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Analysis of Solar X-Ray Data

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RICHARD G. TESKE

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Department of Astronomy

THE UNIVERSITY OF MICHIGAN
COLLEGE OF LITERATURE, SCIENCE, AND THE ARTS
Department of Astronomy

Final Report

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Richard G. Teske

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TYPE III SOLAR RADIO BURSTS ACCOMPANIED BY SOFT X-RADIATION IN THE ABSENCE OF $H\alpha$ FLARES

RICHARD G. TESKE AND TEVFIK SOYUMER

McMath-Hulbert Observatory and Department of Astronomy, University of Michigan

AND

HUGH S. HUDSON*

Physics Department, University of California at San Diego

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ABSTRACT

Several Type III solar radio bursts which occurred in the absence of reportable flares were observed to be accompanied by weak X-radiation detectable at photon energies of between 1.0 and 12.5 keV. The X-rays almost invariably preceded the Type III burst, an observation which suggests that a thermal event precedes the Type III instability.

I. INTRODUCTION

Many solar Type III radio bursts at meter wavelengths are not associated with $H\alpha$ flares. We have recently investigated the relation between isolated Type III solar radio bursts unassociated with reported $H\alpha$ flares and enhancements of solar X-radiation which accompany those Type III bursts. We wish to point out that the results suggest a connection between some aspects of the flare phenomenon and the isolated Type III/X-ray event in the absence of visible flaring.

The X-ray observations which we studied were made in 1967 during the flight of OSO III. The Michigan soft X-ray ion chamber (8–12 Å; 1.0–1.5 keV) has been described elsewhere (Teske 1969; Thomas 1970), as has the University of California hard X-ray telescope (Hicks, Reid, and Peterson 1965; Hudson, Peterson, and Schwartz 1969). In the present investigation, California data from only the 7.7–12.5-keV channel have been used.

Hudson *et al.* (1969) and Culhane and Phillips (1970) have previously examined the correlation between Type III bursts and X-radiation at higher photon energies than those observed by Michigan. No clear distinction between flare-associated and isolated events was made by them. They found that the correlation is statistically no better than the correlation between Type III and solar flares. Hence we expected that 1.0–1.5-keV X-ray enhancements which accompanied Type III bursts in the absence of flares would be extremely rare.

II. OBSERVATIONS

Hudson *et al.* (1969) published their record of an X-ray burst observed at energies of 7.7–12.5 keV accompanying an isolated Type III burst. The Michigan flux curve for this event showed only a minor enhancement. Accordingly, we restricted our search for further events of this type to intervals when the Michigan detector was operating mainly in its higher sensitivity mode. In this mode, time-averaging of data permits us to detect flux variations smaller than $0.00003 \text{ ergs cm}^{-2} \text{ sec}^{-1}$. These time intervals during the year 1967 were examined: April 1–May 4, June 1–June 30, September 1–October 31. A total of 219 Type III events reported in the *Quarterly Bulletin on Solar Activity (QB)* were investigated.

* Now at the Tokyo Astronomical Observatory, Mitaka, Japan.

Our selection criteria were: (i) no $H\alpha$ flare was reported in the ESSA *Solar-Geophysical Data Bulletin* within 15 minutes of the Type III burst; (ii) a soft X-ray enhancement was in progress within 5 minutes of the reported Type III burst. Finally, only ten events that were observed by Michigan, at least past the X-ray maximum, met these criteria. A search of the California data was then made to find if 7.7–12.5-keV enhancements had occurred at these same times. The events are listed in Table 1. The sample in the table is not a complete one, since full-time X-ray coverage was not available.

In Table 1 the times of the Type III burst or burst group, as reported in *QB*, are given in column (2). Three columns give the times of start, maximum, and end of the X-ray burst as seen by the Michigan ion chamber (*upper row*) and by the California scintillator (*lower row*). Columns (9)–(11) give the maximum fluxes observed: the California counting rates for the solar signal and the background are separately listed whereas the background has already been subtracted from the Michigan data. In column (8), Δt is the difference between the X-ray start and the start of the Type III in the sense $\Delta t = t(\text{X-ray start})$ minus $t(\text{Type III start})$. Also given for the Michigan data are the rise time t_1 between start and maximum, the decay time t_2 between maximum and end, and the e -folding decay time τ . Finally, the time-integrated soft X-ray energy at the solar source between 1.0–1.5 keV is given as calculated under the assumption of emission into 4π steradians with no photon scattering.

Averages which are given refer to Michigan data only.

The last event in Table 1 has the same general appearance in the soft X-ray band as many subflare X-ray enhancements and is morphologically unlike the other events listed. The Haleakala, Mitaka, and Carnarvon flare patrols were all observing at the time and made no report of a flare. We have, nevertheless, not included this event in the averages for the other nine events given at the bottom of the table.

Gregory and Kreplin (1967), Teske (1967), and Thomas (1970) have called attention to ubiquitous fluctuations of the soft X-ray background. We must ask whether the present observations are fortuitous associations of Type III bursts with otherwise physically uncorrelated X-ray variations. For the first nine events in the table (we omit the 1967 October 22 event), the Type III occurred during the first half of the 1.0–1.5-keV X-ray burst. The probability that this would occur for unrelated events is 0.018. On the other hand, we cannot rule out the possibility that the phenomena studied here belong with the background fluctuations themselves. Thomas (1970) has provided a frequency distribution of fluctuations in the soft X-ray background observed by the Michigan experiment as a function of their duration: of the 217 events he investigated, half have a duration of 5 minutes or less. Six of the nine events in Table 1 definitely have soft X-ray durations in excess of 5 minutes. Thus the probability that these events belong with the class of background variation investigated by Thomas is 0.16.

III. INTERPRETATION

The sample of events in Table 1 is not large, but some relations appear to emerge from it that are worthy of comment. With the possible exception of the 7.7–12.5-keV aspect of the 1967 September 4 burst, in no event did the reported start time of the Type III event precede the start of an X-ray burst. The average 1.0–1.5-keV burst began 1.4 minutes before the Type III. There is a suggestion that the soft X-ray enhancements may divide themselves into two morphological groups: one with a soft X-ray rise time of 1.1–2.0 minutes and in which the 7.7–12.5-keV maximum tends to follow the 1.0–1.5-keV maximum; a second with a rise time of 4.5–7.3 minutes and in which the harder X-ray maximum precedes the ion-chamber maximum. There would appear to be a continuum of decay times at the softer energies. Those soft X-ray bursts with the faster rise times t_1 may begin only shortly before the Type III, and there may be a connection between t_1 and the reported length of the Type III burst train. No good case can be made for a relation between t_1 or t_2 and the X-ray amplitude.

TABLE 1

X-RAY BURSTS AND TYPE III BURSTS WITHOUT A REPORTED FLARE

Date (1967) (1)	Time of Reported Type III (UT) (2)	Radio Wavelength (3)	Photon Energy (keV) (4)	Start (UT) (5)	Max. (UT) (6)	End (UT) (7)	Δt (Min.) (8)	Michigan $\Delta E(8,12)$ (ergs) $\text{cm}^{-2} \text{sec}^{-1}$ (9)	California Peak Flux ($\text{cm}^2 \text{sec}^{-1}$) (10)	California Back- ground ($\text{cm}^2 \text{sec}^{-1}$) (11)	Rise Time t_1 (Min) (12)	Fall Time t_2 (Min) (13)	Decay Rate τ (Min) (14)	E_{total} (ergs) (15)
April 12.....	0645-0645	m, dkm	1- 1.5 7.7-12.5	0644.4	0645.6	0647.8	-0.6	0.00021	...	...	1.2	2.2	0.6	2.2×10^{26}
May 1.....	2243.5-2243.5	dkm	1- 1.5 7.7-12.5	2240.0 2240	2247.3 2243 2247	2300.6 2300	-3.5	0.00018	...	...	7.3	13.3	8.8	3.5×10^{26}
Sept. 4.....	1355.1-1357.2	dkm	1- 1.5 7.7-12.5	1353.7 1357E	1401.1 1400	1410.0 1411D	-1.4	0.00031	16 16	11	7.3	9.0	6.5	4.6×10^{26}
Sept. 5.....	0110.0-0110.5	m, dkm	1- 1.5 7.7-12.5	0110.0	0111.7 0112	0115.7D	0.0	0.00020	23	U	1.7	> 3.7	...	...
Sept. 10.....	1623.3-1624.7	dkm	1- 1.5 7.7-12.5	1622.0 1619E	1626.8 1625	1632D 1629D	-1.3	0.00022	25	7	4.8	> 5.2	5.0	$> 2.4 \times 10^{26}$
Sept. 11.....	2048-2048	m, dkm	7- 1.5 7.7-12.5	2047.7	2048.8 2050	2049.8	-0.3	0.00004	15	1.4	1.1	1.0	0.7	6.7×10^{24}
Sept. 14.....	1130-1131	m	1- 1.5 7.7-12.5	1127.2	1129.2 1131	1136.8	-2.8	0.00006	3.1	1.3	2.0	7.6	5.9	4.7×10^{25}
Sept. 23.....	2322.2-2324.8 2324-2325	dkm	1- 1.5 7.7-12.5	2322.0	2323.2 2320	2325.5D	-0.8	0.00008	7.2	1.6	1.2	> 2.3	...	...
Sept. 27.....	1201-1202	m	1- 1.5 7.7-11.5	1159.2	1203.7 1201	1206.6	-1.8	0.00009	2.1	0.8	4.5	2.9	2.6	6.7×10^{25}
Oct. 22.....	0105.0-0105.5	m	1- 1.5 7.7-12.5	0100.5 0059	0102.2 0102	0116.5(?) 0112	-5.0	0.00158	20	U	1.7	14.3(?)	...	...
Average...			1- 1.5				-1.4	0.00015	190	1.0	...	...	...	1.6×10^{26}

The apparent discordances of timing of the maxima of the 7.7–12.5-keV bursts on 1967 September 11 and 23 are probably caused by uncertainties in the data; these are the weakest bursts recorded, and the statistical error in the photon-counting rate is large.

We note that only one of these events was accompanied by a reported cm- λ burst. On 1967 September 10 an extremely weak 2800-MHz radio burst began at 1623.5, reached a maximum of $1.4 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$ at 1624.0, and ended at 1624.5.

We have attempted to interpret these observations physically by assuming that both detectors were responding to thermal-bremsstrahlung radiation. The analysis yields, for the different events in Table 1, temperatures and emission measures at the time of the 7.7–12.5-keV peak flux in the ranges

$$6.6 \times 10^6 \leq T_e \leq 15.5 \times 10^6 \text{ }^\circ \text{K}, \quad 1.0 \times 10^{47} \leq N_e^2 V \leq 9.0 \times 10^{47} \text{ cm}^{-3}.$$

These values were calculated by the use of the Michigan flux that was observed at the time of the 7.7–12.5-keV maximum.

At these temperatures, however, thermal free-bound continua contribute significantly to the flux observed by the California telescope near 12 keV (Culhane 1969). Were this taken into account, the derived temperatures would be lowered: the upper limit $15.5 \times 10^6 \text{ }^\circ \text{K}$ would, for example, come down to $\leq 15 \times 10^6 \text{ }^\circ \text{K}$. On the other hand, below $\sim 10 \times 10^6 \text{ }^\circ \text{K}$, line emission from Mg XI $\lambda 9.16$ and Mg XII $\lambda 8.44$ become important contributors to the ion-chamber fluxes, thus confusing a temperature determination based upon a continuum slope. Therefore, only the upper limit to the temperature range derived above, and only the lower limit for the emission measures—which corresponds to the higher temperatures—have any meaning. For these reasons our data permit us to characterize the class of events studied here only by

$$T_e \leq 15 \times 10^6 \text{ }^\circ \text{K}, \quad N_e^2 V \geq 1 \times 10^{47} \text{ cm}^{-3},$$

at the time of the peak of the 7.7–12.5-keV burst, if we assume that the radiation at that time is purely thermal. We have no independent evidence supporting that assumption.

IV. DISCUSSION

There exists a class of Type III radio burst which occurs in the absence of reportable H α flaring and which is accompanied by enhancement of X-rays across the range 1.0–12.5 keV. About 5 percent of all Type III bursts belong with this category. Not every isolated Type III is accompanied by X-rays detectable by our experiment packages, however.

The total soft X-ray energy for these events (Table 1) lies at the lower edge of the time-integrated energies for subflares previously studied with the Michigan ion chamber (Teske 1969). Thomas (1970) has displayed a scatter diagram for soft X-ray burst amplitude for flares of importance ≥ 1 versus rise time for those bursts. The present data appear to form a natural extension of his diagram to small amplitudes and short rise times.

Of greatest significance to us is the fact that the soft X-ray rise precedes the onset of the Type III burst. When the speed of the Type III exciter stream is taken into account, we must still conclude that the X-rays precede the acceleration event. It is therefore unlikely that the initial stages of the soft X-ray burst are heated by the same nonthermal mechanism that produces the Type III exciter stream. Rather, the initial X-ray rise may be a manifestation of an event which leads to the Type III instability.

Kahler and Kreplin (1970) have recently argued that solar flares are triggered by a thermal-runaway event which occurs in coronal condensations at levels where the electron density is in the neighborhood of 10^{11} – 10^{12} cm^{-3} . The physical basis for their model

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is that the temperature derivative of the volume emission coefficient is negative over a range from normal coronal temperatures out to about 14×10^6 °K (Cox and Tucker 1969), at which point the emission-rate curve reaches a minimum. Above this temperature dP/dT_e becomes positive once again. Kahler and Kreplin postulate that the thermal runaway in some fashion leads to further release of energy from nonthermal sources.

We speculate that our observations reveal a similar course of phenomena which, however, do not lead to the production of a reportable H α flare. The peak temperature reached in the events discussed here is probably below that at the minimum of the Cox and Tucker emission-rate curve. In our view there occurs an initial event which deposits energy into a small volume, driving it toward but perhaps not to the minimum in the emission-rate curve and giving rise to thermal radiation which has its greatest contrast against the undisturbed solar flux in the X-ray region of the solar spectrum. During the heating event which begins prior to the meter-wave radio event, the Type III exciter stream is accelerated by an unspecified process. Since the X-ray flux depends upon N_e^2 , we suggest that the electron density in the heated volume will determine whether the Type III burst is preceded by detectable fluxes of X-radiation. On the other hand, a thermal perturbation (the background fluctuations?) may not necessarily result in the production of a Type III burst.

As Culhane has pointed out (cited by Thomas 1970), we may be observing a phenomenon which, under suitable conditions, may act to initiate a reportable flare but which, for some reason, has not been successful in doing so.

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NOTE ON THE ENERGY SCALE OF THE MICHIGAN OSO III ION CHAMBER

Richard G. Teske, Philip E. Hodge, and Simon P. Worden*
Department of Astronomy and the McMath-Hulbert Observatory,
The University of Michigan, Ann Arbor, Mich., U.S.A.

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Abstract. The energy scale of the Michigan OSO III soft X-ray ion chamber has been assessed by using realistic theoretical X-ray spectra. Multiplicative factors by which the data may be corrected are proposed. The factors are only slightly temperature-dependent. A test of the proposed energy scale indicates it is still somewhat uncertain.

1. Introduction

Solar X-radiation has been monitored for many years by means of rocket- and satellite-borne ion chamber detectors. The method of reduction of the ionization current recorded by these devices to an X-ray flux value was early worked out by the pioneers in the field at the Naval Research Laboratory (Kreplin, 1961). In this method, the spectrum shape is fixed by assumption to be that of a black body at some temperature T . Upon justifiable observational and theoretical grounds, the temperature defining the spectral shape appropriate to the 8-20 Å data was selected by them to be $T = 2 \times 10^6$ deg (Friedman, 1960). This value has been used ever since, although the data so reduced have been treated carefully in the full realization of their approximate nature (e.g., Kreplin et al., 1962).

The Michigan soft X-ray ion chamber on OSO III was adapted from an NRL design. Solar soft X-ray fluxes were conventionally determined from the telemetered data by adopting the $T = 2 \times 10^6$ deg grey-body assumption in order to provide a continuity of the observations with those made by NRL. In previous papers concerning our results we have extensively quoted X-ray flux values between 8-12 Å for many observed phenomena on basis of that assumed spectrum. Thomas (1970) concluded that the quoted fluxes were reasonably independent of

*Now at the University of Arizona, Tucson, Arizona.

spectrum, but that they might be systematically a factor of two or three too high.

We have reinvestigated the question of the energy scale of the Michigan instrument and find support for Thomas. The results of our calculations provide correction factors which may be applied to the quoted Michigan fluxes. These correction factors depend upon theoretical spectra, which are not yet completely perfected. A test of the proposed energy scale, described below, indicates that the suggested correction factors are still to some extent uncertain.

2. Calculations

Culhane (1969) has calculated free-free and free-bound continua for thermal plasmas at a variety of temperatures. We directly adopted his spectra for coronal abundances.

Tucker and Koren (1971) have calculated the power emitted in spectrum lines between 0.5 and 70 Å, using coronal abundances, for a wide variety of temperatures. We superposed these emission lines upon Culhane's continua for the calculations which are discussed below.

The ionization current that would be produced when the ion chamber is exposed to the fluxes described by the superposition of emission lines and continua is

$$\frac{i'}{\int N_e^2 dV} = \frac{1.078 \times 10^{-8}}{\int N_e^2 dV} \int_0^{\infty} F(T, \lambda) \epsilon(\lambda) d\lambda \text{ amp cm}^3 \quad (1)$$

where $\epsilon(\lambda)$ is the band-pass of the detector. The flux of X-rays between 8 and 12 Å would be

$$\frac{F(8,12)}{\int N_e^2 dV} = \frac{\int_0^{12} F(T, \lambda) d\lambda}{\int N_e^2 dV} \text{ erg cm s}^{-1} \quad (2)$$

In carrying out our actual data reductions, the quoted fluxes were calculated from (cf. Kreplin, 1961)

$$E(8,12) = 7.75 \times 10^8 i \text{ erg cm}^{-2} \text{ s}^{-1} \quad (3)$$

In Table I we list the electrical currents which would be produced (per $N_e^2 V$) by exposing the ion chamber to a 'realistic' flux of X-rays (from Equation (1)), the 'realistic' flux $F(8,12)$ as calculated from Equation (2) and the flux value that would have been quoted by us had we observed the electrical current i' (from Equation (3)). In the last column is given the correction factor which converts the quoted flux to the 'realistic' flux.

TABLE I

Proposed correction factors for Michigan OSO III ion chamber data

$\log T_e$	$\frac{i'}{\int N_e^2 dV}$ (amp cm ³)	$\frac{F(8,12)}{\int N_e^2 dV}$ (erg cm s ⁻¹)	$\frac{E(8,12)}{\int N_e^2 dV}$ (erg cm s ⁻¹)	Correction factor
6.3	2.99×10^{-62}	1.82×10^{-53}	2.32×10^{-53}	0.78
6.5	3.23×10^{-61}	1.92×10^{-52}	2.50×10^{-52}	0.77
6.7	1.26×10^{-60}	7.57×10^{-52}	9.72×10^{-52}	0.78
7.0	3.59×10^{-60}	2.08×10^{-51}	2.78×10^{-51}	0.75
7.3	2.42×10^{-60}	1.30×10^{-51}	1.87×10^{-51}	0.70

These correction factors indicate that the quoted energy scale for the Michigan data is too high by about 30% for the quiet Sun and by about 40% for phenomena that reach $T_e = 20 \times 10^6$ deg. In general, however, the relative fluxes quoted from our data are independent of spectrum shape, between $2 \times 10^6 \leq T_e \leq 20 \times 10^6$ deg, to within 12%.

Horan (1970) and other NRL observers (Kahler et al., 1970) have found that at the X-ray maximum in flares the appropriate T_e for soft X-rays is in the neighborhood of 10×10^6 to 20×10^6 deg. Thus the relative flux amplitudes quoted by us for flares are perhaps correct to about 7% or better, and time-integrals of energy relatively correct to about 10%.

We expecially note that the instrumental ion chamber current produced per unit emission measure on the Sun is nearly independent of temperature (to within 50%) between $10 \times 10^6 \leq T_e \leq 20 \times 10^6$ K. Thus, during flares the instrument responded chiefly to variations of emission measure. Relative flux data quoted for flares (e.g., Teske, 1969; Thomas and Teske, 1971) thus principally depict the differences in emission measure which characterize the soft X-ray source in various flares.

These conclusions support Thomas's (1970), which were based upon semi-artificial spectra. The corrections proposed here, however, require a test of their acceptability.

3. A Test of the Calculated Response

The above calculations may be tested upon published observations that were made at the same time as our own. One such test may be made using the spectrum recorded on 9 Nov., 1967, by a proportional counter and reported by Culhane et al. (1969). This spectrum is shown as the full line in our Figure 1. At the time of their observation, our OSO III ion chamber current was 2.58×10^{-12} Amp.

Culhane et al. used Culhane's (1969) continuum calculations and fitted their observed spectrum by a coronal model containing two components described by (i) a component at 5×10^6 deg, $N_e^2 V = 1.7 \times 10^{47} \text{ cm}^{-3}$, and (ii) a component at 3×10^6 deg, $N_e^2 V = 5 \times 10^{48} \text{ cm}^{-3}$. Their model failed to fit the observed spectrum longward of $6 \text{ \AA}$ wavelength, and they concluded that there must have existed 'substantial' volumes of plasma at temperatures below 3×10^6 deg'.

We have attempted to fit Culhane et al.'s observed spectrum by a three-component model based upon the theoretical continua and lines utilized in this study. A constraint upon the model is that it must reproduce the observed ion chamber current. The parameters of a three-component model which fits the data are listed in Table II and the resulting fit to the observed spectrum, averaged over $1\text{-}\text{\AA}$ intervals, is shown in Figure 1. Although the spectrum fit is good and the model reproduces the observed ion chamber current, an emission measure of $7.1 \times 10^{49} \text{ cm}^{-3}$ is required.

TABLE II

Three-component model to fit spectrum by Culhane et al. (1969)

$\log T_e$ (deg K)	$N_e^2 V$ (cm^{-3})	Ion chamber current (Amp)
6.3	7×10^{49}	2.09×10^{-12}
6.5	1×10^{48}	0.32×10^{-12}
6.7	1.5×10^{47}	0.19×10^{-12}

This seems rather excessive. From the model of an active region by Christiansen et al. (1960), we obtain a representative columnar electron surface density squared in active regions of

$$\int N_e^2 dh \sim 9 \times 10^{28} \text{ cm}^{-5}.$$

On 9 Nov., 1967, the total plage area was 15300×10^{-6} of a solar hemisphere, yielding

$$\sum A \int N_e^2 dh \sim N_e^2 V \sim 4 \times 10^{49} \text{ cm}^{-3}.$$

We consider this test of the proposed energy scale for our instrument to be a partial success, since the energy required to explain the ion chamber current leads directly through the proposed calculations to a good fit of the observed spectrum. However, the required emission measure appears to be about 80% larger than an acceptable value. If we wish to make the derived emission measure match that predicted from Christiansen's model, we must increase the 'realistic' fluxes per unit emission measure of Table I above those given by the theoretical spectra which were employed, thereby increasing the correction factors and making them closer to unity.

4. Conclusions

Use of 'realistic' X-ray spectra rather than the standard grey-body approximation in calculating ion chamber response leads to the conclusion that flux values quoted for the Michigan OSO III ion chamber are semi-independent of the shape of the thermal spectrum over a temperature range $2 \times 10^6 \leq T_e \leq 20 \times 10^6$ deg, to within 12%, on a relative energy scale. For flares in the range 10×10^6 to 20×10^6 deg, the relative flux values are correct to 7%.

A multiplicative factor which corrects the quoted fluxes to the 'true' fluxes is temperature-dependent, and may be calculated from a suitable theoretical spectrum. The correction factors cannot yet be stated with certainty, but lie in the range 0.7-1.0. If Culhane's (1969) continua and Tucker and Koren's (1971) emission line powers correctly represent the Sun, the correction factors of Table I may be applied directly.

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Figure Caption

Figure 1. The full line is the X-ray spectrum observed 9 Nov., 1967, by Culhane et al. The dashed histogram is the theoretical spectrum fitted to it using the energy scale for the Michigan ion chamber which is proposed in this paper.

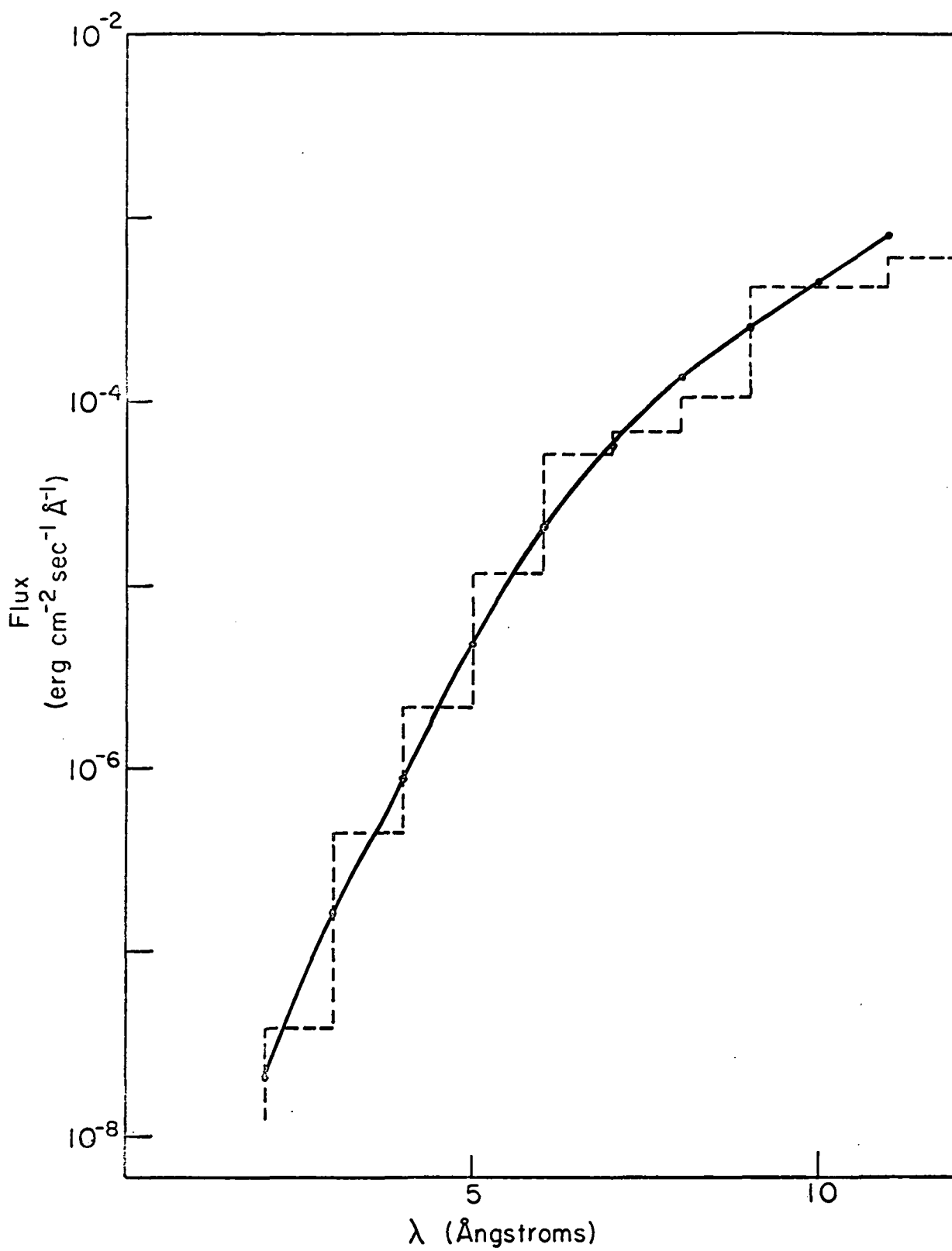


Figure 1

SOFT SOLAR X-RAYS AND SOLAR ACTIVITY

VI. Optical Identification of Activity Associated with X-Ray Background Fluctuations

Richard G. Teske

Department of Astronomy and the McMath-Hulbert Observatory,
The University of Michigan, Ann Arbor, Mich., U.S.A.

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Abstract. Minor H α activity, consisting of small brightenings and small, surge-like spikes, was observed to take place above an active center at the solar limb in good time-association with small fluctuations in the soft X-ray background flux, suggesting that even small dynamical events seen optically are associated with coronal heating. The ratio of H α flux to soft X-ray flux in some of the surges was approximately the same as the ratio already established for flares. The total energy dissipated by the events in a 24-hour period is estimated; it is approximately equivalent to that released by one flare of importance 1 per day.

1. Introduction

Several observers who have conducted experiments to monitor solar X-radiation from spacecraft have noted that presence in their data of short-term, low-amplitude fluctuations of the X-ray background. Gregory and Kreplin (1967) and Teske (1969, Figure 4) have exhibited examples of these fluctuations. The former authors discussed their observations in detail; they found that the contrast of the background fluctuations increases with increasing photon energy. Thomas later investigated the frequency and duration of the background fluctuations which are seen at ≈ 1 keV photon energy (Thomas and Teske, 1971). None of these authors identified an optical feature on the sun as associated with the X-ray variations.

The 8 to 12 Å solar flux was monitored by an ion chamber photometer on the OSO-III satellite (a description and some results have appeared in earlier volumes of this journal). These data demonstrated that the background

fluctuations are almost always present in the solar soft X-ray flux. When solar activity is high the amplitude, duration, and frequency of occurrence of background variations is high, while at low levels of solar activity the X-ray variations are infrequent and of generally lower amplitude and shorter duration. The morphology of the fluctuations is highly varied. Lasting from a few minutes to more than half an hour, they are most often characterized by rise-times which are shorter than the subsequent time to decay and have amplitudes at 1-1.5 keV photon energy ranging from a few percent to more than 20% of the 'quiet X-ray background.'

The X-ray fluctuations represent a transient energy input to the corona whose magnitude and nature it is of interest to explore. We show below that the total energy expenditure associated with them is significantly large when judged in terms of energies dissipated in flares. They thus may represent an important energy leak from active regions (since X-rays below 20 Å come almost exclusively from active centers). The nature of the physical mechanism which sporadically supplies the energy can only remain speculative until the location on the sun of the source volume has been identified and the physical response of the solar atmosphere has been investigated. One place we can start to investigate the problem is to ask whether at least some of the X-ray background fluctuations are associated with optically-identifiable activity on the Sun, and, if so, to undertake to describe that activity.

In this paper we describe surge-like structures in active centers, seen in H α , which were associated with low-amplitude X-ray events. The energy budget for the observed phenomena is assessed.

2. Observations

During an investigation which was designed to examine the relationship of soft X-ray enhancements to eruptive prominences, our attention was claimed by a series of weak X-ray background variations which occurred on 4 September 1967. These variations were generally characteristic of those which have been described by authors cited above. Occurring at the same time as many of the X-ray events were small, faint, surge-like features which were seen on the McMath-Hulbert flare-patrol films above an active region than on the east limb of the Sun. Accordingly, both the H α flare-patrol and the X-ray records were scrutinized in an effort to determine the reality of the relationship. We have only the time-coincidences to guide us, since the Michigan X-ray photometer had no angular resolution on the Sun.

On 4 September 1967, the Sun was very quiet. No major centers of activity were on the disk nor within several days behind either limb. McMath plage 8970 was at that time on the southeast limb and plage 8969 was just behind the

equatorial east limb. By the following day, both regions had moved on to the visible disk. A series of modest small brightenings and spike-like ejections took place in 8970 throughout the interval available on our flare-patrol films (the last half of the UT day). In addition, plage 8969 and other regions on the disk produced some visible H α activity.

Data relevant to the interval of interest are shown in Figure 1, where we present the observed X-ray fluxes, a schematization of the events seen on the flare-patrol films, the intervals of reported flares and the intervals during which flare patrol stations were operating. Flare-patrol coverage was adequate; only two subflares were reported, both of them at the east limb and both well-marked in the X-ray data. Our assessment of the McMath film record indicates that no other visible events of flare magnitude took place.

The X-ray flux curves of Figure 1 are fairly typical of periods when solar activity was moderately low and our X-ray photometer was operating in its higher sensitivity mode. During an hour's operation in sunlight, the flux curves often seem to show a general decline. This is definitely not an instrumental effect, but is solar in origin, indicating that relatively abrupt X-ray rises are followed by considerably slower declines. A good example is the last data record which covers the interval 2130-2225 UT.

The background fluctuations being discussed here are the small variations (for example, the variations which occurred at 1400, 1545, 1650, 1655, 1825, 1902, and 2204) which are seen superposed upon the longer-duration X-ray changes. It is possible that the changes of longer time-scale are also connected, in a general way, to activity taking place in plage 8970. However, we have focussed our interest upon the shorter time-scale events and the possibility of their association with individual optical events that occurred with them.

The limb activity seen to occur on the films, although often of a relatively complex appearance, has been characterized in four broad classes:

- (a) Knobs ('K' in Figure 1): small brightenings of uncertain dimensions (at or below the image resolution) seen on or just above the limb;
- (b) Mound ('M' in Figure 1): a feature extended along the limb and rising detectably above it, sometimes having a jagged upper profile;
- (c) Arch ('A' in Figure 1): a small temporary prominence arch;
- (d) Spikes ('S' in Figure 1): elongated, temporary surge-like features rising above the limb, often two or more at once.

These are illustrated by several photographs in Figure 2. The spike-like structures were often highly inclined to the local radial direction, with

lengths ranging from ≈ 12000 km to ≈ 44000 km.

Most of the dynamic structures seen in 8970 were of modest surface brightness in H α , seldom brighter than plages on the disk and often fainter than that. The activity that was seen to take place is familiar to solar observers and commonly occurs over active regions during their limb passage. As is frequently the case, the activity in 8970 was almost continuous, the structures we have called 'knobs' appearing and evolving (sometimes after a period of hesitation) into 'spikes' which then again subsided into 'knobs,' the cycle then repeating. Nevertheless the activity was resolvable into a series of essentially distinctive events (Figure 1). The analysis of the films and a division of the activity into the various events was carried out without reference to the X-ray data. The films were then examined again to detect activity in other regions on the disk and limbs before comparison with the X-ray flux curves.

All of the minor X-ray fluctuations that occurred during our H α flare-patrol hours were associated with some kind of an optical event. In Figure 1 we have indicated by means of corresponding numbers some of the associations between spike-like events and soft X-ray background fluctuations. Table 1

TABLE I

Frequency of association of minor X-ray enhancements
with different categories of optical events

Type of optical event	Associated with an X-ray event	No X-ray fluctuation occurred	Overlapped with another event	No X-ray data	Total
'Spikes'	11	1	6	4	22
'Knobs'	2	4	3	8	17
'Arches'	1	0	1	1	3
'Mounds'	1	0	0	0	1

summarizes the associations (and failures) that were observed for all four categories of events described above. In general the time-coincidences between H α spike events and soft X-ray events are very good. The large number of matching events strongly suggests that the two are indeed related. Only one spike may have failed to associate with X-rays: this exception is the large spike feature which began at 12^h31^m (Figure 2a). It may be, however, that a weak X-ray event, which was superposed on a declining background, began at 12^h35^m. Table 1 suggests that in many instances the features called 'knobs' were not closely related to production of soft X-radiation.

The last H α flare-patrol frame of the day was taken at 21^h30^m, at the beginning of a fairly large X-ray event. That frame shows still another small spike-like feature developing on the limb above plage 8970.

No cm- λ radio events were reported during the interval being discussed here. Some Type-III bursts were reported: these have been indicated at the bottom of Figure 1. Three of the Type-III bursts may be associated with spike events. See Teske et al. (1971).

Three plage regions may have contributed to the small soft X-ray fluctuations of 4 September 1967: 8955, 8969, and 8970, the latter making the most prolific contribution. All three regions were youthful.

8955 was born on the disk nine days earlier, on 27 August, a sunspot appearing in it the same day. This region produced only subflares (26 of them) during its disk passage.

8969 was a new plage as it rounded the east limb and it died while still on the disk. Only 8 subflares were reported in this region.

8970 was the largest and brightest of the three regions, was also new at east limb passage and produced 29 subflares and 2 flares of importance 1. The incumbent spot group was not especially large, but persisted until early on 14 September. This plage underwent some growth after it had rounded the east limb.

3. Discussion

There is a strong tendency for the X-ray background fluctuations to be best associated with spike-like features which occurred above plage 8970. These dynamic phenomena had the appearance of small surges but, unlike classical surges as described by Giovanelli and McCabe (1958), they were small (of length less than 44000 km), not associated with H α flares (as defined) and were fainter, usually, than plage brightness. Thus we have called them spike-like, or surge-like, to distinguish them from the classical surges. They may, however, have a close similarity to classical surges for the following reasons: (i) The association of the spike-like events on 4 September 1967, with X-ray emission indicates their connection with coronal heating. Tandberg-Hanssen (1959) observed coronal emission lines above two surges and deduced temperatures near 3×10^6 K from the line profiles. (ii) The time-association of three spike-like events with Type-III bursts indicates a possible physical connection. Loughhead et al. (1957) noted the flat visibility distribution of Type-III bursts with solar longitude from 90°E to 30°W, a longitude interval which includes the observations being discussed here. Giovanelli (1958) and

Swarup *et al.* (1960) found that Type-III bursts have a higher probability of association with a flare if a surge accompanies it, while it has been generally recognized (e.g., Malville, 1962) that some Type-III's do not necessarily associate with flares. Our data suggest that nonflare Type-III's may at times associate with nonflare surge-like events. (iii) The small H α 'knobs' at the base of the spike-like events may possibly be considered to be minute subflares. If we choose to make this assertion, the spike-like events may be thought of as the small surge counterpart in a miniature flare/surge event. The lifetimes of the spikes are similar to surge lifetimes (Bruzek, 1969).

However, in what follows we shall be concerned only with a discussion of inferred energetics of the spike-like events.

Because of the significant number of time-coincidences between X-ray enhancements and small spikes which were found on 4 September 1967, we have assumed that on that day the two were indeed physically related. The evidence in our data is, however, that the relative magnitudes of the X-ray and H α aspects of a single event are quite variable. There may be at least three accidental reasons for this: (i) moving material emitting Doppler-shifted H α would not have been easily detectable, depending upon the line-of-sight velocity; (ii) the H α structure of some of the events may have been partly hidden behind the chromosphere at the limb. Both would have affected an estimate of the magnitude of the H α event. The latter effect certainly played a role in the arch structure seen in plage 8969 at about 18^h30^m. (iii) Faint H α material may not have registered on the film above the scattered H α sky-light.

A. ESTIMATES OF ENERGIES ASSOCIATED WITH THE PHENOMENA

We have attempted to estimate the energies which may have been associated with the H α and X-ray aspects of some of the spike phenomena that were observed. The nature of the estimates that were made is described below and the results are given in Table II.

TABLE II

Energies invested in X-ray emission, H α emission
and potential energies of 'Spikes'

Approximate time of event UT	Peak X-ray emission rate erg sec ⁻¹	Total soft X-ray emission erg	Peak H α emission rate erg sec ⁻¹	Total H α emission erg	$\Delta V/\rho$ erg (gm/cm ³) ⁻¹
1253	?	?	2×10^{25}	3×10^{28}	1×10^{41}
1400	1×10^{24}	1×10^{27}	4×10^{24}	8×10^{27}	2×10^{40}
1650	4×10^{23}	8×10^{25}	5×10^{24}	2×10^{27}	2×10^{40}
1655	6×10^{23}	6×10^{26}	2×10^{24}	6×10^{26}	1×10^{40}
1834	5×10^{23}	2×10^{26}	6×10^{24}	3×10^{27}	3×10^{40}

1. Soft X-ray Energy

The course of the X-ray background underlying a fluctuation was estimated: this was sometimes a sloping line. The resulting flux profile of the event was used to calculate the desired peak soft X-ray emission rate (column 2 of Table II) and the time-integral of X-ray emission (column 3). Because of uncertainties as to the location of the real X-ray background, errors in these estimates may be at least a factor of two. The 'observed' energy was multiplied by $4\pi(1 \text{ AU})^2$ to get the energy at the sun.

2. Energy Emitted in H α

Because of the likely possibility that some H α emission was not observed, any estimate of total H α energy must be treated as a lower limit. The method that was used neglects scattering of chromospheric H α by spike material. Lengths and breadths of spike-like features were measured on the films and an emitting area of $2\pi rL$ assigned, assuming cylindrical symmetry and ignoring the ends of the column. The time-integral (column 5 of Table II) was obtained by multiplying half the total emission rate at maximum, given in column 4 of the table, by the time-duration. Two methods of estimating the H α emission rate gave nearly the same results: using $T_{\text{ex}} = 4000^\circ$ (for spicules; Michard, 1959) and $\Delta\lambda_D = 0.8 \text{ \AA}$ (for spicules; Athay, 1958) we obtained $I_{\text{H}\alpha} = 2.0 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$, assuming an optically-thick source. With line profiles of plages and the undisturbed disk (de Jager, 1959), which yield an equivalent width for the H α excess from plages of $\approx 0.12 \text{ \AA}$, we obtained $I_{\text{H}\alpha} = 1.8 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$. Both estimates refer to features of roughly plage brightness. An estimate of spike brightness relative to plage brightness was then used to get the results of Table I, columns 4 and 5. These are lower limits, and errors may be as large as a factor of three.

3. Potential Energy

Again an estimate of the mechanical energy expended in raising the material of a spike above the limb will represent a lower limit because of the possibility of unobserved material. If a cylindrical spike of radius r and length L is inclined at an angle ϕ to the local radius and contains material at constant density ρ , a mass element has potential energy $\rho g_\odot (1 \cos\phi - r \sin\theta \sin\phi) r dr d\phi d\theta$, where θ is an azimuthal angle about the spike's axis. The total potential energy per unit mass density, relative to the original height of the material, is

$$\frac{\Delta V}{\rho} = \pi r^2 L g_\odot \cdot 1/2 L \cos\phi \text{ erg}(\text{gm/cm}^3)^{-1}.$$

Observed values for $\cos \phi$ for spikes as seen projected against the sky ranged from ≈ 0.5 to ≈ 1.0 , and a value of 0.75 was adopted for all. Errors in estimating this lower limit may be a factor of two or more, apart from an estimate of the mass density (see below).

4. Work Done Against the Magnetic Field

It seems likely that the observed spikes, which tilted in much the same orientation and followed much the same paths, extended along the field lines. Thus this energy term was ignored. [If the material of a spike must do work in stretching field lines, the work may crudely be estimated by $A \int (B^2/4\pi) dl$, where $A = \pi r^2$ is the base area of the spike. Since the field lines stretch up and down both sides of the spike,

$$W \approx 1/2 B^2 r^2 L \text{ erg.}$$

For the observed spikes, this term could be of the same order of magnitude as the potential energy or greater, depending upon the value chosen for B.]

5. Work Done Against Coronal Gases was also ignored

B. PEAK EMISSION RATES IN H α AND IN SOFT X-RAYS

Thomas (Thomas and Teske, 1971, Figure 5) has compared the mean peak soft X-ray and H α emission rates for flares in the various importance classes. He found that the peak emission rates are roughly proportional for flares from subflares to those of importance 3. We have compared the peak emission rates for spike-like events (Table II) with Thomas's relationship, see Figure 3. The inferred emission rates appear to extend the flare relationship by more than an order of magnitude.

That the four spike-like events studied here so closely fit an extrapolation of the flare relationship may be fortuitous, given the possible magnitude of errors that have been made in estimating the emission rates. Nevertheless Figure 3 strongly suggests that there may exist an energetic relationship, extending over almost four orders of magnitude, between the H α and soft X-ray aspects of some transient solar phenomena, whether or not the rules of definition require us to use the word 'flare.'

The relationship implied by Figure 3 does not, by itself, necessarily indicate that there is a common initiatory process underlying flare and spike-like phenomena. It does suggest that there might be a common physical means

of sharing an initial energy fund among source volumes at high temperature (X-rays) and at low temperature (H α).

C. TOTAL ENERGY IN H α , X-RAYS, AND POTENTIAL ENERGY

Estimating $N_e \approx 3 \times 10^{11} \text{ cm}^{-3}$ in the H α spikes (as in spicules; Michard, 1959), $\rho \geq N_e M_H \approx 5 \times 10^{-13} \text{ gm cm}^{-3}$ and we find the sum of energies given in Table II amounts to a lower limit of $\approx 1.3 \times 10^{29} \text{ erg}$ for the five well-marked events that were examined. (We have adopted a value for the mass density that is likely a lower limit by assuming the degree of ionization of hydrogen to be unity, thus further minimizing the value of the estimated potential energy.) More than a dozen of the H α spike events described here took place during the latter half of the UT day. We therefore estimate that during a 24-hr period on 4 September 1967, the total energy invested by plage 8970 in dynamic phenomena associated with the X-ray fluctuations was in excess of $4 \times 10^{29} \text{ erg}$. Of this, the soft X-ray emission was roughly $6 \times 10^{27} \text{ erg}$, about 1% of the total.

The energy approaches that radiated at all wavelengths by a flare of importance 1b ($\approx 7 \times 10^{29} \text{ erg}$; see Thomas, 1970). Thus the X-ray background fluctuations in plage 8970 were associated with phenomena which may have dissipated an energy nearly equivalent to one flare of importance 1 per day. The estimated energy radiated by the small fluctuations in the 8 to 12 Å X-ray band during the day represented about 1/10 of the X-ray energy associated with an average flare of importance 1 ($6 \times 10^{28} \text{ erg}$; Teske, 1969). If, however, the longer time-scale X-ray events were also to be associated, this estimate would be increased by at least an order of magnitude. Because these observations refer to an interval when plage 8970 was youthful, vigorous, and growing, it is possible that the estimated averaged rate of energy dissipation was confined to that interval and declined thereafter.

On the other hand, the rate of energy loss represented by the phenomena discussed here is quite small when judged in terms of the overall energy budget of an active region. For example, Osterbrock (1961) estimated that the rate of flow of mechanical energy across the photosphere in active regions is $\approx 3 \times 10^8 \text{ erg cm}^{-2} \text{ s}^{-1}$. The inferred energy loss in the events discussed here, in excess of $4 \times 10^{29} \text{ erg}$ in a 24-hr period, may be time-averaged for comparison. While the area of plage 8970 (as seen in CaII K) could not be measured on 4 September 1967, we guess its area to have been 1500 millionths of the hemisphere on that date ($4.5 \times 10^{19} \text{ cm}^2$), a guess based upon its measured area at CMP and its apparent growth while on the disk. Thus the total energy invested in these events, averaged in time and over the whole calcium plage, was $\approx 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$, a small value when compared to Osterbrock's estimate. Further, the energy loss by plage 8970 via excess H α emissions alone, at an assumed rate of $\approx 1.8 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$ (and assuming a similar H α area) amounted to some $8 \times 10^{30} \text{ erg}$ in a 24-hr period, roughly like one major flare

of importance 3 per day (Bruzek, 1967; see also Warwick, 1962).

4. Summary

Minor brightenings and faint, small surge-like spikes were seen on H α flare-patrol films to occur on the limb of the sun in good time-association with small, short-period fluctuations of the soft X-ray background. The H α activity was of a kind often seen above active regions at the sun's limbs. Because of the close time-association between visible dynamic, spike-like phenomena and X-ray events we suggest that the two were physically related.

The observed X-ray enhancements suggest that the small dynamical events seen in H α at the limb are associated with coronal heating. Our observations cannot currently specify whether the heating is accomplished by a mechanical input via the small spikes or whether spikes represent a mechanical response of the chromosphere to energy conducted out of a heated coronal volume (Kuperus and Athay, 1967). An examination by angularly-resolving experiments of X-ray and other emissions associated with the phenomena discussed here is needed before their physical nature can be assessed. It is possible that these phenomena can be instructive as to mechanisms of energy input to the corona above active regions.

The relative peak emission rates in H α and in soft X-rays for the spike-like events was roughly similar to that observed for flares, suggesting that a single relationship extends over almost four orders of magnitude, from events well below flare magnitude to the great flares of importance 3. Thus there would appear to be a common means of energy partition into H α and soft X-ray emissions.

The total energy dissipated in the small events of 4 September 1967, is estimated to have been in excess of 4×10^{29} erg, with an uncertainty in this lower limit of at least a factor of three. Most of the energy appeared in the form of H α emission and in the supply of potential energy to the material of the spikes, with about 1% appearing as small fluctuations of the soft X-ray flux. While the inferred total energy is nearly equivalent to the energy of one flare of importance 1 per day, it is very small in comparison to the total rate of energy dissipation in an active center.

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Figure Captions

- Figure 1. A schematic representation of optical events observed on 4 September 1967, is given in connection with the soft X-ray flux curves. Gaps in the X-ray data are caused by satellite night and by tape-recorder playback. Symbols on the line above the flux curves refer to activity in plage 8970; symbols above those refer to activity in other regions on the disk. The symbols are defined in the text. A thick bar represents an event of flare magnitude. Numbers placed on the flux curves and just below the symbols representing optical activity are intended to portray some of the associations noted. Reported Type-III bursts are indicated at the bottom of the diagram.
- Figure 2. Some of the spike activity seen to occur in plage 8970 on 4 September 1967, is here pictorialized (see Figure 1).
- Figure 3. Relationship of mean peak emission rates in H α and in soft X-rays for flares (open circles) and for spike events (filled circles). Flare data have been taken from Thomas and Teske (1971).

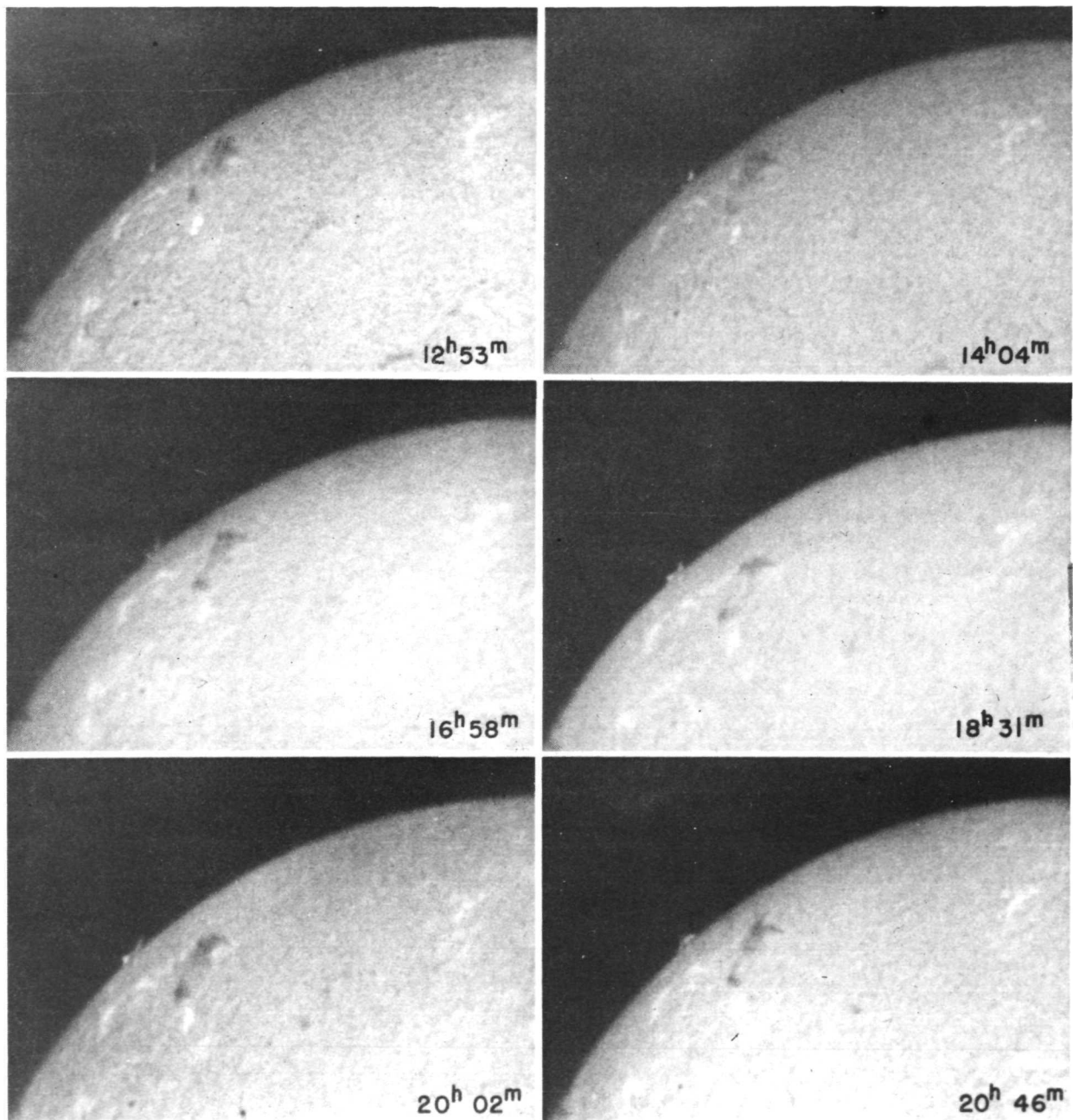


Figure 2

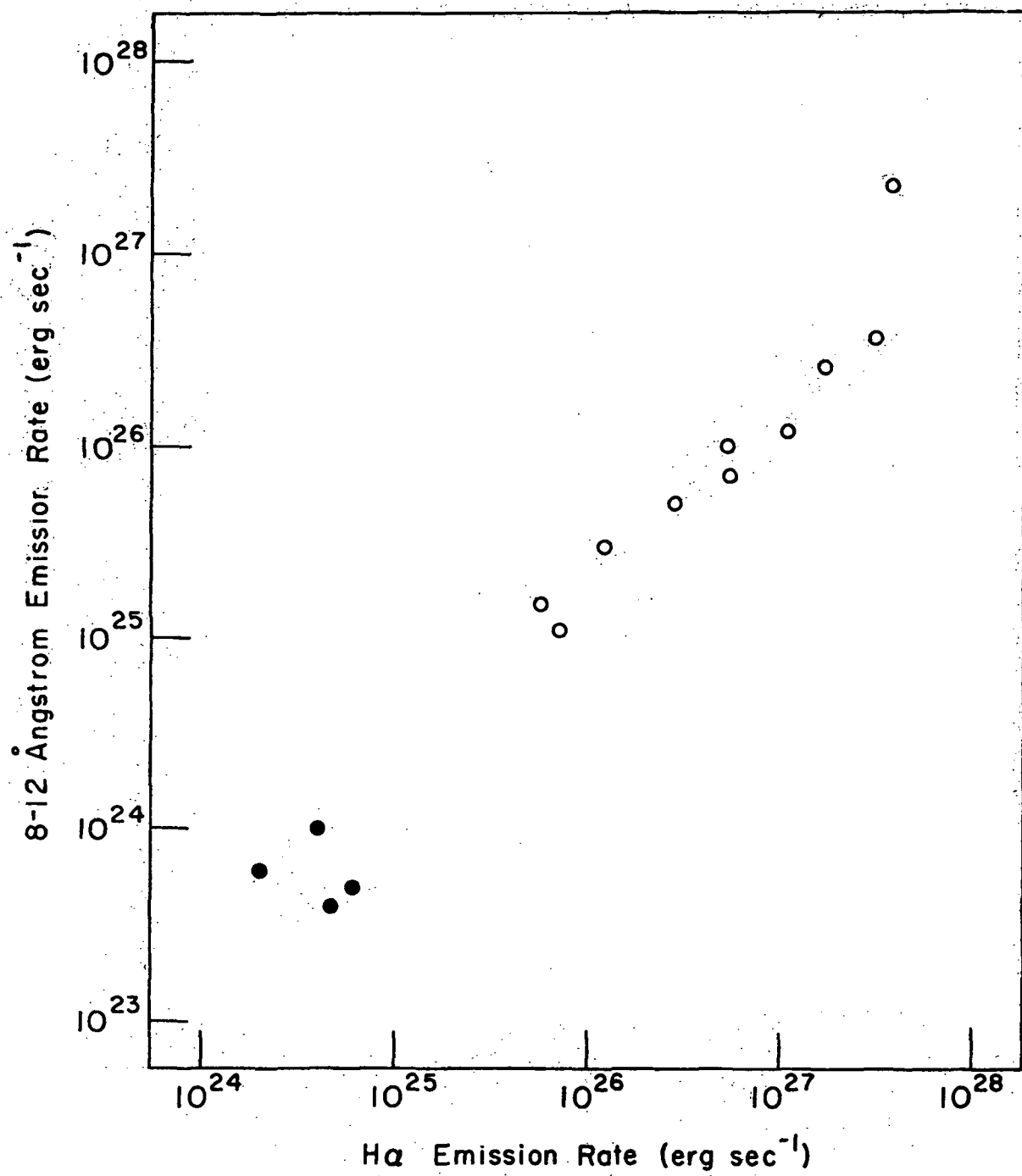


Figure 3

SOLAR SOFT X-RAYS AND SOLAR ACTIVITY

VII. Observational Assessment of the Role of the Type-III Acceleration Mechanism in Establishment of the Soft X-Ray Source Volume

Richard G. Teske

Department of Astronomy and the McMath-Hulbert Observatory
The University of Michigan, Ann Arbor, Mich.

and

Roger J. Thomas

Laboratory for Solar Physics, NASA/Goddard Space Flight Center
Greenbelt, Maryland

Abstract. Peak fluxes of flare-associated 8-12 Å X-ray bursts occur at the time of or shortly after the maximum energy content of the soft X-ray source volume. The amplitudes of flare-associated bursts may thus be used as a measure of the energy deposited in the source volume by nonthermal electrons and other processes. In the mean, the soft X-ray burst amplitude is apparently independent of the occurrence of a Type-III event. This is interpreted to indicate that electrons accelerated by the Type-III process do not directly participate in establishing the soft X-ray source volume.

1. Introduction

Considerable attention has been directed towards the so-called flash phase (Ellison, 1949) or explosive phase (Athay and Moreton, 1961; Harvey, 1971) of solar flares, because it is thought that during this phase, electrons are rapidly accelerated to high energies in the solar atmosphere. A number of flare models have been proposed (e.g., Arnoldy *et al.*, 1968; Takakura, 1969; Holt and Ramaty, 1969; Parks and Winckler, 1971) that explore in particular the possibility that hard X-rays and cm-λ radiation may both be generated by nonthermal electrons that result from the acceleration process.

An important question is whether the nonthermal electrons represent a significant energy supply to other associated aspects of the flare phenomenon. Neupert (1968) and Kahler *et al.* (1970), proposed that fast electrons generated by an initial acceleration event collisionally heat the thermal X-ray source volume in addition to producing nonthermal radiation. Kane and Donnelly (1971) extended the concept further when they deduced that the total kinetic energy of fast electrons is comparable to the energy that is deposited

in the source volume which gives rise to the EUV flash, while Lin and Hudson (1971) have inferred that as much as one-half of the total flare energy is initially represented by the energy of nonthermal electrons. Thus recent observationally-based studies strongly suggest that nonthermal electrons are indeed an important energy supply for the flare event.

In addition to the impulsive onset of flare bursts, by which is deduced the operation of an acceleration mechanism, the occurrence of meter-wave Type-III events also signifies an acceleration process, undoubtedly connected with and perhaps identical to the process which provides the electrons for the microwave burst. The Type-III radiation is considered to be connected with the acceleration of $\sim 10^{35}$ electrons to energies of tens of keV (Wild, 1964). Lin and Hudson found that in two flares accompanied by Type-III radiation at X-ray maximum ($E_e > 22$ keV), the number of electrons escaping from the sun was greater than in two flares not accompanied by Type III. They calculated (their Table II) that the total number of electrons of energy exceeding 22 keV and the aggregate electron energy tended to be greater for the flares accompanied by Type III.

If we adopt the point of view that the Type-III process supplies additional electrons to those provided by the mechanism that gives rise to the impulsive microwave burst, then possibly some of these additional electrons might contribute to the total energy of the thermal X-ray source, depending upon how the electrons propagate out of the volume in which they are accelerated. If some of the Type-III electrons propagate downwards towards the chromosphere, we would expect to observe an enhancement in the energy content of the thermal X-ray volume when flares accompanied by Type III are compared with flares not associated with Type III.

We have tested this idea using soft X-ray data between 8 and 12 Å acquired by an ion chamber photometer on board OSO III. Our results are negative and indicate that the soft X-ray source volume is essentially similar in flares whether or not the meter-wave Type-III event is detected.

In Section 2 we describe our approach to the problem and discuss its validity. Section 3 presents the results.

2. Data Selection and Analysis

A catalog of distinct, nonoverlapping H α flare events for which OSO III data were available was prepared by Thomas (1970) for the period 10 March 1967, to 31 March 1968. Flare events studied here have been drawn from this catalog (Catalog II) which was briefly described by Thomas and Teske (1971).

Only flares of importance 1 which met certain criteria were analyzed for the project reported here. Our method of analysis was straightforward: the sample of flares was divided into groups according to whether a Type-III burst did or did not occur, and mean soft X-ray amplitudes obtained for each grouping of events. These means were then tested against one another to determine if differences in group means were statistically significant. This approach to the data requires some explanation and some justification.

A. SELECTION CRITERIA

Our intent is to demonstrate to what extent the energetic electrons associated with occurrence of the Type-III acceleration process participate in establishing the soft X-ray source in flares.

As we examine flares of greater and greater importance, we find that the peak soft X-ray and H α fluxes increase in the mean (Thomas and Teske, 1971) and that the frequency of association with bursts of Type III also increases (Swarup *et al.*, 1960). However, this may only indicate that the more energetic phenomena are better capable of producing fast-drift bursts. To avoid this possible bias we have elected to examine only flares of importance 1.

In the mean, the total H α emission from a flare is roughly proportional to the total soft X-ray emission (Thomas and Teske, 1971). Since flares of importance 1 will share a common range of total H α emission, the present study thus has attempted to distinguish whether or not a greater proportion of soft X-radiation accompanies the H α aspect in those events associated with Type III.

Only those flares of importance 1 in Catalog II were analyzed which occurred during hours when a swept-frequency station was observing. (Because we were not familiar with the reports from Weissenau, we did not include them in our data if that was the only reporting station.) Only those flares between solar longitudes 75°E - 30°W were examined for the Type III/soft X-ray association. Loughhead *et al.* (1957), showed that the highest visibility of Type III occurs in the solar longitude range 90°E - 30°W. We eliminated importance 1 flares between 90°E - 75°E in this study so as to avoid the inevitable problems of flare importance assignments that arise close to the limb (e.g., Sawyer, 1967). All flares for which as associated Type II and/or Type IV was observed were excluded so as to isolate only the Type III acceleration mechanism (or its absence).

B. USE OF SOFT X-RAY BURST AMPLITUDES

We have used our observed 8 to 12 Å burst amplitudes as a measure of energy deposited in the source volume. This must first be justified.

(i) It is to be expected that individual flares will display a range of equivalent temperature T and equivalent emission measure $N_e^2 V$ which characterize the associated X-ray sources. Horan (1970) has studied these quantities in flares using X-ray observations made at only slightly higher photon energies than those observed by us. His data indicate that at the peak of the 8-12 Å X-ray flux in flares of importance 1 the equivalent temperature of the emitting region is in the range $13 \times 10^6 K$ to $18 \times 10^6 K$. It has been calculated that our ion chamber is insensitive to spectrum distribution in this temperature range (Teske, Hodge, and Worden, 1971): the measured ion chamber current and hence the quoted X-ray flux will vary by about 5%, for a constant emission measure, across this temperature range. These calculations of the ion chamber response took into account free-free, free-bound, and line emissions. We also believe that the soft X-ray source volume in a "mean" importance 1 flare is characterized by a "mean" temperature as well as a "mean" emission measure. Since our instrument is not sensitive to differences in temperature, large differences in mean soft X-ray flux between various sample groups of flares may be taken to indicate variations in mean emission measure.

As was pointed out by Kahler et al. (1970), the total thermal energy content in the soft X-ray source may be approximated by

$$E \sim 2(N_e^2 V)^{1/2} V^{1/2} kT \quad (1)$$

where V is the equivalent volume of the source. Although our peak burst fluxes may be used to specify gross differences in emission measure, these differences would not themselves indicate variations in total thermal energy of the source unless we also have information on V and on T .

To anticipate our results: we have found no evidence for large differences of mean $N_e^2 V$ at the peak of the 8-12 Å flux among the sample flare groups studied. It would be quite fortuitous for N_e and V to vary separately in such a way as to produce this result, hence we believe that in the mean both N_e and V are essentially the same among the sample flare groups. Horan's work shows that at the 8-12 Å burst peak, T in the source varies by less than a factor of two from flare to flare. Hence the total energy content of the thermal source at the time of the 8-12 Å burst peak may be approximately the same, to within a factor of two, among the importance 1 flare groups we have studied.

(ii) Kahler et al., have deduced that the emission measure of the soft X-ray source increases after the X-ray peak, that the temperature slowly declines and that the thermal energy content of the gas remains approximately constant for an extended period of time. If this latter deduction is correct, our use of the 8-12 Å burst amplitudes as a measure of the energy deposited in the source volume is questionable. However, their analysis may be open to question.

In their analyses of both the 9 June 1968, and 9 July 1968, events, Kahler et al., determined temperatures from spectrum fits of free-free bremsstrahlung curves between 5 and 10 keV photon energies, and emission measures from the derived T and a flux in one photon energy channel. They ignored the effects of free-bound emission. As they pointed out, that omission had a small effect upon the derived temperature, which declined during the flares, although too high an emission measure was inferred at each moment during the flares. As temperature declines, the relative contribution of the (neglected) free-bound flux grows (Culhane, 1969) as does, therefore, Kahler et al.'s, overestimate of the emission measure and thus of the thermal energy content of the gas. Using the data published by Kahler et al., we have reanalyzed the 9 June 1968 event taking into account free-bound emissions. We find that although the emission measure $N_e^2 V$ did rise a bit near the X-ray maximum, the thermal energy content of the gas declined after 08^h55^m. Furthermore, at 09^h01^m, the time of the 2-12 Å peak flux observed from Explorer 35, the thermal energy content was actually declining more rapidly than had been suggested by the original analysis.

(iii) Horan (1970) studied variations of temperature and emission measure in many flares. His data may be used with Eq. (1) to show that the thermal energy in the soft X-ray source is near its maximum at the 8-12 Å peak. Horan's work took account of free-bound emissions. The photon energies observed by him were only slightly harder than those observed by us, so that his data and ours refer essentially to the same plasma. In six of eight of Horan's events which we studied, our 8-12 Å burst peak coincided with the time of maximum total energy of the source volume, as deduced from his data, while in the other two the total energy reached its maximum a few minutes before the 8-12 Å burst peak.

In the context of our present project, the work of Kahler et al., appears to provide no objection to our use of the 8-12 Å flux amplitude as a measure of the thermal energy content of the soft X-ray plasma, while Horan's data provide a support for that use. The 8-12 Å amplitude does not, however, provide a measure of the total energy which is deposited during the entire flare event.

It is important to note that while Kahler et al., included the effects of the emission line at 1.9 Å in their work, Horan, and our reassessment of the work of Kahler et al., did not introduce the effects of emission lines which, at the deduced plasma temperatures of 13×10^6 K to 18×10^6 K, may be important in the range of photon energies studied. Meekins et al. (1970), have reported flare spectra which illustrate the relative importance of line and continuum radiation in such events. These spectra indicate that line radiation will not severely affect plasma temperatures deduced from proportional counter experiments under assumptions which neglect the line emission. Indeed, Meekins et al., derived temperatures and emission measures from the continua of their Bragg crystal spectra which were in good agreement with Horan's

values for flares. Thus our claim that the 8-12 Å flux peak is a measure of the maximum energy content of the soft X-ray source, a claim based upon analyses of the observations which neglected line emission, but based upon a theoretical calculation of ion chamber response which included line emission, is not importantly affected by that neglect.

3. Results

A. TYPE-III BURSTS

The sample of importance 1 flares in Catalog II which occurred during swept-frequency station observing hours and between solar longitudes 75°E - 30°W was divided into two groups, depending upon whether a Type-III burst was associated with the flares. For many flares only partial data were available. Mean 8-12 Å amplitudes were calculated for each sample group. The means are compared in Table I. The errors which are given are errors of the mean (m.e.). In the table, P is a parameter, calculated by Student's t-test, expressing the significance of the difference between the sample means. (Energies quoted in Table I have not been corrected via the correction factors suggested by Teske, Hodge, and Worden.)

However, the data in Table I do not take account of possible accidental associations with a Type-III burst which arises from another active center fortuitously at the time of a flare. If N_0 = the real number of flares without Type III and N_{III} = the real number of flares with Type III, the observed quantities are

$$\left. \begin{aligned} N &= N_0 + N_{III} \\ N'_{III} &= N_{III} + kN_0 \end{aligned} \right\} \quad \left\{ \begin{aligned} N_0 &= \frac{N - N'_{III}}{1-k} \\ N_{III} &= \frac{N'_{III} - kN}{1-k} \end{aligned} \right.$$

where k is the probability of accidental association. Assuming that the mean soft X-ray burst amplitude for non-Type-III associated flares, E_0 , has been correctly deduced, the true burst amplitude for Type-III associated flares is

$$E_{III} = \frac{(1-k) N'_{III} E'_{III} - (N - N'_{III}) k E_0}{N'_{III} - kN}$$

where E'_{III} has been obtained from measures which include spurious Type-III associations. k may be ascertained from the observed frequency of occurrence

Table I

Mean values for flare groups analyzed

		Flares Without Type III		No.	Flares With Type III		No.	P
		Imp ln	Imp lb					
8-12 Å Burst Amplitude (ergs cm ⁻² sec ⁻¹)				38		0.0237 ± 0.0014	9	0.85
				11		0.0320 ± 0.0013	9	0.17
8-12 Å Rise-time (min)	all imp l	12.1 ± 1.4		22		14.0 ± 3.3	11	0.46
8-12 Å start minus Type III start (min)	all imp l	---		---		- 9.4 ± 2.9	13	---
8-12 Å max minus Type III start (min)	all imp l	---		---		+ 8.1 ± 3.0	10	---
Cm-λ burst start minus Type III start (min)	all imp l	---		---		+ 2.2 ± 2.5	16	---

of Type III and from the association interval Δt : 12 min was used in this study. Since the daily rate of Type-III occurrence is highly variable and the data used here spanned nearly ten months, we have not computed k in this way. Swarup *et al.* (1960), found that about 20% - 24% of flares are in reality accompanied by Type III. We have found (Table I) $18/67 = 27\%$, without correcting for chance associations.

To examine the possible effects on our results of chance associations, we assumed that half of the associated events were spurious, i.e., $N_{III} = 0.5 N_{III}'$, and computed k and E_{III} under this assumption. In that case, the mean soft X-ray burst amplitude for importance 1n flares with Type III rises to $0.0299 \text{ ergs cm}^{-2} \text{ sec}^{-1}$, while that for the importance 1b flares rises to $0.0322 \text{ ergs cm}^{-2} \text{ sec}^{-1}$. Since we cannot identify the spurious events, we assumed that the mean errors in those values remained the same as before and thus computed that the parameter P for importance 1n flares increases to 0.96 (4% probability that the amplitude difference is due to chance) while P for the importance 1b flares is not significantly changed.

There is no obvious physical reason which might explain why importance 1n flares with Type III should have greater soft X-ray bursts than those without Type III while at the same time the burst amplitudes with importance 1b flares are independent of Type III, as these statistics suggest. Thus the correction for spurious associations does not lead to a clear-cut demonstration that there is any real physical difference.

We therefore conclude that there is no clear dependence of soft X-ray burst amplitude on Type-III association for importance 1 solar flares.

On the average (Table I), the Type-III burst begins well before the soft X-ray maximum (in only one instance did it occur afterwards) and at a time considerably after the commencement of the soft X-ray burst, although a wide scatter exists. There is no detectable relationship between occurrence of a Type III and the impulsiveness of the soft X-rays as revealed by rise times (Table I), even though the Type III, when it occurs, preferably commences on the rising branch of the X-ray curve.

On the other hand, from the same sample of flares we find a tendency for the microwave burst to commence shortly after the Type-III burst (see Table I), thus suggesting a connection between the accelerated electrons (or the acceleration events) which give rise to the two kinds of bursts, but this tendency is not clearly established by the data.

B. DISCUSSION

These results are entirely consistent with an earlier examination of the association of Type-III bursts with soft X-rays in the absence of flares

(Teske, Soyumer, and Hudson, 1971) in which it was found that only a weak soft X-ray rise occasionally accompanies a nonflare Type III, the X-rays beginning somewhat earlier than the fast-drift event. The present extension of that work to flares suggests that the visible fast-drift phenomenon has no significant influence upon the amplitude of the 8-12 Å X-ray burst. According to the arguments of Section 2.B (i) we interpret this result to indicate that the maximum energy content of the thermal X-ray source, which is already weakly established by the time the Type-III acceleration process takes place, is not clearly associated with the occurrence of the visible Type-III event and, by inference, with the mechanism which accelerates the Type-III exciter stream.

The observational basis for models in which nonthermal electrons heat the X-ray source has been confined to photon energies $E_{h\nu} \gtrsim 3$ keV and to the EUV region. Because the flux/time curves at photon energies $E_{h\nu} \sim 1-1.5$ keV used here are so different from those at the higher photon energies, it is questionable whether we may view our data entirely in terms of these models. A second reason for questioning whether the 1-1.5 keV data may be viewed in the context of a collisional-heating model is that the soft X-rays tend to precede both the cm- λ and the Type-III bursts (Teske and Thomas, 1969; Culhane and Phillips, 1970). Thus at least a part of the 1-1.5 keV source may not be the outcome of precipitation of nonthermal electrons.

Evidence in favor of assuming the 8-12 Å source to be mainly heated by electron precipitation from the microwave source lies in the relationship between amplitudes of the soft X-ray burst and the cm- λ burst, and between the time-integrated energies in soft X-rays and cm- λ (Teske, 1969), relationships that are more firmly established by a recent assessment of the energy scale of our ion-chamber detector (Teske, Hodge, and Worden, 1971). Further, the 8-12 Å peak flux follows the cm- λ burst peak, as we would expect from the collisional-heating model.

These energetic and temporal relationships appear to us to indicate strongly that while a significant part of the 8-12 Å burst source is established by electron precipitation, a minor part of the source may be established by other mechanisms. Our present work indicates that the Type-III acceleration process, when it occurs, directly affects the establishment of the X-ray source in only a minor way, if at all.

4. Summary

The work of other investigators cited above indicates that the thermal soft X-ray source volume in solar flares is, at least in part, collisionally heated by nonthermal electrons associated with the impulsive microwave burst. We have previously shown that the 8-12 Å emission from flares is quantitatively

associated with the microwave emission, and infer that an important fraction of the X-ray source being observed at these wavelengths is also the result of heating by electrons connected with the microwave emission. The work reported here indicates that electrons associated with a Type-III event observed at meter wavelengths do not strongly contribute in any direct way to heating the 8-12 Å source.

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SOLAR SOFT X-RAYS AND SOLAR ACTIVITY

VIII. Comparison of Flare H α Intensity Variations with Soft X-Ray Flux Variations

Richard G. Teske and James C. LoPresto*

Department of Astronomy and the McMath-Hulbert Observatory,
The University of Michigan, Ann Arbor, Mich.

Abstract. Examples of H α flare light curves are presented together with the soft X-ray flux curves for the same events. The data appear to require that the H α source be excited by conduction of energy from the soft X-ray source. A qualitative model is proposed.

1. Introduction

The relationship of solar flare X-radiation to flare radiation at other wavelengths has been extensively investigated. At photon energies above 10-20 keV, the X-ray emission associates best with the flare microwave emission (e.g., Arnoldy *et al.*, 1968) and with EUV emission (Donnelly, 1970), while the course of the X-ray event below about 3 keV is best related to the general course of the H α emission (Thomas, 1970; and other papers in this series). However, Vorpahl and Zirin (1969) and Zirin *et al.* (1971) have identified specific H α structures within flares which impulsively brighten in good time-association with the hard X-ray burst. Takakura *et al.* (1971) showed that the hard X-ray and microwave sources in one flare may have been located close to a bright H α knot, while Vaina and Giacconi (1969) demonstrated the spatial similarity of the soft X-ray source and the H α flare.

These observations show that the electron acceleration process signalled by the hard X-ray burst may be observable, at least in some flares, as an impulsive brightening of a part of the H α source. They further suggest that a large volume of plasma above the H α source is the seat of soft X-radiation, which source has a strong spatial similarity to the chromospheric H α event. Recent studies (e.g., Kane and Donnelly, 1971) have emphasized that the flare X-ray burst is a direct consequence of an energy injection process in the lower corona and that the soft X-ray source is probably a secondary product of the energy release process. The relations which thus emerge are confirma-

*Now at Department of Physics, Edinboro State College, Edinboro, Pa.

tion of the view that the $H\alpha$ source may be energetically related to, and probably indirectly a consequence of, energy injected into the lower corona.

In an attempt to study this possible relationship further, we have carried out a program of $H\alpha$ flare photometry in connection with soft X-ray observations that were made from OSO III. The $H\alpha$ intensity variations for flares selected in this program verify the close association of $H\alpha$ emission and soft X-ray emission and further confirm that the $H\alpha$ source is energetically connected with the soft X-ray source in many flares. In Section 4 we argue that, apart from impulsive $H\alpha$ brightenings and the EUV flash, the general course of the $H\alpha$ event is such as to suggest it is produced by energy conduction from the soft X-ray source.

2. Observations

A. X-RAY DATA

The Michigan OSO III experiment, which measured soft X-ray fluxes between 8 and 12 Å, has been described elsewhere (Teske, 1969). All data which were used in the present program had a time-accuracy, relative to UT., of better than 1 sec. We have proposed correction factors which may be applied to X-ray fluxes quoted for this experiment (Teske, Hodge, and Worden, 1972), but they have not been applied to the material presented here. Those correction factors are essentially independent of plasma temperature over the range from 2×10^6 K to 20×10^6 K, and are near 0.76.

B. $H\alpha$ FLARE DATA

$H\alpha$ filterheliograms made with the flare-patrol telescope at the McMath-Hulbert Observatory were utilized in constructing the flare light curves. The telescope is equipped with a Lyot filter having a band pass of 0.5 Å centered on $H\alpha$ and provides a full-disk image of 15 mm diameter photographed on Kodak V-E film. Frame cadence is normally 30 sec between exposures. Each frame contains an image of a clock and an array of photometric spots of differing photographic densities produced by a tube sensitometer. The observing program is carried out in a manner which allows the time of exposure of any frame, as shown by the clock image to be related to UT. within 5 to 10 sec.

Thus the relative timing of the photometric and X-ray material is not expected to be problematical.

Flare light curves were constructed from surface photometry of individual flare-patrol frames, using the same photometric equipment that was employed by

Dodson et al. (1956) in their study of flare light curves. For subflares and flares of simple H α structure, the intensity/time variations for only one or two parts of the flare were examined, while four more complex flares up to six flaring areas were photometered. For each flaring area that was examined, the intensity of the brightest part of that area on that frame was obtained. We avoided study of flares for which there was photographic or visual evidence of strong Doppler shifts in H α .

Intensities in the flares were measured relative to the intensity of the center of the disk as seen at the center of H α . These are the relative intensities which are presented in Figures 1, 2, and 3. Those intensity values may be roughly converted to intensities relative to the continuum near H α at disk center by multiplying them by 0.3 (E. R. Hedeman, private communication).

3. Results

Of the flares examined in this study, the data for a number were selected as representative and are displayed here. Subflares are shown in Figure 1 and flares of importance 1 are shown in Figure 2. One of the two importance 2 flares that we studied is shown in Figure 3. Only a few of the measured intensity curves for the various flaring parts are shown for some of the events. The consistency of the measurements may be judged from the data points inserted in some of the diagrams. We include at the top of each diagram phase curves showing the relative development of H α intensity and soft X-ray flux in the flares.

A. MORPHOLOGICAL SIMILARITIES OF THE H α INTENSITY AND X-RAY FLUX

H α intensity curves and soft X-ray flux curves are quite similar for many flares in all the importance categories represented in this study. Because only the brightest region of each flare part was measured, we infer that in many flares the bulk of the soft X-ray emission is likely associated with the flare parts that are most intense in H α , a result that confirms and extends the work of Vaiana and Giacconi (1969). Our data, however, point to some exceptions in the case of some events.

B. EFFECTS OF MAGNETIC FIELDS

The role of magnetic fields is clearly evident only in data relating to the importance 1 flare of 25 May, 1967 (Figure 2). Of the four flaring segments analyzed, that part designated "B" was located within the penumbral boundaries of the accompanying extensive spot group, apparently between umbrae

of opposite polarity. The segments labelled "C" and "D" were located at the periphery of the spot group while "A" was far from the spot group. The rapid rise in soft X-ray flux beginning at 20^h50^m occurs at nearly the same time as the abrupt brightening of segment "B." However, segment "B" did not become as bright in H α as some of the other flaring areas.

This is the only clear example of such a relationship that we have found.

C. PHASE CURVES

Although the phase curves relating H α intensity to soft X-ray flux are often very different in the various events, some regularities are apparent throughout most of the data.

- (a) Phase curves trending in a clockwise sense predominate over counterclockwise, demonstrating the well-known result that soft X-ray flux maximum tends to follow maximum H α intensity.
- (b) The slopes of the phase curves before H α intensity maximum and after soft X-ray maximum (in the clockwise phase curves; or the reverse in the counterclockwise curves) tend to be similar for a given flare in all the importance categories investigated, although there is considerable variation in slopes among the different events.

This latter tendency supports a view that the H α source and the soft X-ray source are energetically associated and probably share a common energy fund. Energy may be shared between the sources by conduction or by radiation. If the H α source were to be excited primarily by X-ray photons, the slopes of phase curves for all flares of roughly the same area (i.e., importance category) would be similar and the H α source would be diffuse, neither of which is observed. Thus the primary mode of energy transport is very probably by conduction out of the soft X-ray source.

Such a viewpoint is further suggested by the fact that there exists a close proportionality between maximum H α flux and maximum soft X-ray flux for flares of all importance categories (Thomas and Teske, 1971).

4. Discussion

The results of solar flare photometry imply an energetic connection between H α and soft X-ray sources: we suggest that the general H α source may be excited primarily by conduction out of the soft X-ray source. Yet

maximum H α flare intensity as a rule precedes the soft X-ray flux maximum (e.g., Teske and Thomas, 1970). This apparent inconsistency we explain as follows:

Isophotometric analysis of three importance 1b flares by Thomas (1970) showed that although the H α intensity maximum preceded the soft X-ray maximum, the H α flux maximum coincided with it (two cases) or followed it (one case). Generally, the H α flux maximum in flares is reached after intensity maximum because the area of the chromospheric flare then further increases. We have also found (Teske and Thomas, 1972) that the 8-12 Å flux maximum occurs at the time of, or shortly after, the maximum thermal energy content in the soft X-ray source. Thus there is evidence that the H α flux maximum may occur at or after a time when the thermal energy content of the X-ray source is greatest, evidence that is entirely consistent with the hypothesis of conductive excitation of the H α source.

In the context of the present qualitative model, the frequent occurrence of maximum H α intensity before maximum thermal energy content of the soft X-ray volume indicates that the rate of energy flow per unit chromosphere area is greatest then, and declines later as the H α source area expands. Along magnetic field lines connecting the soft X-ray and H α sources, the thermal conductivity ($\propto T_e^{5/2}$) and the temperature gradient must be greatest when the flare reaches its greatest intensity. In many flares at that time, the temperature in the X-ray source volume is at maximum or already declining (data from Horan, 1970; data from Kahler *et al.*, 1970), although its energy content is still increasing. The ensuing expansion of the H α flare area implies that the soft X-ray source begins to be connected to more field lines passing into the chromosphere than previously (although not necessarily by volume expansion). During this phase of further increase in flare area, the conductivity and temperature gradient along the field lines diminishes as T_e in the X-ray source declines, resulting in a drop in flare H α intensity. Soon the energy content of the X-ray source as signalled by the 8-12 Å flux reaches a maximum coincidentally with, or followed shortly by, the maximum H α flux. At such a time the rate of energy injection to the soft X-ray volume has fallen below the rate of loss out of the soft X-ray-H α system. Our data do not suggest whether or not the rate of energy input has fallen to zero by then.

While there is little question that the EUV flash studied by Kane and Donnelly (1971), and the events described by the Big Bear observers (Vorpahl and Zirin, 1969; Zirin *et al.*, 1971) indicate some chromospheric excitation to be a direct consequence of electron impact from the acceleration site, we suggest that the general H α flare emission is a consequence of a conduction process described in outline above.

5. Summary

Comparison of photometric H α intensity curves and soft X-ray flux curves for a variety of solar flares indicates a close energetic relationship between the soft X-ray and H α sources in many of them. This relationship is also apparent in comparisons made by Thomas and Teske (1971) and in Thomas's (1970) isophotometric study of flares and their soft X-radiation. The observational data are consistent with flare models such as those by Carmichael (1964), Sturrock (1968), or Krivsky (1968), in which the H α source is excited by electrons conducted along field lines out of a coronal source. The present study has added some details to a general picture invoked by those models. It requires that the overall H α event in many flares be viewed as essentially a tertiary product of the primary flare mechanism.

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Figure Captions

Figure 1. Subflares. Relative soft X-ray fluxes, E (in $\text{ergs cm}^{-2} \text{sec}^{-1}$ between 8-12 Å), in lower panel; relative logarithms of H α flare intensity, I (in units of H α intensity of disk center), in middle panel; phase curves in the top panel relate H α intensity (ordinate) to soft X-ray flux (abscissa). Dashed curves imply sunrise or sunset on the spacecraft.

Figure 2. Importance 1 flares. For explanation, see Figure 1 description.

Figure 3. Importance 2 flare. For explanation, see Figure 1 description.

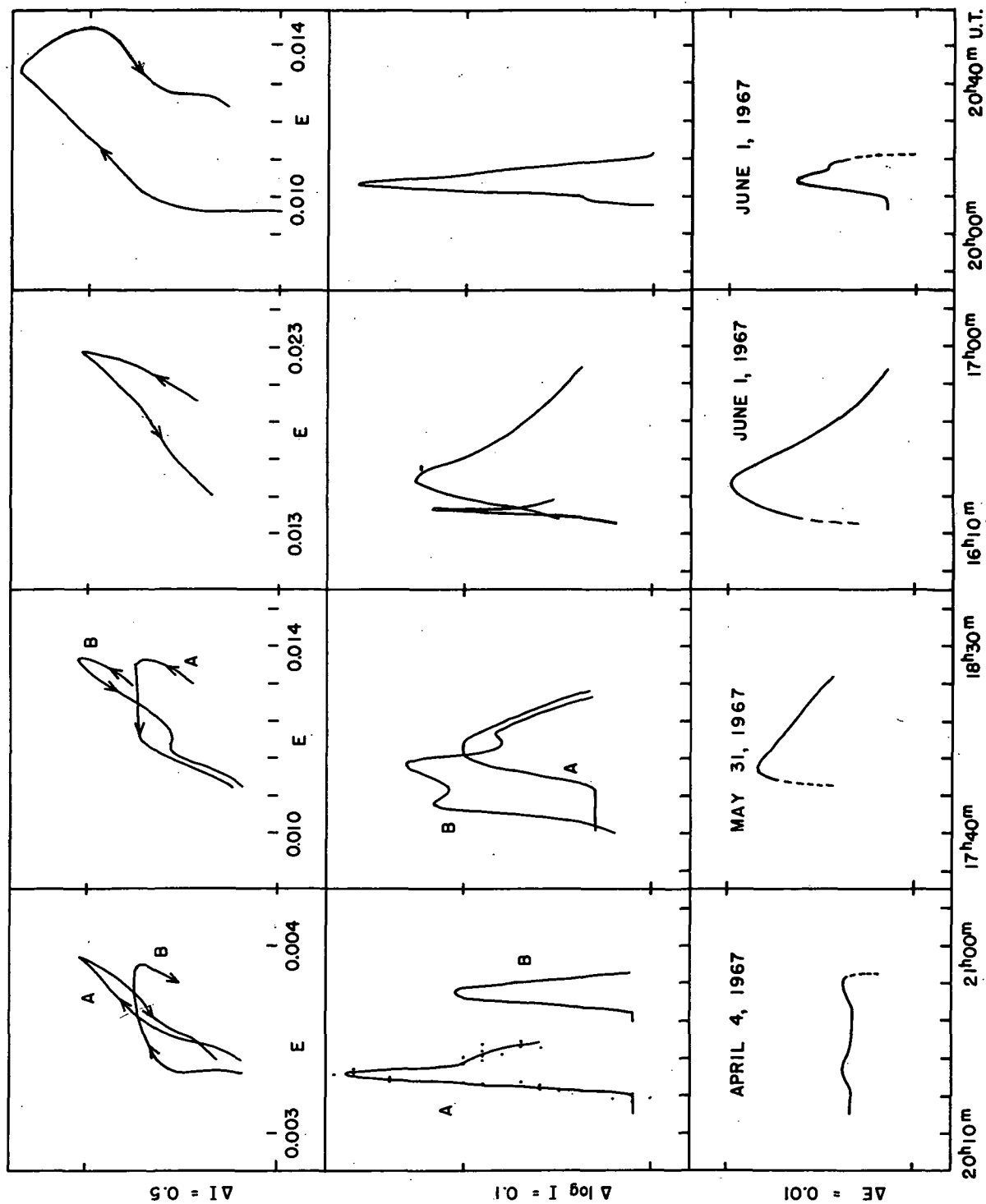


Figure 1

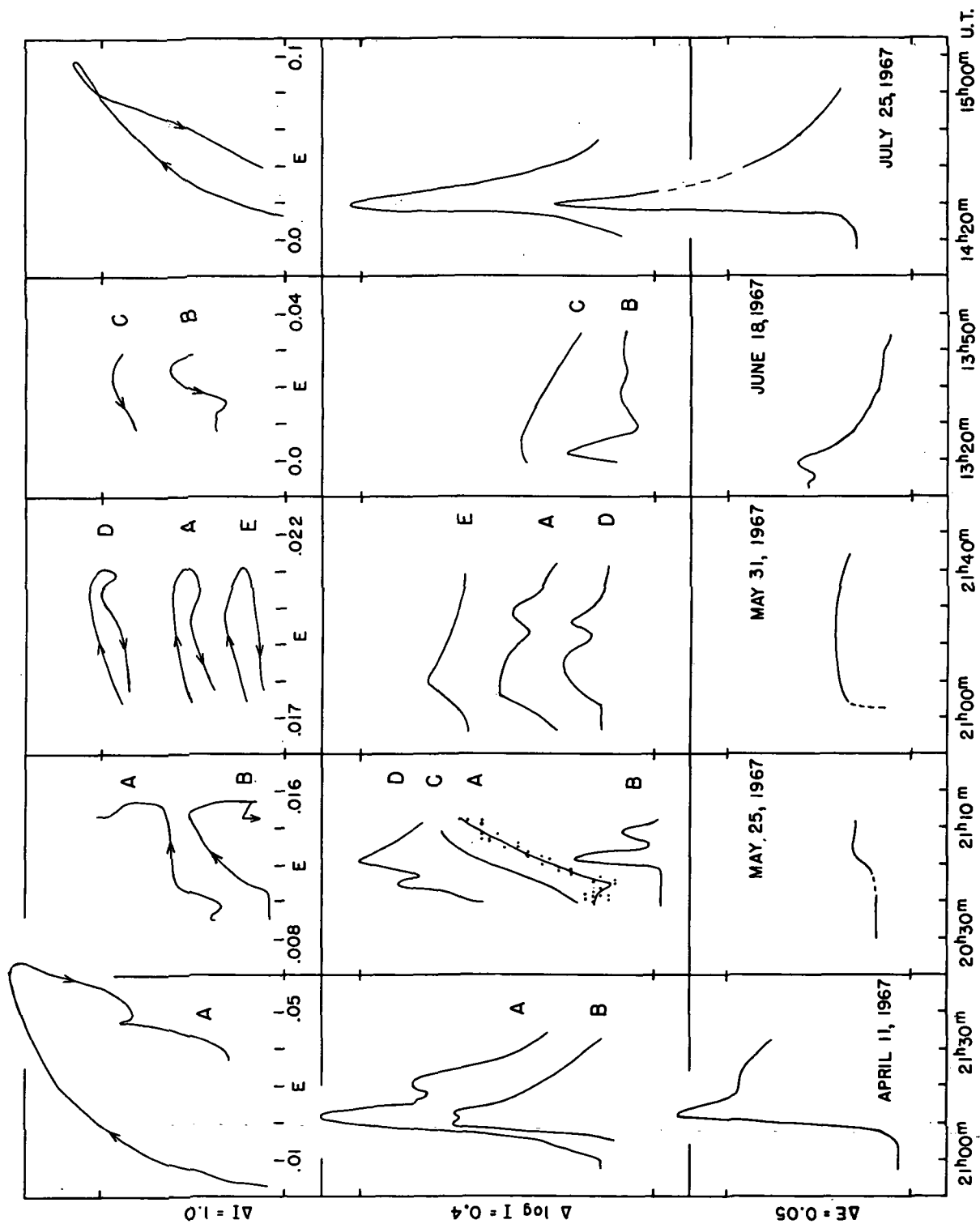
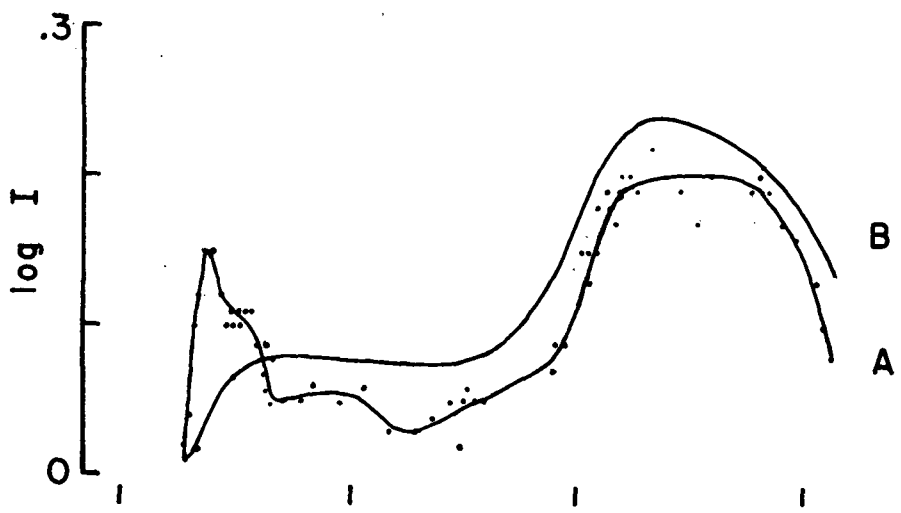
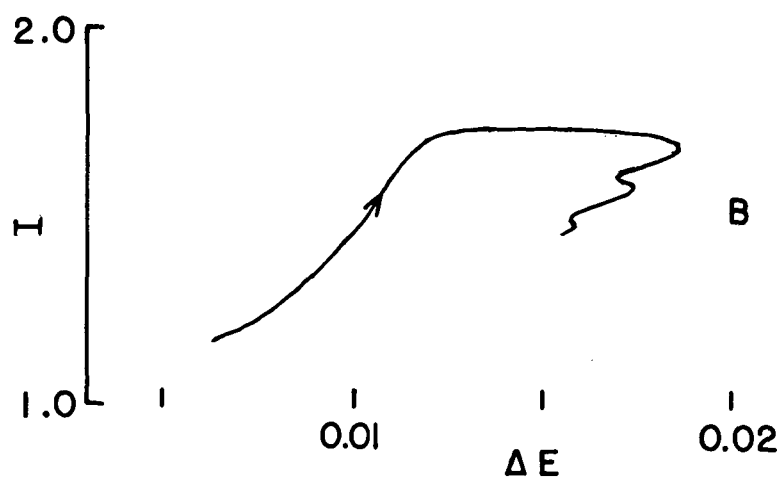


Figure 2



JUNE 5, 1967

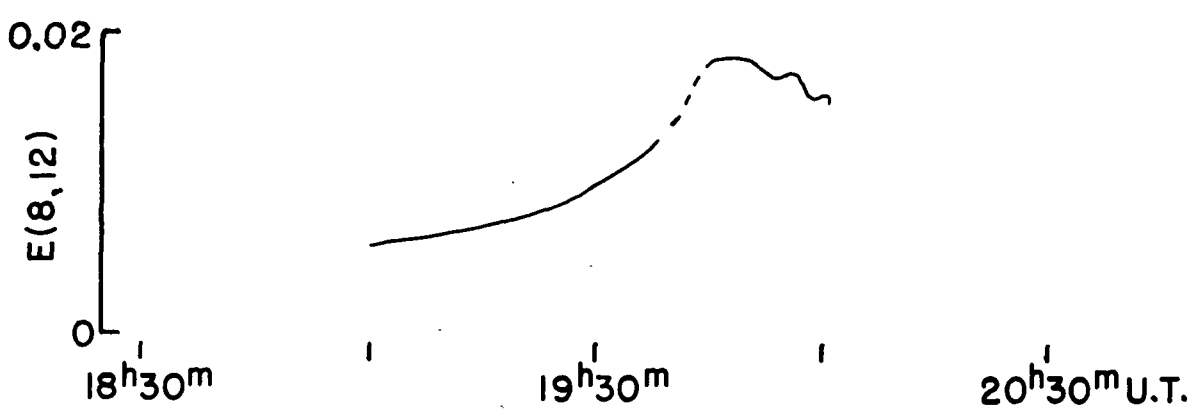


Figure 3

SOLAR SOFT X-RAYS AND SOLAR ACTIVITY

IX. Relation of Gross Magnetic Field Structure to Flare Soft X-Ray Burst Amplitude

Richard G. Teske, John T. Vollertsen, and Philip E. Hodge
Department of Astronomy and the McMath-Hulbert Observatory,
The University of Michigan, Ann Arbor, Mich.

Abstract. The amplitude of 8-12 Å flare bursts is not strongly related to the magnetic class of the sunspot group in which the associated H α flare occurs, nor to a gross index of the position of the H α flare within sunspot fields. Flares occurring in spot-free active centers are accompanied by weaker soft X-ray bursts than are those occurring in spotted regions, however. The data may be consistent with a qualitative model which supposes the H α phenomenon to be excited by conduction out of the soft X-ray source.

1. Introduction

Usually, the most energetic of solar flares occur within active regions containing strong and often complex sunspot magnetic fields. Cosmic ray flares, for example, tend to appear in δ , $\beta\gamma$, and γ spot groups and display particular characteristics as regards their shape, development, and position within the magnetic field structure (Ellison *et al.*, 1961; Krivsky, 1968). Many lesser flares are observed in regions of apparently simple field topology in which the field intensity and gradients are relatively smaller than in the great spot groups. Among these flares there is a welter of morphological characteristics, although they frequently develop in distinctive positions with respect to the magnetic field (e.g., Smith and Ramsey, 1967). However, a nonnegligible fraction of flares of great area are found to take place in regions without sunspots which are presumably embraced by fields with a photospheric intensity of 150 G or less (Dodson and Hedeman, 1970), while minor flares of importances 1 and 1- regularly occur in great spot groups. Often large and complex groups traverse the sun's disk without producing any major flares at all. Thus the observational case for an invariable relationship between flare magnitude and photospheric magnetic field intensity and configuration is not a perfect one. It is nevertheless undeniable that a loose relationship exists.

Sweet (1969) has critically reviewed theories of solar flare mechanisms. Of those mechanisms reviewed as having some merit, only those proposed earlier

by him (Sweet, 1958) and by Krivsky (1968) require an initially complex pattern of sunspot polarities. None of the mechanisms requires a particular field intensity for its operation, although lower limits are implied if each is indeed to supply energy successfully on a short enough time scale in the solar case. It is therefore not possible to select a particular mechanism as applicable to flares entirely on the basis that most energetic events tend to take place in strong fields or near strong field gradients. Nevertheless it is of considerable interest to inquire about the role of magnetic fields in the energetics of various phenomena which accompany the H α flare. In this paper we have considered the relationship of flare soft X-ray emission to some characteristics of the surrounding magnetic fields.

Thomas and Teske (1971) noted that the amplitude of 8-12 Å flare X-ray bursts accompanying importance in flares tended to be significantly greater for flares arising in "prolific" active centers than was the burst amplitude with importance in flares in "nonprolific" active centers. Regions found to flare prolifically are often those with strong and perhaps complex spot groups. Thus there may be a basis for believing that the magnetic field structure controls soft X-ray burst amplitude. A high-resolution soft X-ray photograph of a flare (Vaiana and Giacconi, 1969) showed that the brightest part of the X-ray source, emitting more than 50% of the energy between 3-18 Å, bridged the region's magnetic neutral line. In summarizing their rocket observations, Krieger et al. (1970), suggested that bright, preflare X-ray emitting areas which are associated with bipolar magnetic structures in active regions become the site of the most intense flare X-ray emission. It thus appears that magnetic field structure influences the location, at least, of the soft X-ray source.

We have obtained observations of solar soft X-rays between 8-12 Å wavelength during the time period March, 1967-May, 1968 (Teske, 1969; and other papers in this series). Flare soft X-ray bursts which were observed have been compared with H α flare and sunspot magnetic field data in an attempt to discern whether, and in what way, magnetic field intensity and complexity might mitigate or amplify the energy released as soft X-rays during flares.

2. The Data

Recent observational work (Kane and Donnelly, 1971; Lin and Hudson, 1971) has emphasized that the soft X-ray source is probably a secondary product of the flare acceleration process. That work, however, indicates that the energy deposited in the soft X-ray volume is linked to the total energy of accelerated electrons. Brown (1971) has summarized the arguments theoretically. We have found that the 8-12 Å burst amplitude is a good measure of the maximum energy content of the soft X-ray source to within a factor of two (Teske and Thomas,

1972). Thus it appears reasonable to utilize the 8-12 Å burst amplitude as a rough analog of the energy provided by the acceleration process, and we have done so in this paper.

We have compared the soft X-ray burst amplitude for flares with the gross qualitative photospheric magnetic field characteristics—intensity and complexity—at the location at which the H α flare occurred. Thus the position of the H α flare within a spot group has served in this work as an indicator of the rough characteristics of the magnetic field in the vicinity of energy injection. Certainly this assumption is dubious at best, since the electrons exciting the H α source have been transported along field lines from elsewhere. Recognizing that fact, we have necessarily simplified our procedures by asking only rather simple questions of the data, such as those below.

- (a) What was the Mt. Wilson magnetic class of the sunspot group?
The recognition that the most energetic flares often take place in δ , $\beta\gamma$, and γ groups is based upon observation of the visible H α phenomenon, and so H α flare occurrence within such groups must have some meaning as to the role of field structure at the site of energy injection.

We consider it likely (Teske and LoPresto, 1972) that the H α source is largely a tertiary phenomenon, being excited by conduction from the soft X-ray source—itself a product of the primary acceleration event. Since, however, the electrons involved in heating of the soft X-ray and H α sources are confined to magnetic flux tubes, presumption of the foregoing hypothesis does not necessarily militate against using the H α flare as tracer of magnetic field intensity at the acceleration site.

- (b) How close was the H α flare to strong magnetic fields? We hypothesize that electrons which excite H α in regions of strong field (e.g., near sunspots) have arrived from regions of strong fields above the active center, while electrons impinging upon the chromosphere to excite H α in regions of weak fields (e.g., far from sunspots) have arrived from locations of relatively weak fields.
- (c) Was the H α flare located between bipolar spots or at a distance from the locus of direct magnetic connection of bipolar spots? According to flare models by Sturrock (1968) and by Krivsky (1968), for example, flare occurrence between bipolar spots implies energy injection near a region of closed magnetic loops.

Flares selected for study in this program were taken from a catalog by Thomas (1970) which lists all isolated, nonoverlapping flares observed by OSO III between 7 March, 1967, and 31 March, 1968. Heliocentric coordinates for these flares were taken from the Quarterly Bulletin on Solar Activity (QB).

Generally, flares are irregular, often patchy, as seen in H α . The QB heliocentric coordinates are approximately the center of gravity of the H α emission and, as such, are only a rough guide to the location of flare emission within an active region. The quoted flare coordinates were used by us to locate the H α brightness center on the McMath-Hulbert daily sunspot maps, taking into account the solar rotation between the time of the flare and the time at which the spot map was drawn. Relative positional uncertainties of spots and flares within 15° of the solar limb were considered to be too high, and these data were discarded. By eliminating them we also avoided the usual limbward difficulties of sunspot magnetic field classification and of flare importance assignment.

The remaining flares in the list were then categorized both as to (i) the Mt. Wilson magnetic class of the spot group, and (ii) the flare position within the spot group.

Magnetic classification of sunspots on the Mt. Wilson system was achieved by appeal to reports from Mt. Wilson, Crimean Astrophysical Observatory and Rome, and to occasional measures made at McMath-Hulbert. These data were carefully reconciled when necessary, and some data discarded if reconciliation was questionable or impossible.

A qualitative classification scheme was developed to describe the location of a flare within sunspot magnetic fields; this scheme is outlined in Table I and illustrated in Figure 1. In the classification, a suffix "1" indicates a flare located within 3° heliographic of a major sunspot umbra, a suffix "2" indicating a flare farther than that from any major umbra. Ambiguities and uncertainties in positional classification led to several events being discarded.

Finally, the mean soft X-ray burst amplitudes for importance 1 flares in each of the groupings were derived and intercompared.

3. Results

A. UT DEPENDENCE OF X-RAY BURST AMPLITUDE

We have previously found from scrutiny of the flare catalog (Thomas and Teske, 1971) that soft X-ray burst amplitudes accompanying flares rated importance 1n in the UT interval 0600-1400 ("European" observing hours) tend to be lower, in the mean, than burst amplitudes recorded with importance 1n flares occurring at other times, and have attributed it to nonuniformities in the reporting of flare areas. This effect is found to persist in the data studied here and so we have discarded data relating to the 0600-1400 UT time interval.

TABLE I

Positional classification of importance 1 flare

Designation	Description
Suffix "1"	Within 3° heliographic of a major umbra.
Suffix "2"	Farther than 3° heliographic of a major umbra.
$\alpha 1, \alpha 2$	α groups. Not in weak fields of smaller spots.
$\alpha E1, \alpha E2$	α groups. In weak fields of smaller spots.
A1, A2	Between major spots of opposite polarities, but not in strong fields, not between small spots.
AE1, AE2	Between small spots of same polarity, in non- α groups.
B1, B2	Directly between major spots of opposite polarities.
C1, C2	Beyond ends of non- α groups, or far outside non- α groups.
D1, D2	Between spot groups.
DE1, DE2	Between small spots and between spot groups.
E2	Between small spots of non- α group without a major umbra.
F1, F2	Between major umbrae of same polarity in non- α group.
NS	No sunspot in region.
NS-C2	An indeterminate case, usually 6° - 8° from nearest spot.

B. EFFECTS OF AGE OF ACTIVE CENTERS

Thomas and Teske (1971) also noted that for importance 1 flares there appeared to be a correlation of mean 8-12 Å burst amplitude with age of active center as measured in solar rotations. We have accordingly asked if there is an age effect in the present flare sample (all importance 1 flares, vs. only importance 1n used by Thomas and Teske, but drawn from the same flare catalog). No clear age effect was found. Further, the mean ages of active centers within which the flares of our sample occurred were essentially the same so that it is unlikely that an age effect could markedly influence our results. Therefore we have not taken account of the ages of active regions in the present work.

C. SOFT X-RAY BURST AMPLITUDE AS A FUNCTION OF MT. WILSON MAGNETIC CLASS OF SPOT GROUP

Table II lists the numbers of importance 1 flares which fell into each

TABLE II

Soft X-ray and 2800 MHz burst amplitudes as a function
of Mt. Wilson Magnetic Class
(Importance 1 flares only)

Mt. Wilson Class	8-12 Å X-rays			2800 MHz		
	Mean (ergs cm ⁻² sec ⁻¹)	N	p.e.	Mean (10 ⁻²² wm ⁻² Hz ⁻¹)	N	p.e.
all α	0.0194	13	0.0170	11.7	8	12.9
all β	0.0173	58	0.0096	18.3	27	15.0
βγ	0.0224	34	0.0152	72.4	13	62.0
γ	0.0204	5	0.0102	10.	1	----
δ	0.0212	15	0.0086	40.2	13	39.6

category of the Mt. Wilson magnetic spot classification together with the mean soft X-ray amplitude and probable error. The most significant difference in the means occurs in a comparison of βγ with bipolar (β, βp, βf) spot groups, and this difference is only significant at the 18% level (18% probability that the difference is due to chance). Comparison of flares in α with those in γ and δ spots provides a smaller difference with a greater than 50% probability that the difference is due to chance. Thus it appears that the magnetic complexity of a spot group is not a strongly controlling factor in determining the maximum energy in the soft X-ray source accompanying importance 1 flares.

D. SOFT X-RAY BURST AMPLITUDE AS A FUNCTION OF FLARE POSITION

In Table III we list the numbers of flares which fell into the various

TABLE III

Soft X-ray and 2800 MHz burst amplitudes
as a function of positional class
(Importance 1 flares only)

Positional Class	8-12 Å X-rays			2800 MHz		
	Mean (ergs cm ⁻² sec ⁻¹)	N	p.e.	Mean (10 ⁻²² W m ⁻² Hz ⁻¹)	N	p.e.
O1, Oe1	0.0338	3	0.0356	15.0	6	14.2
O2, Oe2	0.0174	8	0.0085			
A1, Ae1	0.0148	14	0.0071			
A2, Ae2	0.0197	12	0.0104			
B1	0.0237	25	0.0137	44.4	11	26.3
B2	0.0240	13	0.0139	22.0	5	13.9
C1	0.0200	9	0.0072	18.8	7	10.0
C2	0.0153	22	0.0092	39.5	16	53.8
E2	0.0187	4	0.0126	-----	--	----
F1, F2	0.0242	5	0.0226	139	3	80.0
NS	0.0043	7	0.0031	10	1	----
NS-C2	0.0177	9	0.0114	14.4	3	9.3
all "1"	0.0220	56	0.0140	29.2	27	20.0
all "2"	0.0182	63	0.0104	27.6	34	37.7
all A	0.0170	26	0.0088	17.8	15	8.2
all B	0.0238	38	0.0136	37.5	16	21.9
all C	0.0166	31	0.0087	33.2	23	44.8
all D	0.0191	4	0.0092	345	1	----

positional classes, together with burst amplitude means and their probable errors. We summarize the results as follows.

- (a) Importance 1 flares occurring directly between major spots of opposite polarities (B category) produce significantly stronger soft X-ray bursts than flares occurring in regions without spots (1.5% probability that the difference is due to chance). All comparisons reliably indicate a significant weakness of soft X-ray bursts with importance 1 flares in spot-less regions.

Other comparisons produce less reliable results:

- (b) Importance 1 H α flares occurring directly between major spots of opposite polarities (B category) probably produce somewhat stronger bursts than flares occurring beyond the ends of bipolar groups (C category)—(8% confidence level).
- (c) Importance 1 flares occurring directly between strong spots of opposite polarities (B category) possibly give rise to somewhat stronger soft X-ray bursts than do flares which are not directly entangled within the strongest fields presumably joining those spots (A category)—14% confidence level.
- (d) Importance 1 H α flares occurring within 3° heliocentric of major umbrae (suffix "1") may produce slightly stronger bursts than flares which occur far from major umbrae (suffix "2")—25% confidence level.
- (e) Other comparisons which were made indicated even less reliable differences in mean soft X-ray burst amplitude.

E. ANALYSIS OF ASSOCIATED 2800 MHz BURSTS

We have carried out the same analysis as before, with respect to 2800 MHz burst amplitude for those importance 1 flares in our sample, using peak fluxes listed in QB. When both a short burst (duration < 10 min) and a longer burst (duration > 10 min) occurred with a flare, the amplitude for the shorter burst was employed in the expectation that this was the part that signaled the acceleration event. If the only observed radio burst had a duration longer than 10 min, its amplitude was listed and so identified. The analysis was carried through with and without the longer burst: the results are essentially the same.

Table II collects the mean 2800 MHz burst amplitudes for short-duration bursts (as defined here) accompanying importance 1 flares in each category of the Mt. Wilson magnetic classification. A comparison of events in $\beta\gamma$ spot groups with those in bipolar (β , βf , βp) and in unipolar (α , αp , αf) regions shows the differences to be significant at below the 1% level. There is greater than 30% probability that other differences in mean burst amplitude are due to chance.

A comparison of mean burst amplitudes with the various positional categories is shown in Table III, again only for the short-duration events. No reliable differences in mean burst magnitude were noted.

- (a) Importance 1 flares occurring directly between major umbrae of

opposite polarities (B category) may produce somewhat stronger 2800 MHz bursts than do flares occurring in spot-less regions and far from spots (NS-C2 category), but there is about a 30% probability that this observed difference is due to chance.

(b) Other comparisons yield even less reliable differences.

F. CONCLUSIONS

(1) The complexity of magnetic field structure as deduced from sunspot polarity data does not seem to be a strong controlling factor in determining the amplitude of soft X-ray bursts—and hence the maximum thermal energy in the soft X-ray source—with flares of importance 1. On the other hand, it appears that the amplitude of short-duration 2800 MHz bursts with importance 1 flares in $\beta\gamma$ spot groups is higher than with importance 1 flares in simple bipolar groups and in unipolar groups as well.

(2) The position within a spot group at which the H α flare occurs appears to be only slightly related, if at all, to both the soft X-ray and 2800 MHz burst amplitudes. It has previously been noted (Teske and Thomas, 1969; Culhane and Phillips, 1970; Thomas and Teske, 1971) that soft X-ray bursts accompanying flares in prolifically-flaring active centers are often more energetic than those bursts which accompany flares in active regions which produce fewer flares. It now appears that this effect is more closely linked to the rate of flaring than to the gross magnetic structure of the underlying spot group. That some particular details of the magnetic configuration not revealed by the sunspots may be important is not, of course, ruled out by the present analysis.

(3) In consonance with Dodson and Hedeman's work on major flares of importance 2 and 3, we find that those importance 1 flares which arise in spot-less regions produce a weaker soft X-ray burst than do importance 1 flares in spotted active centers.

4. Discussion

On the basis of flare photometry it has been suggested (Teske and LoPresto, 1972) that the general H α emission from a solar flare event is excited by thermal conduction out of the soft X-ray source. Under this hypothesis the peak H α flux, which is reached at or shortly after the time of peak energy content in the soft X-ray source, is determined mainly by the energy content of that source. The results of our present assessment of the relationship of magnetic fields to the maximum energy content of the X-ray source with importance

1 flares—as measured by the amplitude of the 8-12 Å burst—may be consistent with that hypothesis.

An importance 1 flare is defined by the I.A.U. as an event whose area on the chromosphere lies within the range 100-250 millionths of the solar hemisphere. In general, the H α intensity of the flaring area also lies within a certain range subject to physical laws but not, at this time, to formal definition. Thus the rate of energy loss by H α emission from an importance 1 flare is restricted to some loose range of values. We suggest that the establishment, by the flare process, of a soft X-ray source having a thermal energy content within a particular range of values will often give rise to an importance 1 flare. Energy is conducted from that source to the chromospheric H α source along magnetic field lines. The great range of soft X-ray burst amplitudes with importance 1 flares and the overlap of burst amplitudes among flare importance classes (Teske and Thomas, 1969) is therefore, on the conduction hypothesis, indicative of significant differences in the conduction process and in the relative rates of conductive and radiative energy losses from the X-ray source among different flares. The present result, that the maximum soft X-ray source energy with importance 1 flares is in the mean independent of spot magnetic field complexity thus suggests that within sunspot groups the gross nature of field topology does not strongly control the mean area on the chromosphere which is connected by field lines into a soft X-ray source of given maximum energy, nor does it strongly control the gross details of conductive and radiative energy loss.

Our present analysis further indicates that, in spot-less regions, a flare of area appropriate to be called importance 1 is accompanied by a less energetic soft X-ray volume than is the case for spotted regions of whatever magnetic complexity. Flares in spot-less active centers tend to be of slightly lower H α intensity than those which arise in spotted regions. This has been remarked by Dodson and Hedeman (1970) for flares of importances 2 and 3, and our sample of importance 1 flares shows it as well: for flares in spotted active regions, the proportions of flares designated "faint," "normal," or "bright" are about 5%, 68%, and 28%, while our sample of flares in spot-less regions—which is small—contains 1 designated "faint," 6 designated "normal," and none designated "bright." Thus in the mean we would expect a slightly lower peak H α flux from spot-less flares, in agreement with the lesser mean energy of the soft X-ray source.

The diminished brightness of the H α event in spot-less centers of activity may be a consequence of greater magnetic field divergence between the soft X-ray volume and the chromosphere as compared with spotted regions. On the other hand the lessened magnetic field intensity above spot-less regions may provide less magnetic confinement of the soft X-ray source with a resulting lower temperature of the source and thus a decreased rate of downward energy conduction per unit chromospheric area. In distinguishing between these possibilities it may be important to note that in our flare sample, 38% of importance

1 flares in strong magnetic fields within 3° of major sunspot umbrae were designated "bright," while only 18% of those farther from major umbrae were so classified. Importance 1b flares tend to be accompanied by stronger soft X-ray bursts than are importance 1n and 1f (Thomas and Teske, 1971). It is also of interest to recall that in many flare models the time scale for the flare process is fixed by the relative diffusion velocity of field and fluid, and is thus inversely dependent upon magnetic field intensity. Dodson and Hedeman emphasized the long time scale for major flares in spot-less regions.

In either case mentioned above (greater field divergence or less magnetic confinement in spot-less regions), a flare of area such as to be classified importance 1 which occurred in weak fields could be excited by conduction out of a soft X-ray volume of less energy than would be the case in active centers embraced by stronger spot fields. We remark here that the above interpretations may be applied as well to the very weak relationships noted in items (b), (c), and (d) of Section 3-A.

It thus appears that, for importance 1 flares, the observed relationships of mean soft X-ray burst amplitude to spot magnetic class may be reconcilable with the conduction hypothesis; that hypothesis may be required by the lower burst amplitude and peak H α flux from flares in spot-less regions.

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Figure Caption

Figure 1. The positional classification for flares that was used in this study (Table I) is schematically depicted here. A flare occurring at each position indicated by an "X" would have been accorded the designation indicated. Sunspot magnetic polarities are indicated by (N) or by (S).

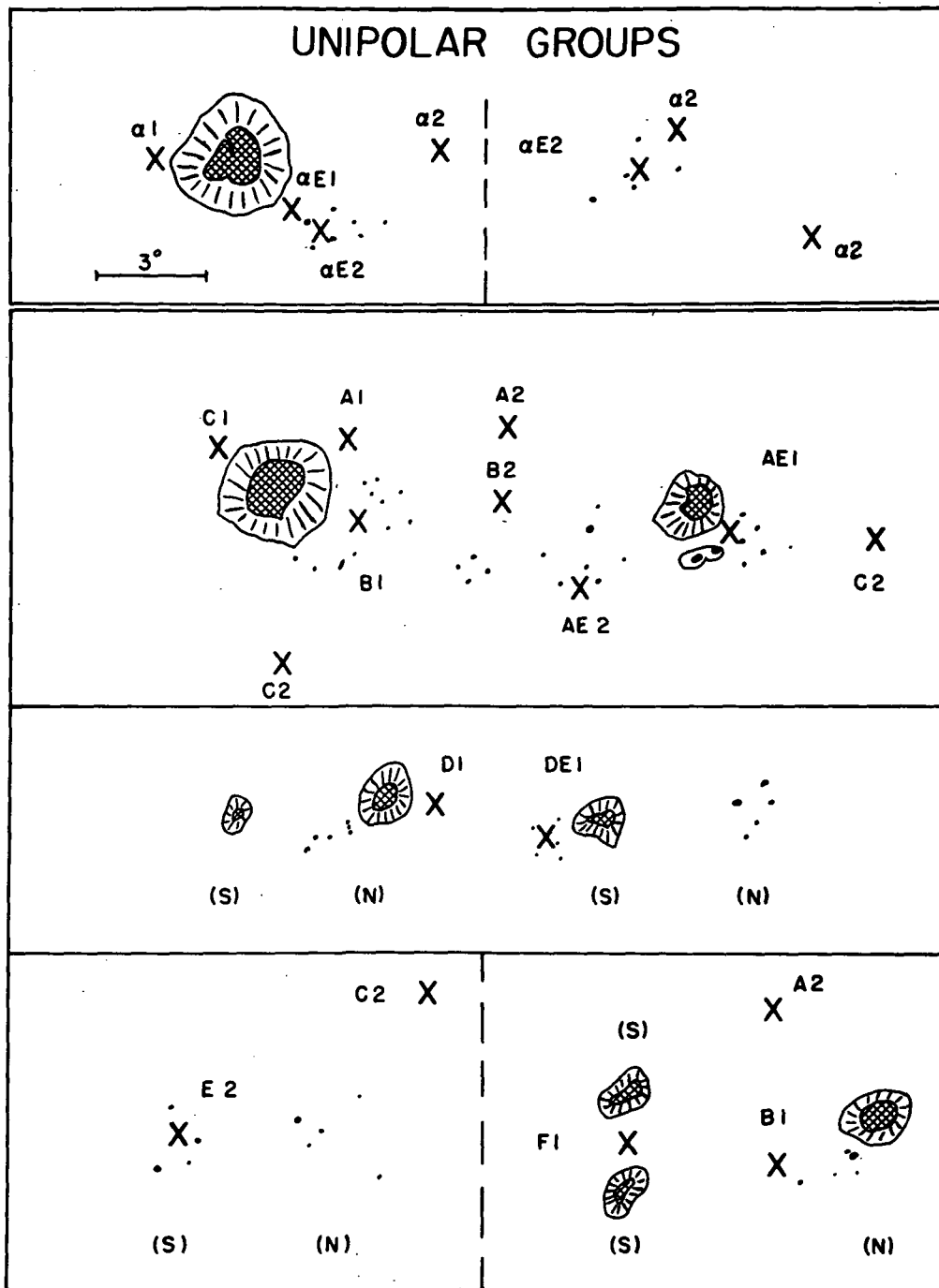


Figure 1