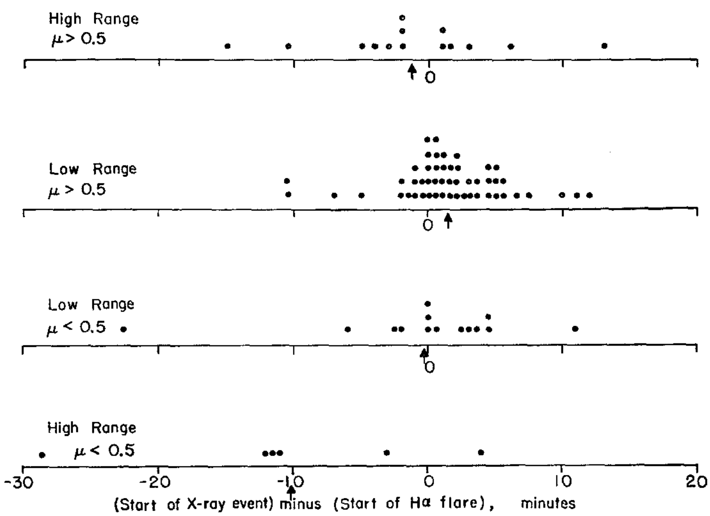

Fig. 4. Comparison of reported starting times of Hα flares and associated soft X-ray enhancements. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values. Data are divided according to instrumental sensitivity range at beginning of event and according to $\mu = \cos\theta$.

TABLE II

Mean differences between Hα and soft X-ray starting times

Sensitivity of detector	$\cos\theta \geqslant 0.5$	$\cos\theta < 0.5$	Confidence that center-limb differences are real
Low sensitivity	+1.5 min (X-rays are late)	−0.25 min (X-rays are early)	75 %
High sensitivity	−1.3 min (X-rays are early)	−10.3 min (X-rays are early)	99 %
Confidence that sensitivity differences are real	95 %	–	

When our detector was operating in its mode of low sensitivity, where on the average an X-ray rise of $\Delta E = 0.00048$ ergs $\text{cm}^{-2}\ \text{sec}^{-1}$ is needed before it can be detected as an increase, the X-ray start tends to come after the Hα start-time. However, when the detector was operating in its high sensitivity range, in which an increase only 1/25th as great may be discerned, there appears to be a definite tendency for the X-ray rise to precede the earliest reported cinematographic or photographic Hα start-time, especially towards the solar limb. Usually the early rise of X-rays is very slow, with an abrupt increase in rate of rise at about the reported time of start of the Hα flare, or shortly thereafter. Figures 5, 6 and 7 reproduce typical flux-curves for three events. The center-limb effect found here is one in which the X-ray start-time relative to the Hα start-time becomes even earlier for flares near the limb.

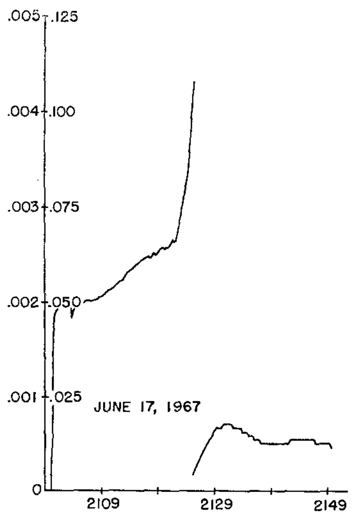

Fig. 5.

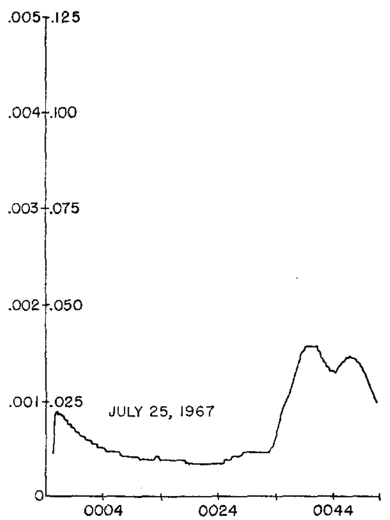

Fig. 6.

Fig. 5. A representative soft X-ray flux curve for an importance-1n flare (N29 E64) on June 17, 1967. Note scale change at 21^h25^m. For explanation of scales, see Figure 1a caption. This flare has early X-rays. Satellite sunrise: 21^h00^m.

Fig. 6. A representative soft X-ray flux curve for an importance-1f flare (N29 E44) on July 25, 1967. Only two stations were reported by QB to have observed the flare, and this event is therefore not in our catalogue. Low-sensitivity operation only. X-rays appear to be late. For explanation of scales, see Figure 1a caption. Satellite sunrise at beginning of record.

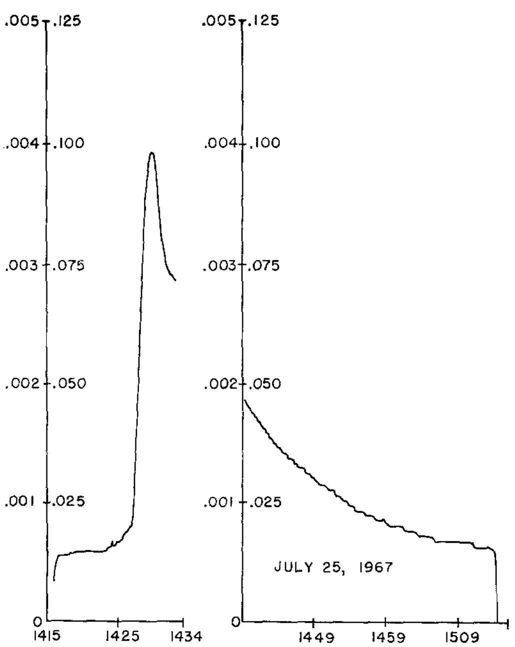

Fig. 7. A representative soft X-ray flux curve for an importance-1b flare (N28 E39) on July 25, 1967. Soft X-rays show early increase at 14^h18^m. Low-sensitivity operation only. Sunrise and sunset at beginning and end of record.

Because the early appearance of X-rays has great importance in understanding the flare event as a whole, and because their early appearance may be of considerable interest in possible flare-warning devices in future space applications, we have taken care to assure ourselves of the reality of our observations. All cases where other earlier reported flares might have caused confusion have been studied and eliminated from the material used. We reserve a detailed discussion for Section 4.

2. *Times of Maxima*

Only rarely does a flare of importance $\geqslant 1$ fail to carry our detector into its range of low sensitivity, so we need not distinguish sensitivity range in discussing maximum times. Figure 8 presents the time-differences found. In preparing Figure 8, reported times of maxima from the QB were used, after elimination of events with double maxima and of nearly simultaneous events overlapping in time. Table III summarizes the work. There appears to be no strong reason to believe that a center-limb effect exists. On the average, the X-ray flux maximum lags the Hα intensity maximum by about 3 min.

Hα flares occurring near the limb are apparently of shorter duration and usually are less easily visible than are flares which occur towards disk center (Dodson *et al.*, 1956), an effect probably caused by absorption of visible radiation in the chromosphere. Because the flare-associated X-radiation is perhaps less affected by absorption

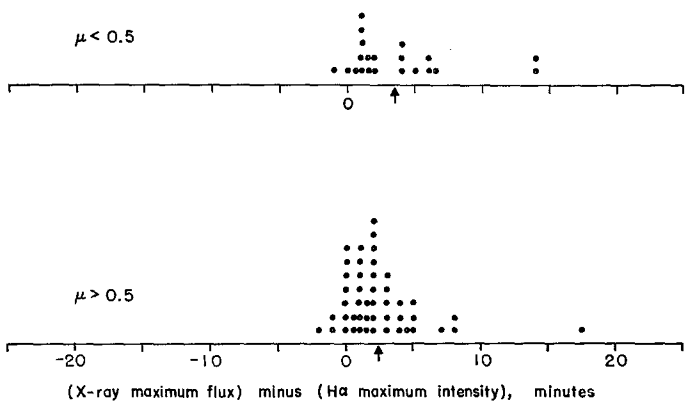

Fig. 8. Comparison of reported times of maxima of Hα flares and associated soft X-ray fluxes. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values.

TABLE III

Mean differences between Hα and soft X-ray maximum times

$\cos\theta \geqslant 0.5$	$\cos\theta < 0.5$	Confidence that center-to-limb difference is real
+2.4 min (X-rays are late)	+3.6 min (X-rays are late)	80 %

processes (however, cf. WARWICK and WOOD, 1959) we seem to find that the X-ray bursts begin anomalously early towards the limb, while it is likely that the start of the flare is just hard to see. However, the relative times of maxima of Hα and X-rays for $\mu<0.5$ and for $\mu>0.5$ suggest that the deduced maximum time of the Hα event near the limb is not markedly affected by the process that lessens its visibility.

C. TIME-RELATIONS BETWEEN CM-λ AND X-RAY BURSTS

1. *Starting Times*

Although we have selected as start-time for an X-ray event that time at which the flux-curve changes slope, the start-time of a cm-λ event is judged by the radio observers as that time when the flux-density has risen through one flux unit (SGDB, Descriptive Text). We have therefore built in a bias towards recording slightly earlier start-times for our X-ray events, but it is a bias no worse nor better than some other arbitrary definition of 'start-time'. We have previously noted (TESKE, 1969) that, for flares, an increment of 2800 MHz flux density by 5 flux units (5×10^{-22} W m^{-2} Hz^{-1}) is accompanied by an X-ray increment $\Delta E(8, 12)$ of 0.005 ergs cm^{-2} sec^{-1}. At the one flux unit level (see Figure 3), the soft X-ray increment is crudely 0.001 ergs cm^{-2} sec^{-1}, or about one step in our low sensitivity flux records. Thus our definition of 'start-time' is in reasonable accord with the cm-λ definition for those data acquired in our low sensitivity mode. The data acquired in the high-sensitivity mode are about 25 times more sensitive, however.

To assess relative starting times we have used the Canadian 2800 MHz or 2700 MHz reports and the 3750 MHz reports from Toyokawa. Figure 9 and Table IV

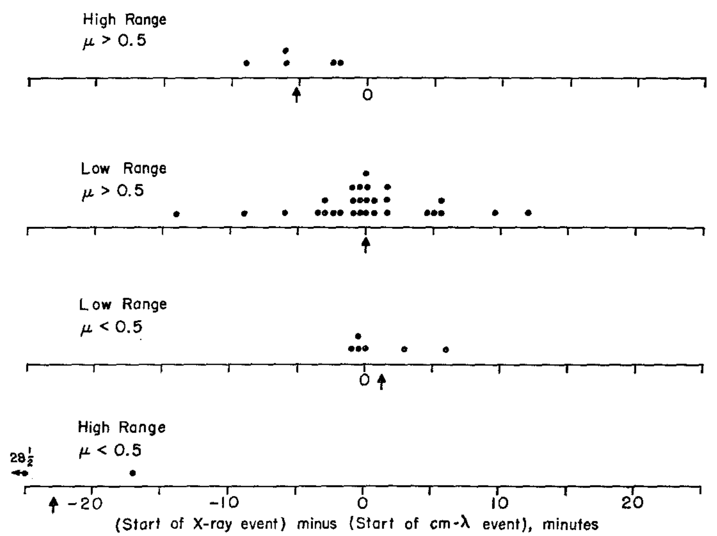

Fig. 9. Comparison of reported starting times of cm-λ bursts and soft X-ray enhancements. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values.

TABLE IV

Mean differences between cm-λ and soft X-ray start times

Sensitivity of detector	$\cos\theta \geqslant 0.5$	$\cos\theta < 0.5$	Confidence that center-limb differences are real
Low sensitivity	0.0 min	+1.2 min (X-rays are late)	43 %
High sensitivity	−5.1 min (X-rays are early)	−22.8 min (X-rays are early)	99 % (?)
Confidence that sensitivity differences are real	96 %	–	

show that, when we were recording in low-sensitivity mode, the X-ray burst and cm-λ burst on the average began within a minute of one another, and that there is no clear center-limb effect. Some X-ray bursts in low range in fact began quite late relative to the cm-λ burst. On the other hand, data acquired in the high-sensitivity mode give a different result: without exception the X-ray increase begins many minutes earlier than the cm-λ burst. We have no confidence in the apparent center-limb difference for our higher sensitivity range, since for the sample under investigation there are only two elements in the limb sub-set.

The strong tendency for a weak soft X-ray enhancement to precede cm-λ bursts is undoubtedly at least partly caused by the relative sensitivities of the instruments employed in detecting the radiation. The tendency is also indicative of physical conditions in the flare volume, to which the mechanism that gives rise to the soft X-radiation is more sensitive than is the mechanism that generates cm-λ radiation (see Section 4 and cf. White, 1964). In those cases where an early and slow rise of soft X-rays is seen, the rate of X-ray rise usually increases near the reported starting time of the cm-λ burst.

2. *Times of Maxima*

As Figure 10 and Table V show, the X-ray maximum almost invariably follows the cm-λ maximum, by 3–6 min on the average, and there is no clear center-limb effect. Thus, the radio maximum occurs on the rising branch of the soft X-ray flux curve. On the other hand, hard X-rays reach their maximum coincidentally with the cm-λ maximum (Arnoldy *et al.*, 1967).

There are two highly discordant limb data points in Figure 10, designating cases where the X-ray maximum preceded the cm-λ burst maximum by 34 min, and followed it by 31 min. Both events took place within 10 hours of one another and were both associated with events in plage region 8942 which was then on the East limb. We are inclined to consider them as being related to complex events which may have taken place partly behind the limb, since during the preceding 24 hours at least two significant X-ray events occurred in association with flares apparently going on behind the limb. Nevertheless we have not excluded the former two events from the valid data.

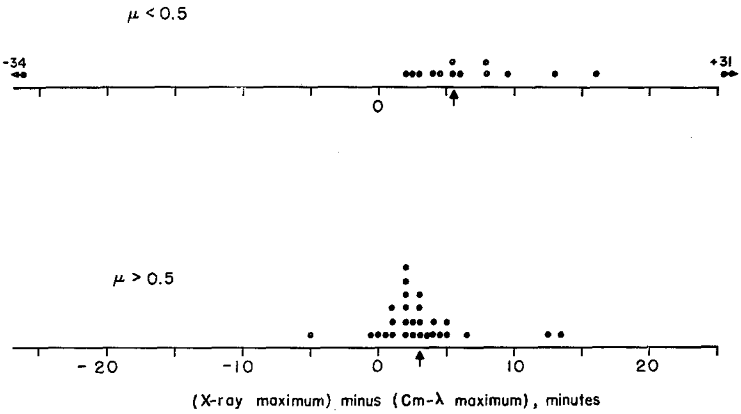

Fig. 10. Comparison of reported maxima of cm-λ bursts and soft X-ray fluxes. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values.

TABLE V

Mean differences between cm-λ and soft X-ray maximum times

$\cos\theta \geqslant 0.5$	$\cos\theta < 0.5$	Confidence that center-to-limb difference is real
+3.1 min (X-rays are late)	+5.6 min (X-rays are late)	67 %

In summary we find a marked tendency for a weak enhancement of soft X-radiation to precede the reported starting times of cm-λ bursts which are associated with flares. The soft X-ray maximum in flare events almost invariably follows the cm-λ maximum by 3–6 min. There is a similar, marked relationship between Hα maximum intensity and soft X-ray maximum flux, with the X-ray maximum following the reported Hα maximum by about 2–4 min. On the other hand, there is a considerable dispersion in the relative starting times of Hα flare and soft X-rays, though a definite tendency towards an early enhancement of soft X-rays is also found. The dispersion in the relative X-ray/Hα starting times is not improved by making comparisons with, for example, the starting times for flares adopted in the *Quarterly Bulletin*.

Dodson *et al.* (1954) have examined the relationships between Hα flare and 2800 MHz timing. They found that the two events tend to start together (on the average, the Hα flare preceded the radio event by 0.6 min), but that the radio burst reached maximum, on the average, 3.4 min before the Hα maximum intensity. We can deduce from the flare sample studied by us that the cm-λ flux reaches maximum roughly 1–2 min before flare maximum, in reasonable agreement with their result.

The distributions of time-differences both for the X-ray/cm-λ and X-ray/Hα maxima are significantly non-random at the 99% confidence level. This effect is introduced by the presence in our sample of a very few events in which the X-rays reached maximum very late.

There appears to be no dependence of the relative timing of soft X-rays, Hα and cm-λ emission upon the spectrum of the radio burst event. Reported maximum radio flux densities were plotted for each event to produce our version of a burst spectrum. The events were sorted among seven categories of spectrum shape and the relative timing investigated for each category. No clear relationship between burst spectrum and 'earliness' or 'lateness' of X-rays emerged. Our negative results are consistent with the conclusions of TAKAKURA (1967), who found that the spectrum characteristics of impulsive microwave bursts do not divide them into distinctly different subgroups.

4. Analysis

A. STARTING TIMES: THE PREDECESSOR EVENT

The foregoing discussion of our data points out that usually a weak enhancement of soft X-rays precedes the start of the cm-λ event by some minutes. Apparently the soft X-rays also tend to precede the start of the Hα flare.

In Figure 1a we illustrate the X-ray flux curve and the Hα intensity curves for the early phases of an importance-1 flare on April 11, 1968. In this event, which is representative of our sample of events having early soft X-ray fluxes, the X-ray rise began about 15 min prior to the first Hα brightening. There is no photometric evidence in Figure 1a that the region brightened significantly in Hα prior to the onset of the flare (which began in the position labelled D), although our curves show a minimum in Hα surface brightness just prior to 1315 UT. Photometric examination of other active centers on the disk at this time also gives no evidence of an Hα enhancement which may have been associated with the soft X-ray flux. We have therefore concluded that the X-rays which were observed prior to the flare depicted were generated by physical processes taking place in the vicinity of the plage.

While cm-wave activity was recorded near the time of the X-ray event, there does not appear to be a clear relationship like that found in many other events. A weak 2700 MHz burst was reported by Pennsylvania beginning at 1310.5 UT and lasting for 5.2 min. A series of weak 2700 MHz bursts was reported to have followed, the next beginning at 1323.6, after the small X-ray peak but at the time of the strong rise in X-rays. At 2800 MHz, a burst was recorded to have started at 1335, in good time-association with the optical flare.

In contradistinction to the lack of clear evidence for Hα brightening with the soft X-ray emission after 1315, a subtle brightening of the same plage region did accompany an X-ray event 3 hours later (Figure 1b). Too meager to be reported as a flare, the Hα intensity in two posititions (B and C) increased by only about 4% of the intensity of the Hα continuum measured at disk center. Although the soft X-ray amplitude of this event is equivalent to the amplitude of the small peak between 1320.5 and 1323.5 (Figure 1a) no certain Hα increase accompanied the small X-ray peak in the earlier event.

It has previously been pointed out (GREGORY and KREPLIN, 1967; TESKE, 1967) that fluctuations of the solar soft X-ray flux occur frequently, often accompanying fluctuations in the Hα brightness of parts of plages. Of the flare events which we believe were accompanied by early soft X-rays, two were available for study on our flare patrol films. One is illustrated in Figure 1a. The other is an importance-1b flare on July 25 (Figure 7). In both cases we were unable to find other plages on the disk which showed Hα brightening, and so have ascribed the X-ray origin to a pre-flare event. While our full sample of early X-ray enhancements might be partly contaminated by the effects of X-ray background fluctuations not associated with the pre-flare region, a study of the frequency of these fluctuations for the period of 10 March 1967 to 18 April 1967 shows that less than 20% of our flare X-ray enhancement start-times will be in error by 1 min or more because of confusion with the background variations. Thus the majority of the early events really represent a class of phenomenon in which soft X-ray emission precedes the optical brightening.

An X-ray event morphologically similar to that illustrated in Figure 1a is shown in Figure 11. A weak X-ray burst began at 0842 UT, reaching a low maximum at

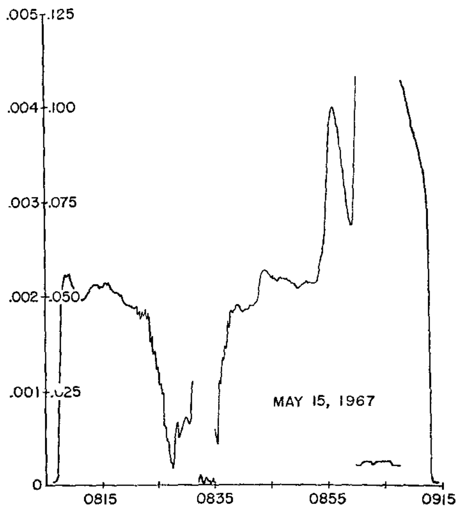

Fig. 11. Soft X-ray flux curve for importance-1n flare (S13 E79) on May 15, 1967. Strong particle interference occurs between 08^h21^m and 08^h40^m. Note changes of scale at 08^h59^m and 09^h08^m. Sunrise and sunset at beginning and end of record.

0844 UT. In this case, however, the earliest reported Hα start time was 0854, at the time the second soft X-ray rise began. Flare maximum was reported at 0902 UT.

Because of the relatively broad wavelength band of our detector, we cannot specify with certainty the nature of the soft X-rays in the flare predecessor. We speculate, however, that the early increase of soft X-rays prior to a flare is caused by an increase in temperature in the pre-flare coronal volume, and that the X-rays are thermal in origin (KAWABATA, 1966).

Solar X-ray spectra have been obtained by, e.g., FRITZ *et al.* (1967), NEUPERT *et al.* (1967) and by WALKER and RUGGE (1967). These spectra show the presence of emission lines of helium-like and hydrogen-like ions of NeIX, NeX, NaX, NaXI, MgXI and MgXII, among others. Table VI lists the wavelengths of some of the salient lines of these ions which are observed to lie within our band-pass. No recombination continua have been identified by these observers.

TABLE VI

Some emission lines observed in the solar X-ray spectrum

Identification	wavelength (Å)
NeIX	11.56
	13.44
	13.55
NeX	9.36
	9.48
	9.71
	10.24
	12.13
NaX	11.00
	11.08
NaXI	8.02
	8.46
	10.02
MgXI	9.16
	9.23
MgXII	8.42

Because the efficiency of our detector increases rapidly towards shorter wavelengths, down to 7.94 Å, an increase in line emission from these ions and from recombination continua will be more readily detected by our higher efficiency at shorter wavelengths. However, because of the manner in which the data are reduced (a black-body energy distribution is assumed), the measured flux increase may not accurately reflect the true flux increase.

Ionization equilibrium calculations have been carried out for these ions. The neglect of dielectronic recombination in the calculations is not serious, in this case, below $T_e \sim 10^7$ K, and we find that the hydrogen-like ions of Mg, Na, Ne become important constituents at temperatures between 3.5×10^6–5×10^6 K.

The weak soft X-ray increase which precedes the reported cm-λ event in some flares and the relationship between times of maxima are consistent with a schematic model which may be developed as follows.

During the initial X-ray rise, the cm-wave flux densities may remain sensibly unchanged in a typical event (Figure 9). Following ACTON (1968) we assume that the pre-flare coronal condensation is optically thin to cm-λ radiation, and so write for the radio flux density (KUNDU, 1965)

$$S = 2 \times 10^{-45} T_e^{-1/2} \int N_e^2 \frac{dV}{A_0} \text{ W m}^{-2} \text{ Hz}^{-1}, \tag{1}$$

where A_0 = area of solar disk and $dV = A\, ds$, in which A = area of burst.

The energy being detected in our band-pass originates as line emission (Table VI) and in the continuum. The continuum radiation is predominantly recombination emission at temperatures near 2×10^6 K (MANDEL'ŠTAM, 1965). In our band-pass it arises principally from recombination of O VIII, Ne IX, Ne X, Na X and several intermediate stages of Fe ionization. These free-bound emissions may be the primary contributor. FRITZ *et al.* (1967) observed that the continuum/line ratio was 2 in the wavelength interval 10–20 Å.

In the recombination continuum of an ion in the ith stage of ionization, the volume emission coefficient integrated over wavelength (ELWERT, 1954) is proportional to

$$j_{FB} \propto N_{Z,\, i+1} N_e T_e^{-1/2}. \tag{2}$$

The volume emission coefficient in an emission line (e.g. POTTASCH, 1964; EVANS and POUNDS, 1968) is proportional to

$$j_L \propto N_{Z,\, i} 10^{-5040W/T_e} N_e^2 T_e^{-1/2}. \tag{3}$$

We may estimate $N_{Z,\, i}$ and $N_{Z,\, i+1}$ from formulae given by POTTASCH (1963), providing dielectronic recombination may be ignored and that $N_e \lesssim 10^{10}$ cm^{-3}. If only 2 stages of ionization dominate (the ith and $(i-1)$th):

$$\frac{N_{Z,\, i}}{N_{Z,\, \text{total}}} = \{1 + \phi[Z, I_{i-1}, T_e]\}^{-1}, \tag{4}$$

where

$$\phi[Z, I_i, T_e] = \left\{3.8 \times 10^{-3} \left(3.1 - \frac{1.2}{Z} - \frac{0.9}{Z^2}\right) \frac{T_e}{N_0 I_{i-1}^3} \zeta 10^{-5040 I_{i-1}/T_e}\right\}^{-1}. \tag{5}$$

Here, the symbols are as defined by Pottasch.

At temperatures above $T_e \sim 2 \times 10^6$ K, and for the ions of interest, ϕ decreases with increasing temperature. Line emission from hydrogenic ions, and from the continua of helium-like and hydrogen-like ions, therefore increases with T_e.

We assume that the flare predecessor event occurs in a single homogeneous volume V, for purposes of illustration. The X-ray flux from the region, which is observed to increase, is given by

$$E_{FB} \propto \frac{[T_e^{-1/2} N_e^2 V]}{N_e \{1 + \phi[Z, I, T_e]\}} \tag{6}$$

$$E_L \propto \frac{[T_e^{-1/2} N_e^2 V]\, 10^{-5040W/T_e}}{\{1 + \phi[Z, I, T_e]\}}. \tag{7}$$

At the same time the radio flux-density remains essentially constant:

$$S \propto [T_e^{-1/2} N_e^2 V] \simeq \text{const}. \tag{8}$$

Thus an initial increase in temperature in the volume is required, although expression (8) requires other, simultaneous changes.

The conditions imposed by expression (8) are restrictive, but physical changes taking place prior to the flare need only follow (8) approximately. In particular we note the exponential dependence of E upon T_e for the line emission, while S depends upon $T_e^{-1/2}$. A simple adiabatic compression of a spherical volume of radius r requires ($\gamma = 5/3$) $T_e \propto r^{-2}$ and $S \propto r^{-2}$, possibly ruling out such a compression as the flare predecessor event.

Detailed theoretical calculations of the solar X-ray flux have been carried out by MANDEL'ŠTAM (1965). His results show that in the temperature range $2 \times 10^6 \lesssim T_e \lesssim$ $\lesssim 3 \times 10^6$ K an increase of about 10% in T_e approximately doubles the soft X-ray flux between 8–12 Å in both the lines and continuum. Although FRITZ *et al.* (1967) observed a continuum/line ratio significantly different from that predicted by Mandel' štam's calculations, it is certainly likely that the trend of flux increase with temperature predicted by him is essentially correct.

The X-ray flux increment in the flare predecessor, when it occurs, is usually a fractional part of the total background soft X-ray flux, that is, the solar X-ray flux is not doubled. Because the radiation arises from a single active center, it may represent an increase in soft X-radiation from that region of a factor of 2 or more. For the April 11, 1967 event, we estimate an increase of some 200–300% from the pre-flare region alone. According to Mandel'štam's calculations, such an increase can be attributed to a temperature increase of from 200000–400000 K. This increment in T_e in the active center leads to a decrease in 2800 MHz radiation from the whole sun of a few tenths of a flux unit, if we assume no other changes take place.

That the temperature increase during the flare predecessor event is not large is attested by other observations from OSO-III. NEUPERT (1968) obtained a flux curve at 1.87 Å (Fe XXV?) in the flare of July 25, 1967 (see our Figure 7). Our soft X-ray flux began a weak rise 9 min prior to the first enhancement at 1.87 Å. NEUPERT *et al.* (1969) also published flux curves at 1.87 Å and at 11.8 Å (Fe XXII?) for the importance-3 flare of May 6, 1967 (see our Figure 12). Our soft X-ray flux began a weak increase 12 min prior to the first increase in the Fe XXII line, which rose in intensity nearly simultaneously with the Fe XXV line. Both these lines require rather more extreme excitation conditions than do the lines of Table VI. On the other hand, the Fe XXII line does overlie the O VIII recombination continuum, which is expected to be strongest at $T_e \sim 2.5 \times 10^6$–4×10^6 K.

If our interpretation of the flare predecessor radiation is correct, an initial rise in temperature of no more than 2 to 4×10^5 K occurs in the pre-flare coronal volume. Following this initial thermal stage, which may be abrupt in many events and is protracted through minutes in the class of phenomenon being described here, particle

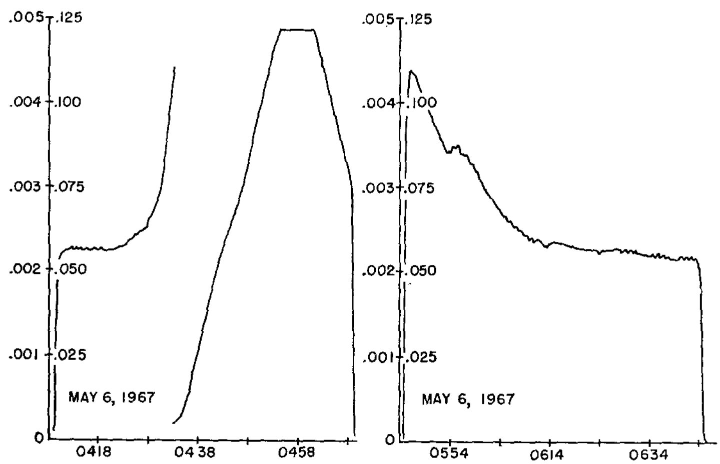

Fig. 12. Soft X-ray flux curve for importance-3n flare (S21 W35) on May 6, 1967. Note change of scale at 04^h33^m. Record is off-scale between 05^h45^m and 05^h00^m. High-sensitivity operation only between 05^h44^m and 06^h44^m. Sunrise and sunset at beginning and end of each record.

acceleration takes place. The non-thermal particles give rise to keV-range X-rays (e.g. ARNOLDY *et al.*, 1967) and to cm-wave bursts (TAKAKURA and KAI, 1966).

B. TIMES OF MAXIMA: TRAPPING OF ELECTRONS

The thermalization of fast particles and their further production of X-ray emissions has been discussed by NEUPERT (1968). A further interpretation of our results offers more evidence in support of the schematic flare model put forward by him.

Usually, a rapid rise in soft X-ray emission closely coincides in time to the start of the microwave burst, even in those cases where the radio-frequency radiation was preceded by a weak X-ray increase. However, the soft X-ray maximum follows the cm-λ maximum by roughly 4 min.

TAKAKURA and KAI (1966) attribute the impulsive cm-λ burst to synchrotron radiation generated by a fast electron stream. They assume that particle acceleration ceases at the time of the burst peak, after which the burst decay is caused by loss of trapped electrons as well as by synchrotron and gyroemission losses. Electrons with small enough pitch angles may escape the trapping region on a time-scale given by the 'deflection time' defined by SPITZER (1967).

$$t_D = \frac{1}{8\pi N_e \omega p_0^2 (\varphi - G) \ln \Lambda} \cong \frac{2.4 \times 10^{12}}{N_e} \varepsilon^{3/2} \text{ sec}. \tag{9}$$

The constant, which depends only weakly upon conditions in the coronal volume, has been calculated for $N_e \sim 2 \times 10^{10}$ cm^{-3}, T_e(flare)$\sim 10^8$ K, T_e(corona)$\sim 10^6$ K. For the range of conditions

$$0.2 \leqslant \varepsilon \leqslant 1.0, \quad 10^{10} \leqslant N_e \leqslant 10^{11} \text{ cm}^{-3}, \tag{10}$$

we calculate that

$$2 \leqslant t_D \leqslant 240 \text{ sec}. \qquad (11)$$

We are here assuming that the electrons being lost out of the trapping region interact with denser material in the lower corona and there excite the bulk of the thermal radiation being detected by us.

If the peak of the impulsive microwave burst represents the end of acceleration of electrons, which are presumed then to be lost from the trapping region by thermalizing collisions, we would expect the peak thermal soft X-radiation to occur between a few seconds and a few minutes later. The observed average time lag is consistent with $\varepsilon \sim 1$ and $N_e \sim 10^{10}$ cm^{-3}. Because some electrons will be lost almost at once, the fast X-ray may be nearly coincident with the beginning of the impulsive radio burst.

Our inability to find a relation between radio burst spectrum and differences in times of radio and X-ray maxima also seems consistent with the above scheme. TAKAKURA and KAI (1966) computed the loss rate for all electrons of energy $\varepsilon < 1$ and for different magnetic field strengths. They found that for an increase in field H from 500 to 1000 gauss, the loss-rate of electrons is not substantially increased. Thus, since the maximum in the radio flux density spectrum is directly proportional to H, we expect no relationship between lag time of maxima and the frequency of the maximum in the radio spectrum, nor is one found. Because there is also no apparent difference in lag times for bursts with and without a strong meter-wave and long decimeter-wave component, we deduce that at least the geometry and strength of the magnetic field are not critical to the production of soft X-radiation. However, they may affect the amplitude of the X-ray burst.

That the locus of X-ray production is spatially associated with solar magnetic fields is apparently shown by the very important flare X-ray photographs taken by VAIANA *et al.* (1968).

The schematic model for soft X-ray production presented here requires a close relationship between total soft X-ray energy and total cm-λ energy in flares. ARNOLDY *et al.* (1967) have shown such a relation exists for hard X-rays. TESKE (1969) suggests that such a relation might also exist for the soft X-rays. Although our schematic model does not require that the Hα energy in a flare be related to the X-ray energy, one of us (Thomas, unpublished) has shown that on the average the maximum Hα flux is directly related to the maximum soft X-ray flux in flares.

5. Summary

Observations of soft X-rays ($8 \leqslant \lambda \leqslant 12$ Å) associated with solar flares reveal that there is a strong tendency for a weak enhancement of X-radiation to precede the cm-λ burst and a weaker tendency for X-rays to precede the Hα brightening. For some flares, then, there occurs a predecessor event which in our interpretation corresponds to the heating of a volume above the active center. The temperature rise may be

2 to 4×10^5 K. Because of the requirement of expression (8) the predecessor event may not simply take the form of a compressional adiabatic heating. Following the initial gentle X-ray rise in this class of phenomenon, a more abrupt rise is seen usually in good time-association with the impulsive radio burst.

We attribute the lag of X-ray maximum relative to the cm-λ maximum to trapping of the high-energy electrons accelerated by the flare process itself. Thermalization of electrons escaping from the trapping region produces soft thermal X-radiation which constitutes the bulk of the radiation observed by our detector. The precipitation of electrons from the trapping region may continue for a long time following great flares.

There is a relationship between X-ray burst amplitude and cm-λ burst amplitude in the sense that strong cm-λ radiation is accompanied by strong soft X-radiation. Additionally, we have found that flare-rich active centers tend to produce flares which are stronger emitters of both microwave radiation and X-radiation than are flares occurring in flare-poor active centers.

Acknowledgments

This work has been sponsored under Contract NAS5-3176 with the National Aeronautics and Space Administration.

References

Acton, L. W.: 1968, *Astrophys. J.* **152,** 305.
Acton, L. W., Chubb, T. A., Kreplin, R. W., and Meekins, J. F.: 1963, *J. Geophys. Res.* **68,** 3335.
Arnoldy, R. L., Kane, S. R., and Winckler, J. R.: 1967, *Solar Phys.* **2,** 171.
Dodson, H. W. and Hedeman, E. R.: 1964, *Planetary Space Sci.* **12,** 393.
Dodson, H. W. and Hedeman, E. R.: 1968, World Data Center A Report UAG-2, August.
Dodson, H. W., Hedeman, E. R., and Covington, A. E.: 1954, *Astrophys. J.* **119,** 541.
Dodson, H. W., Hedeman, E. R., and McMath, R. R.: 1956, *Astrophys. J. Suppl.* **2,** 241.
Donnelly, R. F.: 1968, ESSA Technical Report ERL81-SDL2, July.
Elwert, G.: 1954, *Z. Naturforsch.* **9a,** 637.
Evans, K. and Pounds, K. A.: 1968, *Astrophys. J.* **152,** 319.
Fritz, G., Kreplin, R. W., Meekins, J. R., Unzicker, A. E., and Friedman, H.: 1967, *Astrophys. J.* **148,** L133.
Gregory, B. N. and Kreplin, R. W.: 1967, *J. Geophys. Res.* **72,** 4815.
Kawabata, K.-A.: 1966, *Report Ionosph. Space Res. Japan* **20,** 118.
Kundu, M. R.: 1965, *Solar Radio Astronomy*, Interscience, New York.
Mandel'štam, S. L.: 1965, *Space Sci. Rev.* **4,** 587.
Neupert, W. M.: 1968, *Astrophys. J.* **153,** L59.
Neupert, W. M., Gates W., Swartz, M., and Young, R. M.: 1967, *Astrophys. J.* **149,** L79.
Neupert, W. M., White, W. A., Gates, W. J., Swartz, M., and Young, R. M.: 1969, *Solar Phys.* **6,** 183.
Pottasch, S. R.: 1963, *Astrophys. J.* **137,** 945.
Pottasch, S. R.: 1964, *Space Sci. Rev.* **3,** 816.
Spitzer, L., Jr.: 1967, *Physics of Fully Ionized Gases*, Interscience, New York.
Takakura, T.: 1967, *Solar Phys.* **1,** 304.
Takakura, T. and Kai, K.: 1966, *Publ. Astron. Soc. Japan* **18,** 57.
Teske R. G.: 1967, *Astron. J.* **72,** 832.
Teske, R. G.: 1969, *Solar Phys.* **6,** 193.
Underwood, J. H.: 1968, *Science* **159,** 383.

Vaiana, G. S., Reidy, W. P., Zehnpfennig, T., Van Speybrock, L., and Giacconi, R.: 1968, *Science* **161**, 564.

Walker, A. B. C., Jr. and Rugge, H. R.: 1967, *Astron. J.* **72**, 825.

Warwick, C. and Wood, M.: 1959, *Astrophys. J.* **129**, 801.

White, W. A.: 1964, *AAS-NASA Symposium on Physics of Solar Flares* (ed. by W. N. Hess), NASA SP-50, p. 131.