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OBSERVATION OF THE SOLAR SOFT X-RAY COMPONENT; STUDY OF ITS RELATION TO TRANSIENT AND SLOWLY-VARYING PHENOMENA OBSERVED AT OTHER WAVELENGTHS

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Abstract. Solar X-rays from 8–12 Å have been observed with an ion chamber photometer and fluxes derived from the observations after an assumption concerning the spectral distribution. The time variation of the X-ray flux correlates well with the radio flux, plage index, and sunspot number. Comparisons of X-ray and optical events are given; flares seem to produce soft X-rays, but some soft X-ray bursts are apparently not associated with flares. The total energy involved in the soft X-ray bursts may be a significant amount of the total flare radiation.

1. Instrumentation

The Michigan soft X-ray ion chamber photometer is located in the wheel of OSO-III. The ion chamber is filled with about one atmosphere of dry nitrogen gas and has a 5-mil thickness aluminum foil window; the efficiency of response as a function of wavelength for such an ion chamber has been published (ACTON *et al.*, 1963). The detector responds principally to energy in the wavelength range 8–12 Å, though there is also a low efficiency of response between 2–5 Å. In OSO-III, the cadence of main-frame telemetry rate and wheel rotation rate results in roughly one word of solar soft X-ray data and two words of particle background data for each period of wheel rotation.

Data generated by the instrument are converted to energy fluxes $E(8, 12)$ ergs $cm^{-2} sec^{-1}$ for the wavelength band 8–12 Å under the assumption that the radiation is distributed as in a black-body curve for 2×10^6 K (KREPLIN, 1961). If the slope of the actual flux-distribution curve departs from the assumed one (e.g., NEUPERT *et al.*, 1967; FRITZ *et al.*, 1967; RUGGE and WALKER, 1967), the true energy flux may be approximately recovered by applying a correction factor (Figure 1). Attempts are being made to utilize observations obtained during occultations of the sun behind earth's atmosphere near satellite dawn and twilight to determine spectral slopes for the flux distribution which may be appropriately applied to this experiment.

Two automatically-selected ranges of operation are incorporated into the instrument, one with a high dynamic sensitivity (3400/l) and one with a lower dynamic sensitivity (125/l) covering a total flux range $0 < E(8, 12) < 0.12$. The instrument has been saturated by the peak emission from great flares. An electrical calibration occurs about every 6 min, and has shown that the instrumental energy scale has been stable to about 1% since launch. The absolute calibration is probably within 6% of correct.

Reliability of operation may be verified by using the sun itself as a standard source. There exists a good statistical – and physical – relationship between the 2800 MHz solar flux and the soft X-ray flux (e.g., Figures 2 and 3). Comparison of these two fluxes for April 1967 and for August 1967 separately gave very closely the same relationship. Over that 5-month interval, at least, no changes in ion-chamber response occurred.

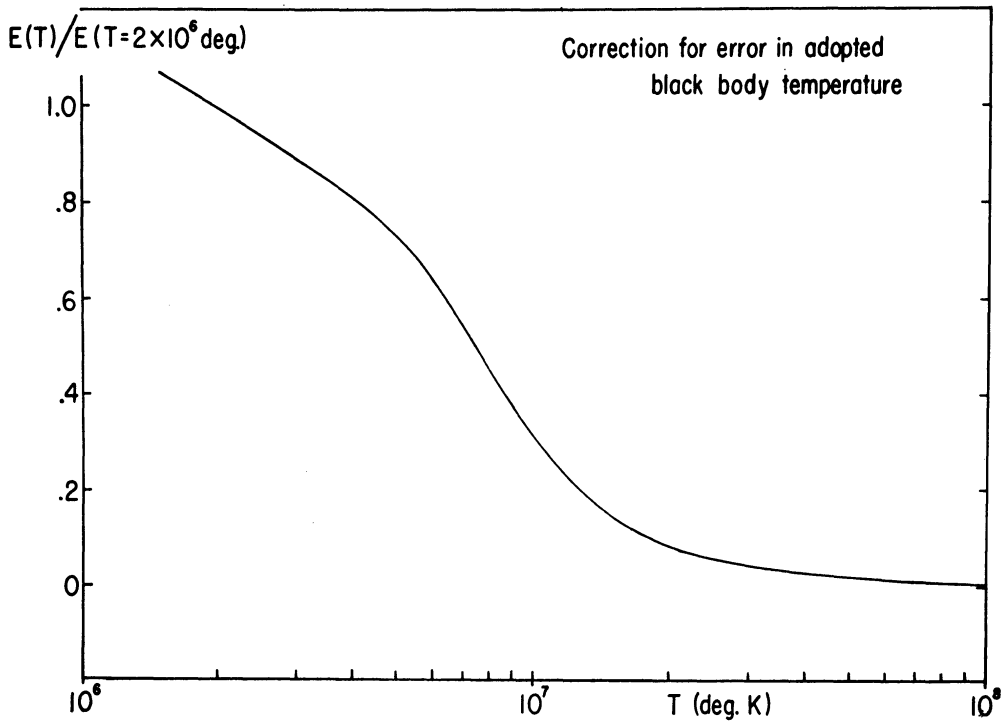

Fig. 1. If the true solar flux distribution with wavelength approximates a black-body curve for temperature T (abscissa), energy fluxes quoted in this paper must be multiplied by the value of the ordinate.

2. Observations of the Non-Flaring Sun

The slow variation of soft X-ray flux with solar activity is shown in Figure 2 for the period March through August 1967. The index which is here used to characterize the quiet X-ray sun is the daily base-level, which is the lowest known flux reached during the day and is thus an index of the non-flaring sun. The X-ray base-levels are still preliminary, since complete 24-hour data have not yet been analyzed for the full six months.

As may be judged from Figure 2, the soft X-ray daily base-level correlates well with other indices of the general level of solar activity: the 2800 MHz daily solar flux ($\rho = 0.82$), a McMath-Hulbert Observatory plage index ($\rho = 0.72$) and the Zürich sunspot number ($\rho = 0.78$). Hence, the major component of the soft X-radiation being observed arises in the active centers (cf. UNDERWOOD and MUNEY, 1967). The base-level enhancements of August 18/19 and of August 30/31, apparently uncorrelated with the other solar indices, coincide with East and West limb passages of a major active center on the sun (McMath plage region 8942) and apparently show it to have been strongly limb-brightened in X-radiation.

In addition to its correlation with the 2800 MHz flux density, the soft X-ray background changes in a predictable way with radio flux density at other frequencies

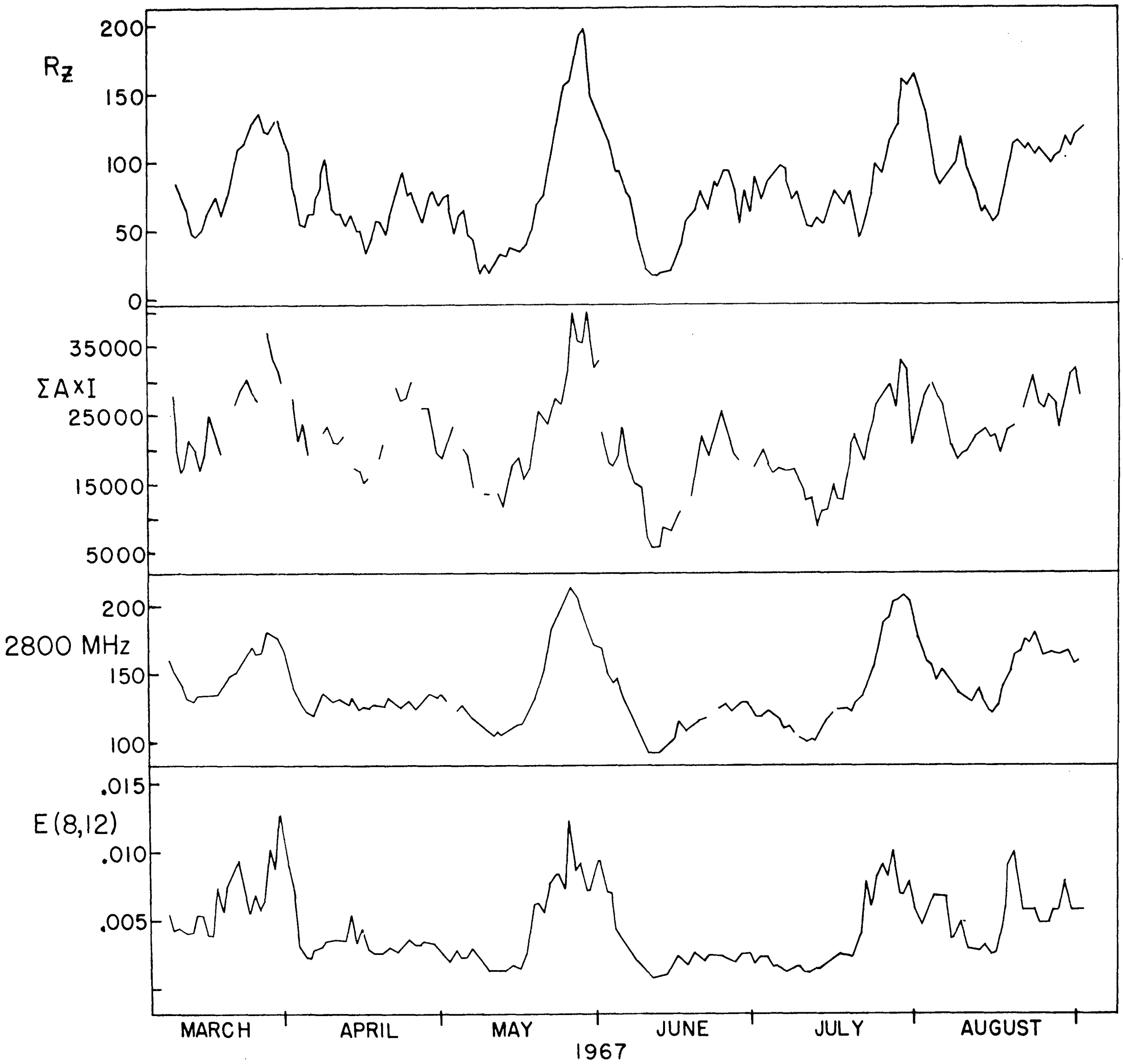

Fig. 2. Soft X-ray base level fluxes (bottom) are compared with the 2800 MHz daily flux density, with a plage index which is the sum of products of plage areas by excess intensity in the Ca II K line core, and with the Zürich daily sunspot number (top).

(Figure 3). For a given variation $\Delta E(8, 12)$ of soft X-ray flux, the variation of radio flux density is greater at 2800 MHz, and is less at higher and lower frequencies. A linear fit seems adequate for the data so far examined. When the data for Figure 3 were assembled, no account was taken of possible center-limb effects.

Figure 4 contains data for four days which are representative of a range of solar activity conditions. In the figure, each point represents a 67-second time-average of

X-ray flux. Vertical bars represent satellite night, which is about 35 min long. Satellite day is about an hour long. Times which are given, so as to provide a time-scale, refer to the time of a satellite dawn. For May 11, May 5, and June 1, times are discontinuous across satellite night, while for April 15 the time is continuous.

On May 11 quiet solar conditions prevailed: the daily 2800 MHz flux density of 104.0 was lowest since late December 1966 and no regions of significant activity were present on the visible solar hemisphere. These quiet conditions are reflected in a nearly flat, uniform X-ray flux-time curve. Arrows indicate the reported starting times for two subflares. We have associated the nearby X-ray enhancements with those flares.

In contrast, on May 5 the X-ray flux-time curve was constantly disturbed, showing significant variations throughout the period of time depicted. On this date a flare-rich plage region (No. 8791) was located in the Southwestern quadrant of the disk, and

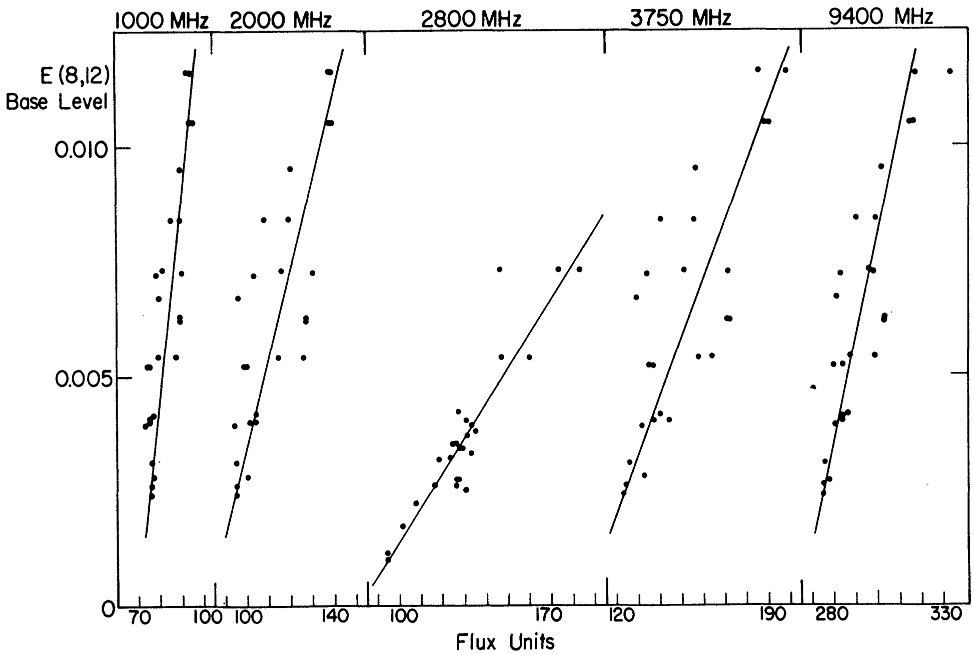

Fig. 3. Radio flux densities at 2800 MHz are those reported by Algonquin Radio Observatory (Ottawa) and at other frequencies are those reported by the Research Institute of Atmospherics at Nagoya University (Toyokawa). Radio and X-ray fluxes were observed simultaneously when no flares were occurring. The Toyokawa and Ottawa data represent samples during different months. One flux unit equals 10^{-22} W m^{-2} Hz^{-1}.

the 2800 MHz daily flux density was 125.8. Arrows point to enhancements which we have associated with subflares reported during our X-ray observing hours on May 5.

The flux-time curve for April 15 again refers to moderately active solar conditions, when the 2800 MHz flux stood at 123.2. It is inserted in Figure 4 to demonstrate operation of the instrument as it switches from its range of higher dynamic sensitivity to its range of lower sensitivity. The major enhancement in the diagram accompanied a reported subflare. The second enhancement was not accompanied by a reported optical event. We have tentatively associated it with a small event in plage No. 8760 on the Northwest limb, not seen very clearly on our flare films. There occurred a weak brightening of the plage, and a surge-like, faint feature was seen projecting above the limb. Times of beginning, maximum and end of the event coincide in time with the X-ray increase.

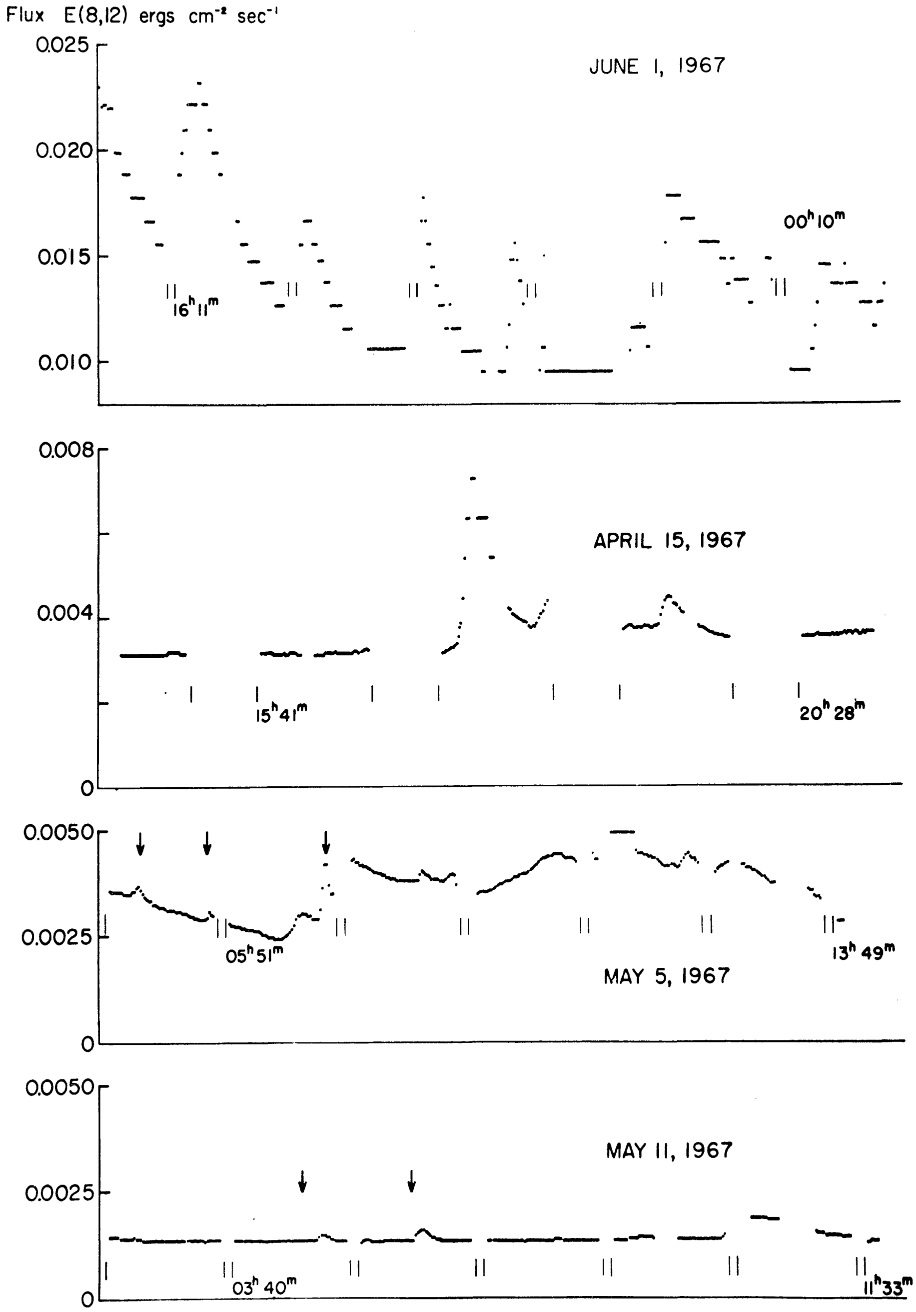

Fig. 4. Representative data for four days in 1967.

At times of great solar activity, such as on June 1, the solar soft X-ray flux varies almost constantly through a great range of flux values. On that date the 2800 MHz flux was 169.7. McMath plage region No. 8831, then in the Northeast quadrant of the disk, was at its peak of flare activity on June 1 and June 2. Enhancements of

X-ray flux seen in our record for June 1 accompanied subflares and flares of importance 1. X-ray flux increases which accompanied subflares on June 1 were generally greater than those accompanying subflares on the other dates in Figure 4.

Flare associated X-ray enhancements will be discussed in the next section.

Our data show that during times when no reportable optical events occur on the sun, the solar soft X-ray flux may still undergo some variations. Sometimes these non-flare X-ray fluctuations can be identified with fluctuations in Hα plage intensity and with events at the limb, but often there is no clearly-associated optical Hα counterpart. At times of relatively high solar activity, as evidenced by a relatively high X-ray base-level or by a relatively high 2800 MHz flux, these non-flare X-ray fluctuations occur frequently, with an amplitude of $\approx 10\%$ or more of the average flux level, and on a time scale of tens of minutes. As solar activity moderates, the X-ray fluctuations also moderate as to their amplitude and frequency of occurrence. At the quietest times seen so far, the X-ray flux-time curve becomes smooth, showing only occasional fluctuations of very small amplitude.

3. Observations of Active Events

The relationship of soft X-ray flux enhancements to transient solar events observed optically and at radio wavelengths is being more clearly outlined by the OSO-III data. As regards flares, the times of beginning, maximum and ending of the X-ray events, as well as the total flux enhancement, appear to be statistically related to the timing of the optical event and to its importance classification. (See, however, the discussion by Underwood (1968).)

We have attempted to determine the frequency with which X-radiation accompanies flares. The study has been limited to those hours during each day for which we have already reduced data.

In a sample of 57 subflares reported on a world-wide basis, 51 were definitely accompanied by X-rays. Of 47 subflares which were observed cinematographically at the McMath-Hulbert Observatory during March, April and May of 1967, 44 were definitely accompanied by soft X-rays. The three 'failures' occurred when our X-ray detector was operating in its range of lower sensitivity. If the subflare sample is confined to those subflares observed cinematographically at McMath during hours when the X-ray detector was operating in its higher sensitivity range, then it appears that all the subflares were associated with X-ray emission, although at times it was very weak emission.

Only six flares of importance 1 were observed cinematographically at the McMath Hulbert Observatory between March 10 and June 30 and during hours for which we already have reduced data. Each was accompanied by a significant X-ray increase. Only 23 out of 26 importance-1 flares reported on a world-wide basis during hours for which we have reduced data from March 10 through May 31, had X-rays with them. None of the three 'failures' was reported by more than one observing station, however, and they may be accidental reports.

Hence, we are of the opinion that probably all flares are the site of emission of soft X-rays, although at times the emission is indeed minor (Figure 4). In order for a flare-associated enhancement to be recognizable in our data as reduced so far, its duration and amplitude must be such as to yield a time-integrated flux between 8 and 12 Å of a few times 10^{25} ergs at the sun, assuming emission into 4π steradians and no photon scattering.

On the other hand, we have asked with what frequency visible flares or other active events accompany X-ray bursts. In a sample of 79 flux enhancements of all sizes recorded during March, April and May of 1967, only 57 bursts could be identified with flares reported on a world-wide basis and four with limb events such as surges leaving 18 of them, or 23% which could not be identified with reported optical phenomena. More than half of these remaining bursts occurred during European observing hours, where subflares are usually not reported as a matter of course. The average flux enhancement for the unidentified bursts was smaller than the average flux enhancement accompanying reported subflares in the same sample.

Time-lapse filtroheliographic flare patrol films made at the McMath-Hulbert Observatory have been examined in connection with some of the preliminary X-ray data. The total film examined is about equivalent to 35 days of full-time day-light flare patrol. Two relatively large X-ray bursts have been found which are not clearly associated with visible flare activity; both are somewhat smaller than the enhancement usually associated with flares of importance 1. One of these may have possibly been associated with activity behind the Southwest limb (July 11). The second took place near the time of a subflare on the disk, but is in very poor time-association with the Hα event (July 29).

Studies of individual flare events in connection with the X-ray data have permitted us to draw some tentative generalizations which will be investigated further as more data are reduced. Sources for the studies include the McMath-Hulbert flare patrol films, the ESSA Solar-Geophysical Data Bulletin, HAO Preliminary Reports, flare and SID lists from McMath and Manila and radio data from Toyokawa, Hiraiso, Sagamore Hill and Ottawa.

X-ray enhancements associated with flares appear to be fair guides to flare importance in the sense that subflares tend to be associated with smaller enhancements than flares of importance 1, and so on, yet flares within a given importance class may give rise to a great range of X-ray flux.

Generally the Hα flare and the X-ray event begin at about the same time. The Hα intensity peak will most frequently precede or coincide with the X-ray maximum. In about 20% of flares the Hα maximum intensity follows the X-ray peak. In flares of importance 1^- and 1 the Hα and X-ray events tend to end together, while in major flares the X-rays tend to outlast the visible event for a length of time which depends upon flare importance. Following the great flares of March 22 and May 23, 1967, the soft X-ray flux remained above pre-flare levels for at least five hours. Many exceptions to these generalizations have been observed. For example, sometimes the visible flare will begin two or three min before the X-ray flux begins to increase (Figure 5). Again, following the importance-2 flare of May 6, 1967, the soft X-ray flux returned to its pre-flare level quite precisely and almost at once after the flare was reported to have ended. Flare events occurring close to the sun's limb sometimes demonstrate the greatest departures from these generalizations, an effect which is probably connected with the well-known decreased visibility and shorter duration of flares near the limb.

Examples of X-ray bursts accompanying flares of importance 1 and 2 are shown in Figures 6 and 7, together with photometric Hα intensity curves (intensity expressed in arbitrary units) and the accompanying cm-λ bursts. In both events a slow brightening in both Hα and X-rays preceded the cm-λ burst. At that time the flares abruptly brightened in Hα and X-rays.

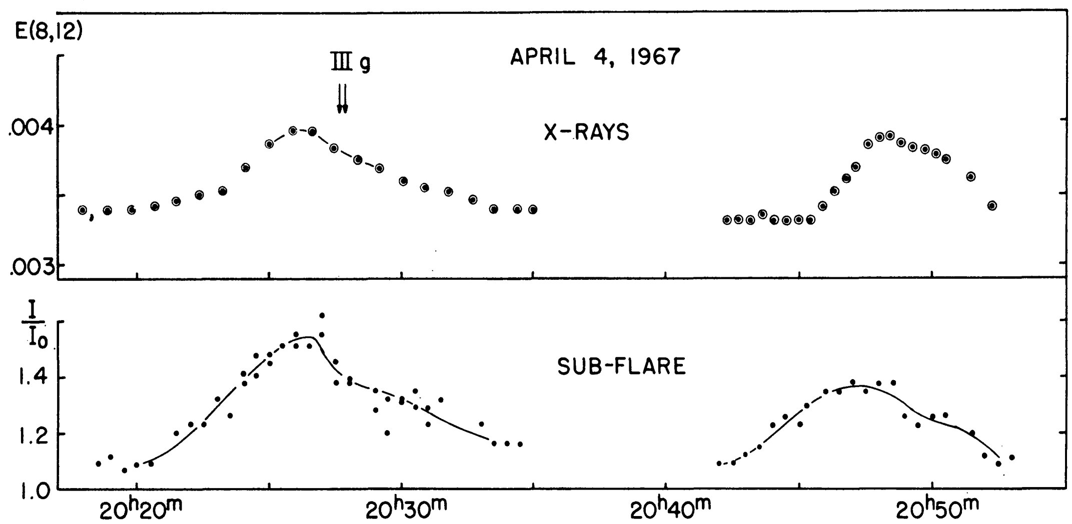

Fig. 5. Photometric Hα intensity curves for two subflares (lower) and the associated X-ray flux enhancements. The sun was occulted behind earth's atmosphere beginning at about 20^h51^m. The first subflare (S20E22) was associated with a great ejection of dark material, the second (S25E50) was not.

In the July 25, 1967 event (Figure 6), the importance-1 flare lasted until after 15^h00^m, although the Hα light curve has not been carried along that far. The subflare which began at 14^h50^m on that date did not affect the X-ray record probably because our instrument was then operating in its 'flare mode' of low dynamic sensitivity, in which the weak emission accompanying subflares is often not detected (cf. Figure 5, where operation was in the higher sensitivity mode).

While the Hα and X-ray curves often appear qualitatively similar, as in Figures 6 and 7, the structure of the soft X-ray burst is usually very different from the structure of the accompanying cm-λ burst. Typically, the maximum of the cm-λ burst occurs some minutes prior to the X-ray maximum (≈80%), more rarely the two maxima coincide within a minute (≈15%) and in still rarer cases a weak cm-λ maximum occurs after the soft X-ray peak. Thus, the X-ray maximum tends to associate itself most clearly with the post-burst phase of the radio emission at centimeter wavelengths. On the other hand, there is a strong tendency for the soft X-rays to begin their increase earlier than the reported beginning of the cm-λ burst.

This latter effect is suggestive of physical conditions in the flare volume, to which the mechanism that gives rise to the soft X-radiation is more sensitive than is the mechanism that generates cm-λ radiation. In flares, an increase of 2800 MHz flux density by 5 flux units (5×10^{-22} W m^{-2} Hz^{-1}) is accompanied by an X-ray increment $\Delta E(8, 12)$ of 0.005 ergs cm^{-2} sec^{-1} (Figure 8). The relationship in the slowly-varying component (Figure 3) is such that an increase of 70 flux units at 2800 MHz accompanies an increment in X-ray flux of $\Delta E(8, 12)$ of 0.005 ergs cm^{-2} sec^{-1}. WHITE (1964) noted a similar sensitivity in the 2–8 Å flux.

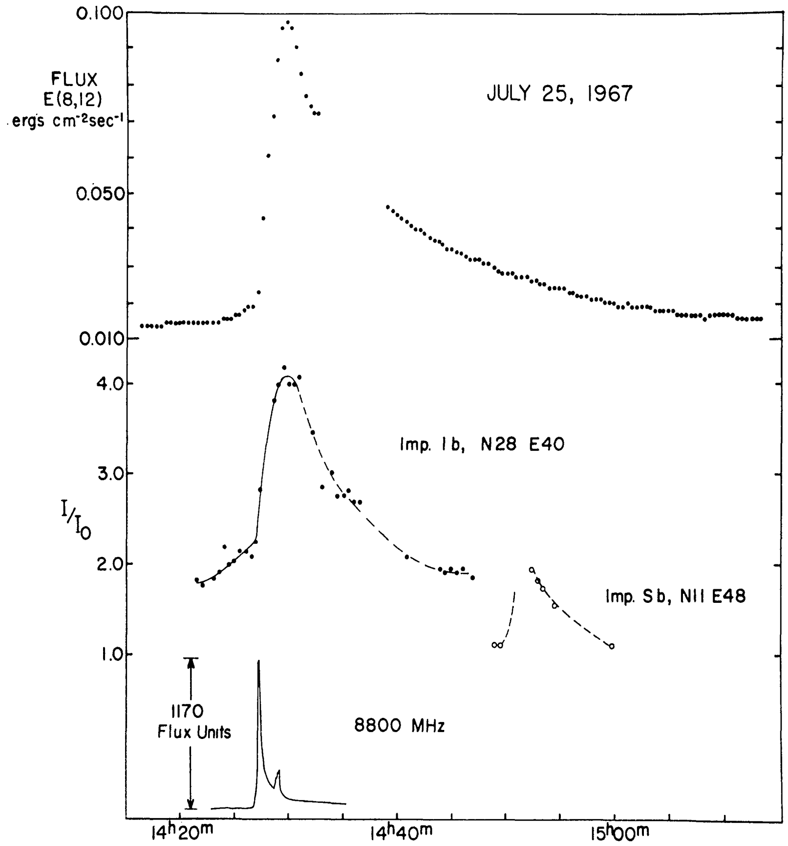

Fig. 6. The gap in the X-ray record (top) occurred during tape-recorder playback. Clouds interfered with the Hα flare observations (center). The 8800 MHz record was reported by Sagamore Hill (lower).

4. X-Ray Energy Emitted by Flares

Information concerning physical conditions in flares may be obtained through knowledge of the energy invested by flares in various parts of the electromagnetic spectrum and in particle and plasma emissions. Further, the total energy emitted by flares and the time scale for its release are constraints upon possible flare mechanisms. Thus, it is of interest to obtain from our data some indication of the total energy emitted as soft X-rays.

Because the spectral distribution of X-radiation is a function of time during a flare event (RUGGE and WALKER, 1967; CULHANE *et al.*, 1963), time-integrals of flare energy between 8 and 12 Å are uncertain, and it is difficult to estimate at this time what the uncertainty is. It may not be overly pessimistic to estimate errors by up to a factor of 3 for ordinary flares, and by up to a factor of 5 for flares of importance 2 and 3, in the sense that the measured total energies may be too high.

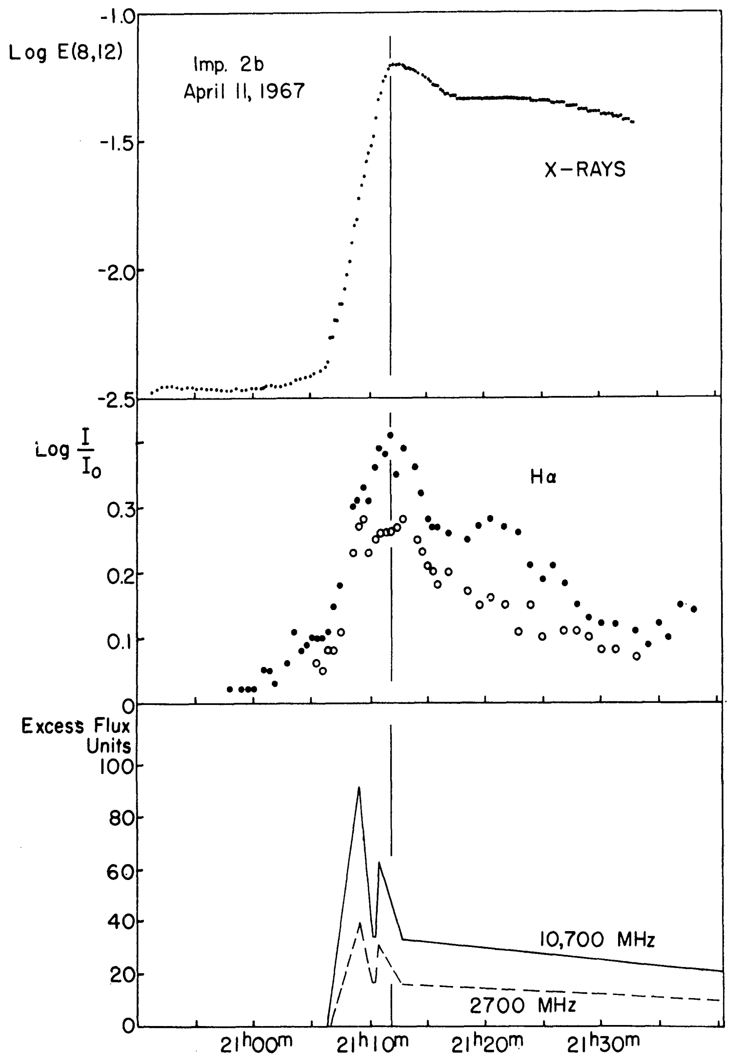

Fig. 7. The importance-2b flare took place at S23W72. Hα intensities measured in two parts of the flare are shown on a logarithmic scale, as are the X-ray fluxes. The cm-λ event is drawn schematically for two frequencies according to author's interpretation of data in ESSA Solar-Geophysical Data Bulletin.

TABLE I

Total Flare Energies $\int E(8, 12)dt$

Date (1967)	Importance	No. of Flares	Mean Energy (ergs)	Range (ergs)
–	1^-	8	3×10^{27}	7×10^{25} – 8×10^{27}
–	1	8	6×10^{28}	1×10^{28} – 2×10^{29}
March 22	3^-	1	$\approx 10^{30}$ (Total)	–
May 23	2, 2, 2, 2	4	$> 5 \times 10^{30}$ (Total)	–

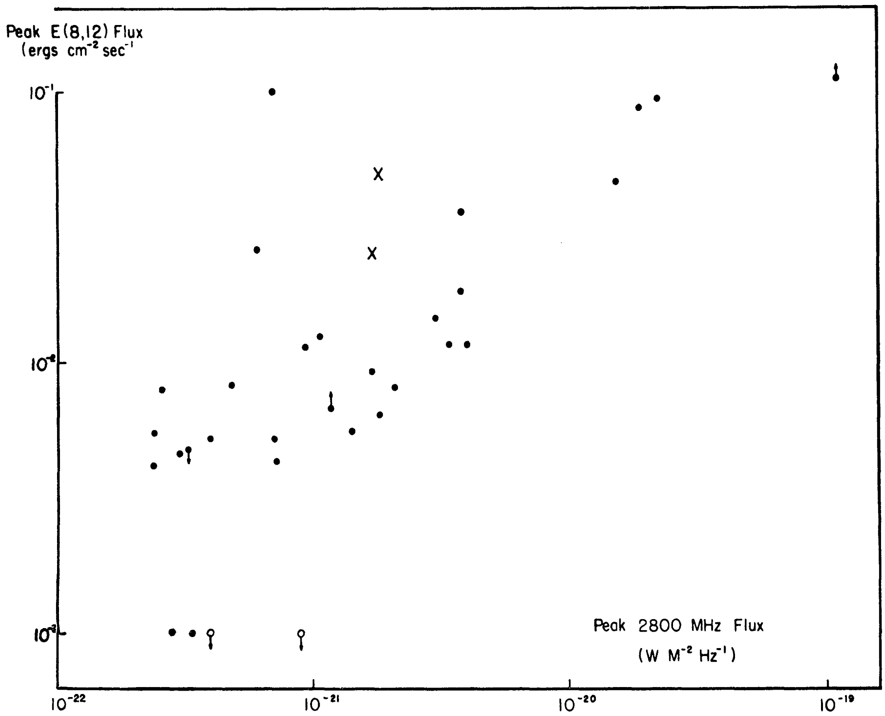

Fig. 8. Relation of peak fluxes for associated X-ray and cm-λ events. Filled circles: simple bursts with flares; crosses: complex bursts with flares; open circles: simple bursts without reported flares. All values are as measured at the earth, uncorrected for earth's orbital eccentricity.

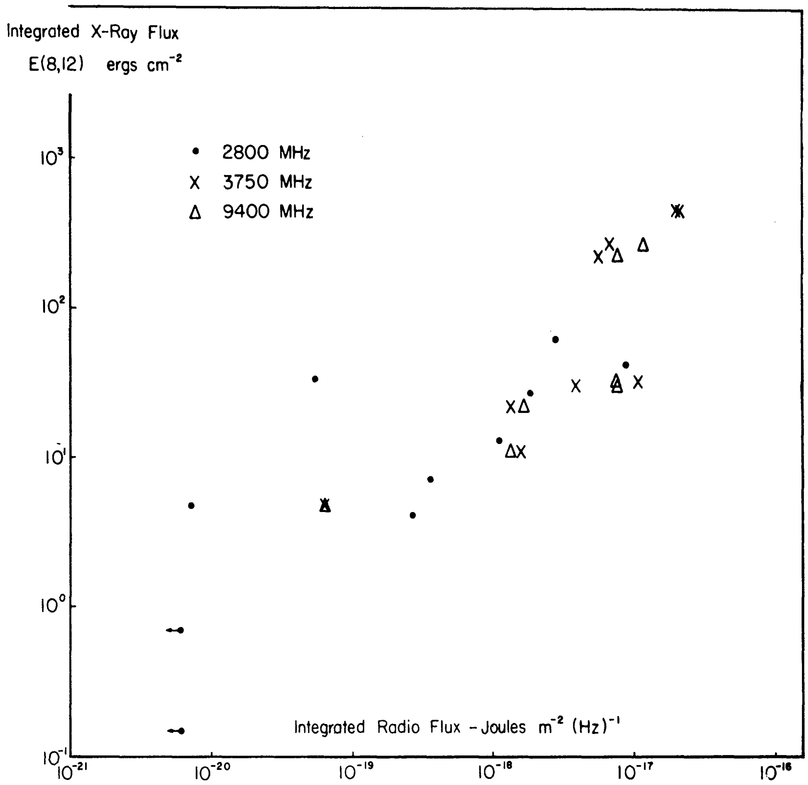

Fig. 9. Relation of time-integrals of X-ray and cm-λ events. The 2800 MHz point at 5.5×10^{-20} Joules m^{-2} Hz^{-1} represents an event on July 11 which was not clearly flare-associated. The two 2800 MHz points towards lower left represent estimated upper limits based upon no report during observing hours. All values as measured at earth, uncorrected for earth's orbital eccentricity.

We have assumed that the flare radiation is released into 4π steradians and that none of the inwardly-directed photons are scattered. Time-integrals of energy measured by us in a number of flares, and computed for the wavelength band 8–12 Å are summarized in Table I. The estimates in the table should be viewed as upper limits.

The energy radiated by flares at cm-wavelengths is related to the soft X-ray energy in the sense that large X-ray events tend to accompany large cm-λ events and *vice versa*. Peak X-ray flux and peak cm-λ flux density in associated events are plotted in Figure 8. We note that the X-ray peak is still high enough at a radio flux density peak of 1 or 2 flux units to be clearly discernable in our data. It appears likely that even smaller X-ray bursts than those investigated may be accompanied by unreportably small radio bursts.

When time-integrals of energy at cm- and X-ray wavelengths are examined, we find again that there is a strong tendency for the greater X-ray events to accompany the greater radio events (Figure 9). Time-integrals of radio flux density in Figure 9 were obtained by multiplying tabulated mean fluxes by tabulated durations. Arnoldy *et al.* (1967) have shown that a definite relation like that suggested by Figure 9 exists for the 10–50 kV X-rays. Further study of our data will be necessary before quantitative relations can be confidently established with them.

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SOLAR SOFT X-RAYS AND SOLAR ACTIVITY

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

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(Received 15 January, 1969)

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

1. Introduction

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

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

2. Observations

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

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

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

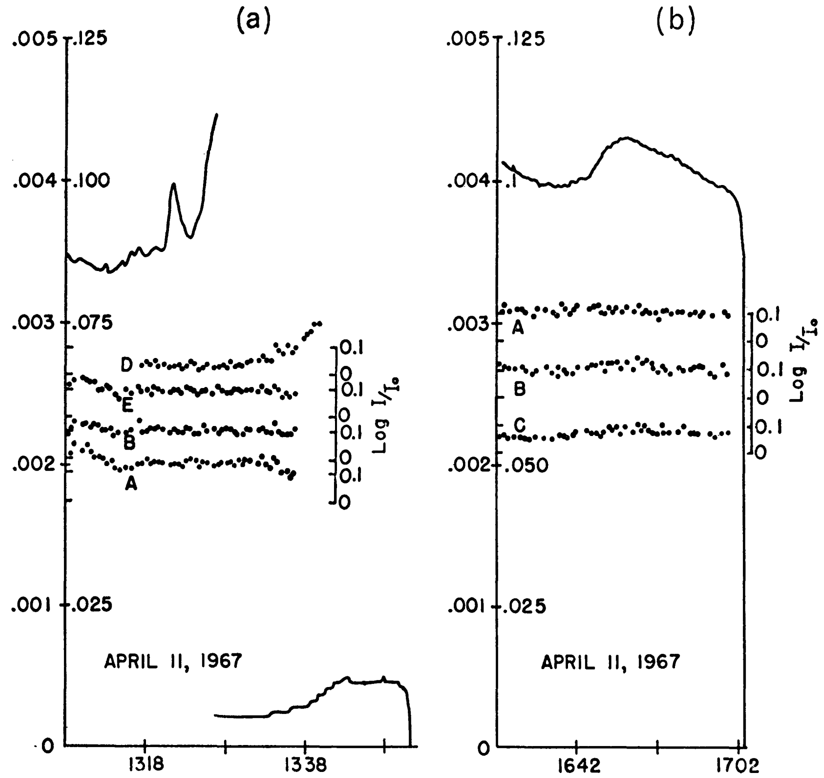

Fig. 1. – (a) Importance-1b flare (N22 W24) of April 11, 1967. Abscissa: Universal Time in hours and minutes. The solid curves are X-ray fluxes. Note change of ordinate scale at 13^{h}26^m. Left-most ordinate scale is for high-sensitivity operation (prior to 13^{h}26^m) and the additional ordinate scale is for low-sensitivity operation. Units are $E(8, 12)$ ergs cm^{-2} sec^{-1}, at earth, in band-pass 8–12 Å. Dots are intensity measures made in 4 parts of the region on Hα filtroheliographic flare patrol films, expressed in $\log_{10} I/I_0$ (right ordinate scale). I_0 is the intensity of the Hα image at the center of the disk. Only the initial flare phases were studied photometrically. Satellite sunset occurs at 13^{h}53^m. – (b) Non-flare brightening in the same region (N22 W24) on April 11, 1967. X-ray detector operation in high-sensitivity range only. Parts B and C of the region brightened perceptably beginning at about 16^{h}42^m. Satellite sunset at 17^{h}03^m.

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

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

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

3. Discussion of the Observations

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

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

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

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

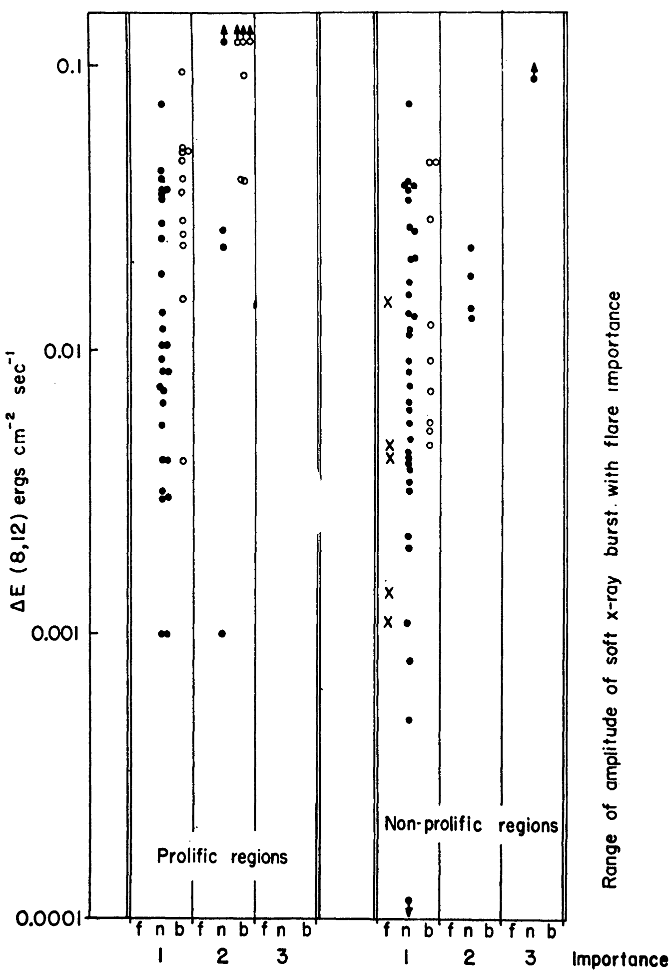

Fig. 2. Soft X-ray flux enhancements observed in flares of importance $\geqslant 1$, divided according to flare importance and brilliance and further divided as to whether the flares occurred, in our estimation, in flare-rich or flare-poor active centers.

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

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

TABLE I

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

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

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

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

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

B. TIME-RELATIONS BETWEEN Hα FLARES AND X-RAY BURSTS

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

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

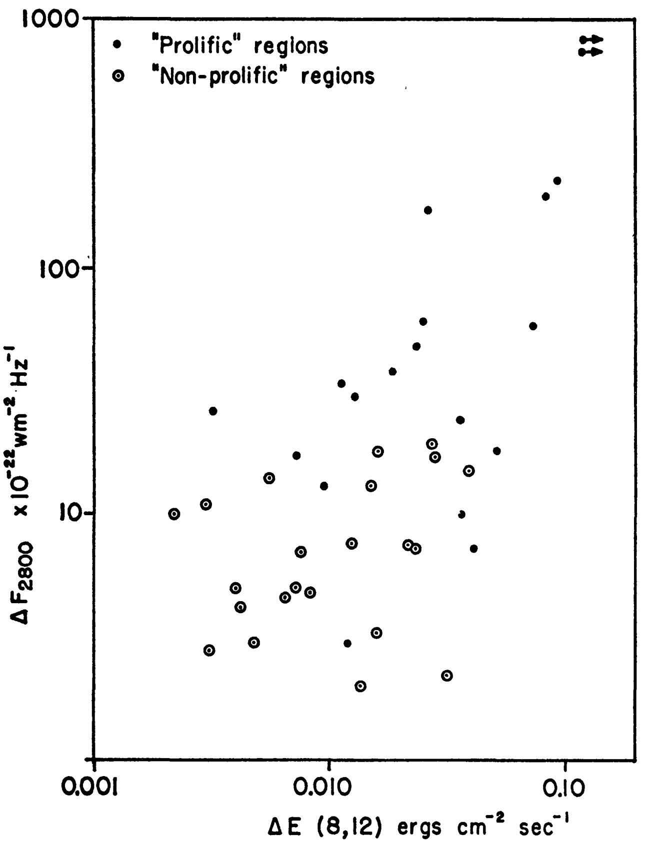

Fig. 3. Comparison for individual flares of associated enhancements of soft X-ray flux and 2800 MHz flux. Large dots and circled dots identify events in flare-rich and flare-poor regions.

1. *Starting Times*

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

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

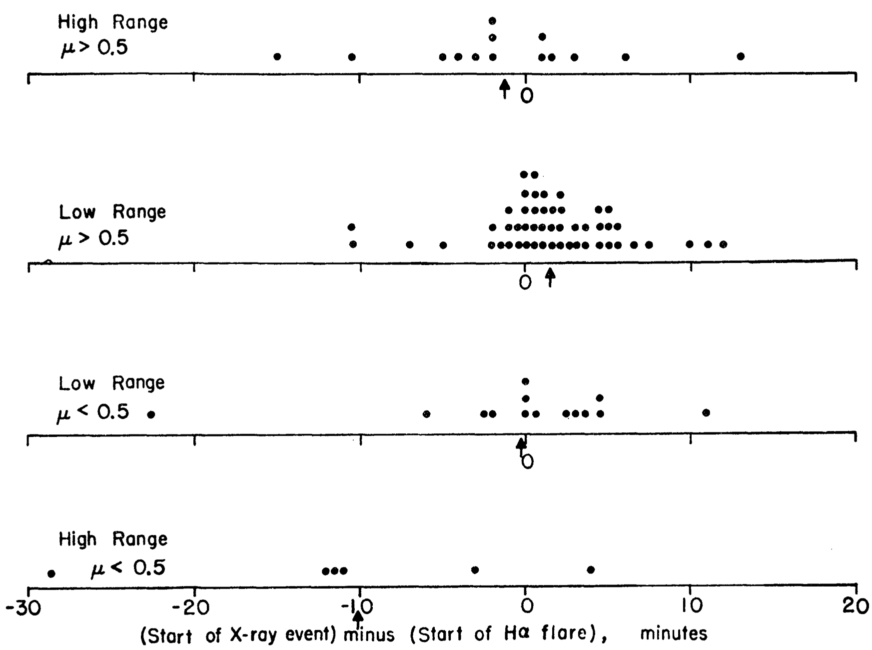

Fig. 4. Comparison of reported starting times of Hα flares and associated soft X-ray enhancements. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values. Data are divided according to instrumental sensitivity range at beginning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

TABLE II

Mean differences between Hα and soft X-ray starting times

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

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

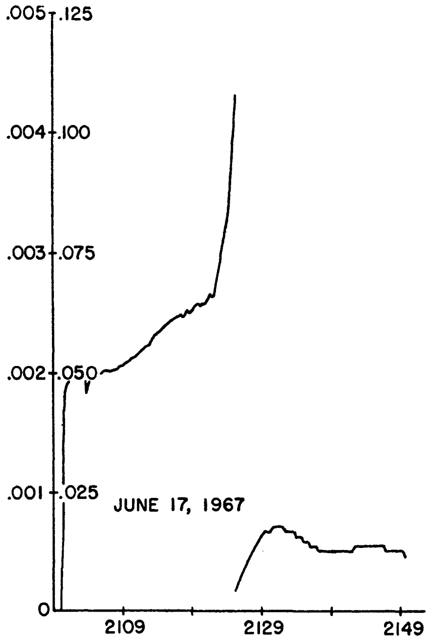

Fig. 5.

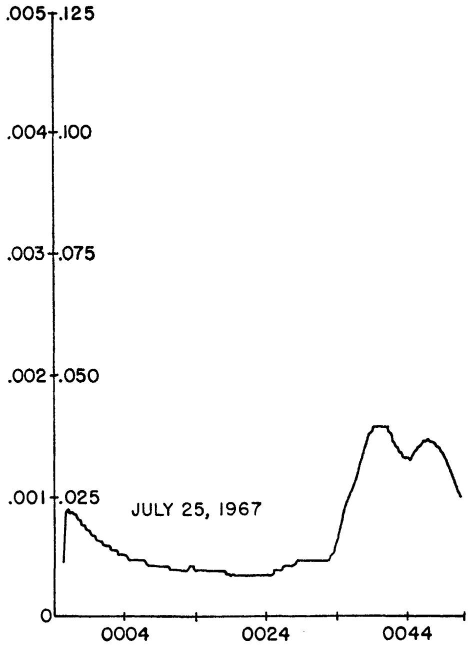

Fig. 6.

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

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

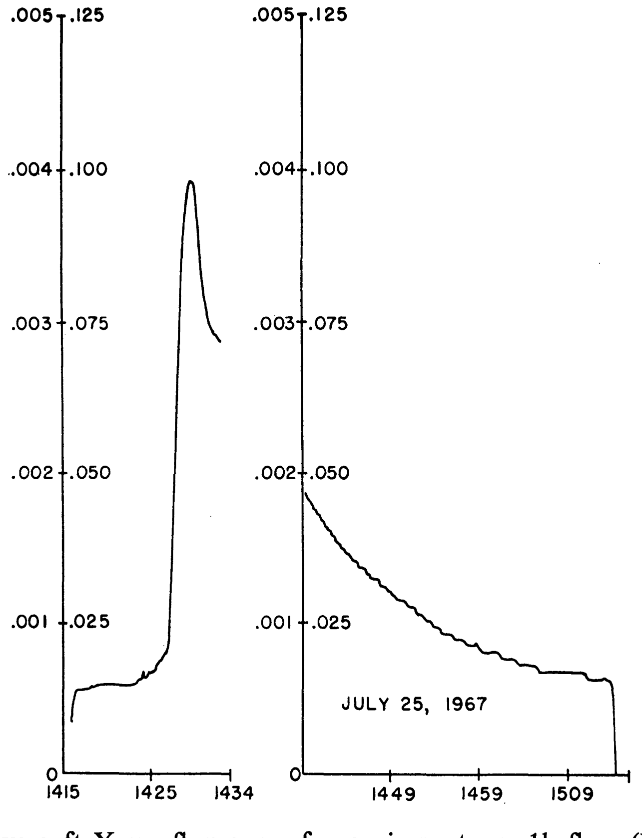

Fig. 7. A representative soft X-ray flux curve for an importance-1b flare (N28 E39) on July 25, 1967. Soft X-rays show early increase at 14^h18^m. Low-sensitivity operation only. Sunrise and sunset at beginning and end of record.

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

2. *Times of Maxima*

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

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

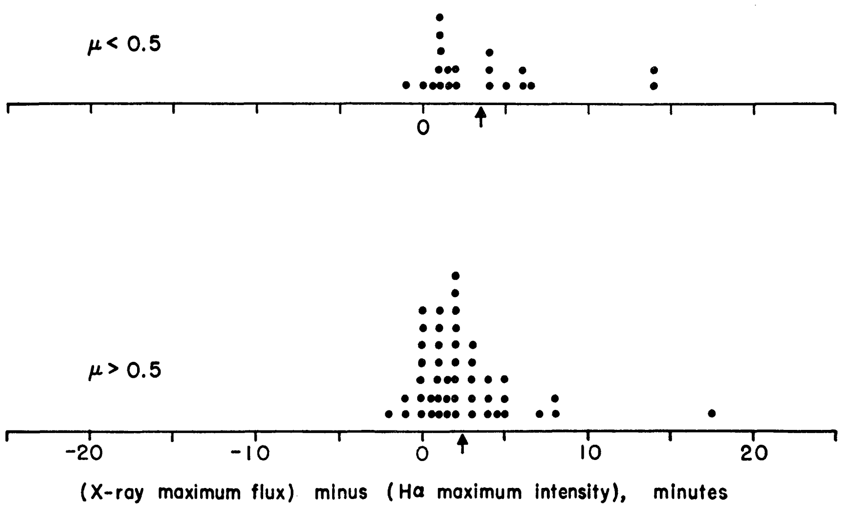

Fig. 8. Comparison of reported times of maxima of Hα flares and associated soft X-ray fluxes. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values.

TABLE III

Mean differences between Hα and soft X-ray maximum times

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

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

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

1. *Starting Times*

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

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

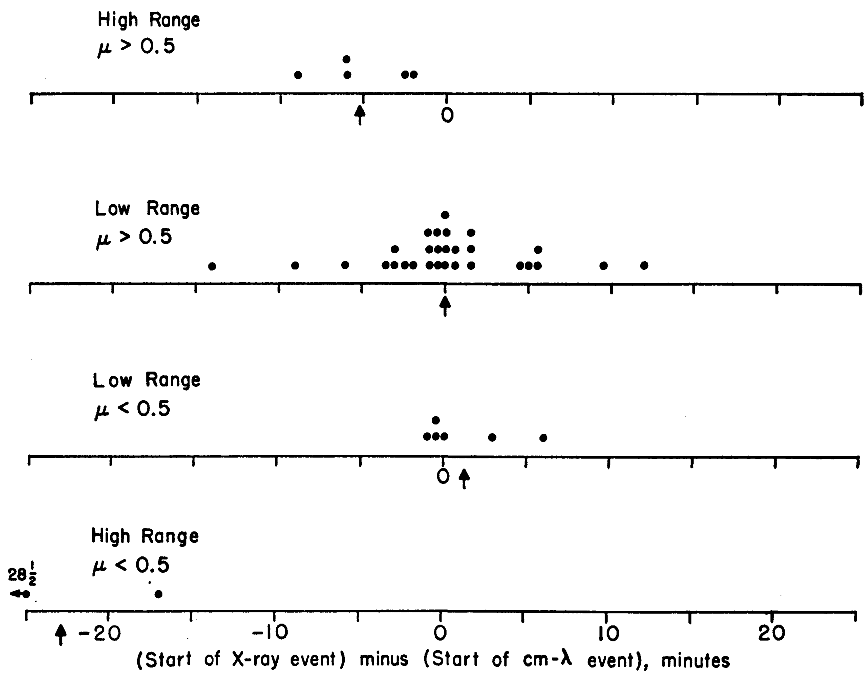

Fig. 9. Comparison of reported starting times of cm-λ bursts and soft X-ray enhancements. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values.

TABLE IV

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

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

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

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

2. *Times of Maxima*

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

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

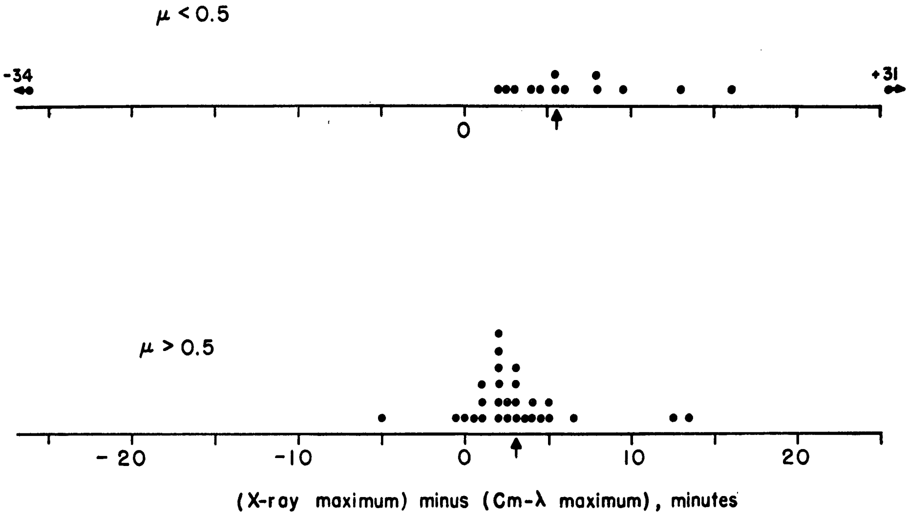

Fig. 10. Comparison of reported maxima of cm-λ bursts and soft X-ray fluxes. Each dot is a single event. Relative times are in the sense that *negative* indicates early X-rays. Arrows point to mean values.

TABLE V

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

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

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

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

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

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

4. Analysis

A. STARTING TIMES: THE PREDECESSOR EVENT

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

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

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

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

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

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

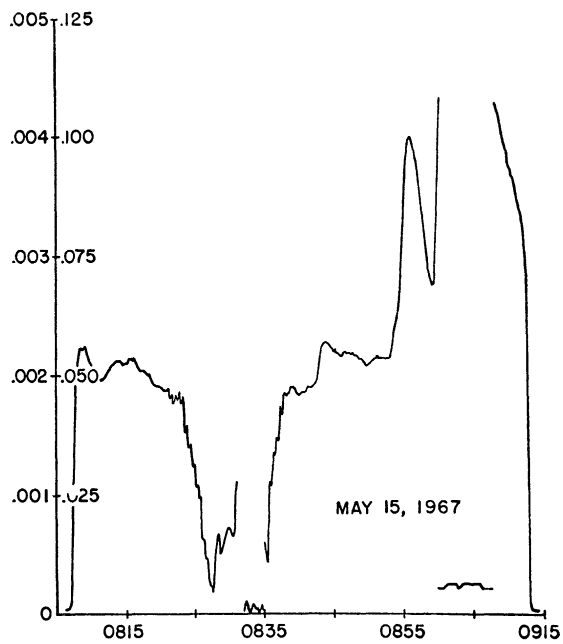

Fig. 11. Soft X-ray flux curve for importance-1n flare (S13 E79) on May 15, 1967. Strong particle interference occurs between 08^h21^m and 08^h40^m. Note changes of scale at 08^h59^m and 09^h08^m. Sunrise and sunset at beginning and end of record.

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

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

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

TABLE VI

Some emission lines observed in the solar X-ray spectrum

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where

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

Here, the symbols are as defined by Pottasch.

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

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

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

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

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

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

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

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

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

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

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

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

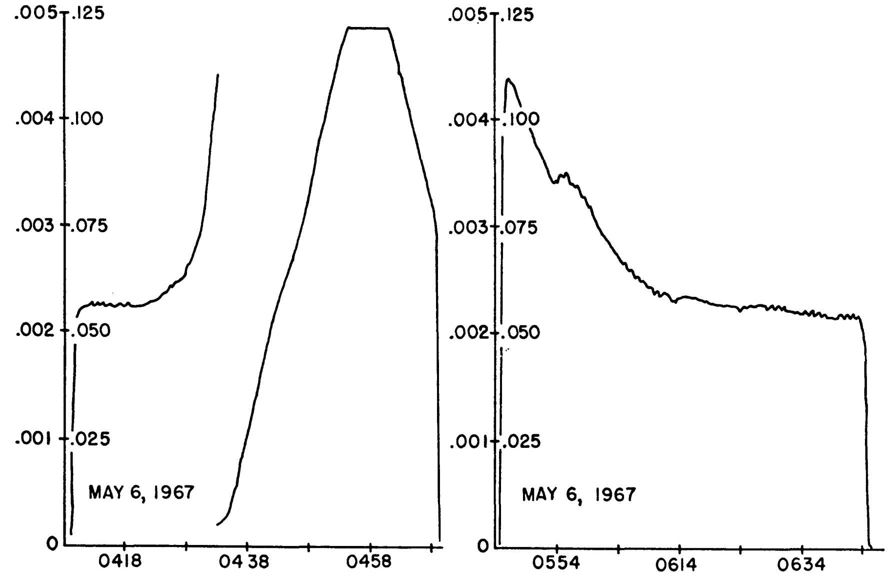

Fig. 12. Soft X-ray flux curve for importance-3n flare (S21 W35) on May 6, 1967. Note change of scale at 04^h33^m. Record is off-scale between 05^h45^m and 05^h00^m. High-sensitivity operation only between 05^h44^m and 06^h44^m. Sunrise and sunset at beginning and end of each record.

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

B. TIMES OF MAXIMA: TRAPPING OF ELECTRONS

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

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

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

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

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

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

we calculate that

$$2 \leqslant t_D \leqslant 240 \text{ sec}. \tag{11}$$

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

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

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

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

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

5. Summary

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

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

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

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

Acknowledgments

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SOFT SOLAR X-RAYS AND SOLAR ACTIVITY

II. Relation of Solar Soft X-Radiation to the Course of Solar Activity March 10, 1967 - May 18, 1969

Summary

The performance of the Michigan OSO-III X-ray ion chamber has been evaluated elsewhere in this report. Briefly: the instrumental energy scale remained stable to within a few percent during the interval March 10, 1967, at least through April, 1968. Thus a long-term analysis of the data obtained by it and a comparison of these data with the detailed course of solar activity could be instructive and meaningful.

We have, accordingly, assembled our soft X-ray data into summary form and have related it to detailed optical and radio records of solar activity obtained and compiled at the McMath-Hulbert Observatory. The comparison covers the time period March 10, 1967, through May 18, 1968.

The summary X-ray records are shown graphically in Figures 1 through 9. These summaries were prepared by students from our original data, which were computer-drawn plots of X-ray flux vs. time, in the following way. The original plots were scanned by individuals who noted time-breaks that were due to (1) satellite night, (2) tape-recorder playback, (3) particle interference, or (4) other causes such as noise. For a given uninterrupted data segment the starting time, ending time, maximum flux, and minimum flux during that time segment were recorded. Information for all data segments of whatever time length were then punched on cards and used as input to a computer program which prepared the data summaries in graphical form.

These summaries (Figures 1 through 9) are plotted in 27-day blocks which correspond to "Bartels days." The maximum flux and minimum flux are plotted as short horizontal lines of length equivalent to the length of the data segment, and both are joined by a vertical line placed at the middle of the time interval. Data segments shorter than 8 min were not plotted, because of the small time-scale used in the summaries.

Apparent in the figures is the slow fluctuation of X-ray background associated with the general level of activity on the visible solar hemisphere. High background levels are seen during disk passages of great centers of activity in late March and early April, late May, late July and early August, mid-December, 1967, and in late January and early February, 1968. These vari-

ations and the others which are apparent in the data summaries have been associated by us with the appearance and detailed behavior of active centers on the sun.

X-ray enhancements on a time scale of many hours are seen in association with great flares such as the PCA flares of March 22 and May 23, 1967, and with flares having significant gradual-rise-and-fall or prolonged post-burst enhancements at centimeter wavelengths such as on May 3, May 26, late on August 18, and on September 19, 1967. Long enduring X-ray enhancements are also seen in connection with verified major loop prominence systems such as those on June 1, and October 30 and 31, 1967. In addition there are curious, long-enduring but minor X-ray events such as those on February 22-23 and March 19, 1968 (and a few major ones like that of June 3, 1967), which have no clearly identifiable optical counterpart. Some of these may be associated with flares behind the sun's limb, as was the case early on August 18, 1967.

Flare-associated spikes stand out on the summary graphs. Not all the flares during the depicted time interval are represented, since many were missed by OSO-III, and not all flare-associated spikes portray the true X-ray amplitude because in numerous cases the X-ray maximum was missed. In terms of the total rate of flaring, the great regions of July-August, 1967, are well-portrayed by numerous spikes. The great δ spot group of January-February, 1968, on the other hand, was not so productive of flares having significant X-ray enhancements, although that region provided the highest background flux during the 14 months analyzed here.

Differences in endurance of X-ray emission following flares can be seen for the events of April 26, May 6, and May 10, and for the flare on May 3, all in 1967. The former three flares were all short-lived as X ray events, and all occurred in the same plage region, while the latter event occurred in a separate plage and was protracted over many hours. We have found that certain active centers consistently give rise to flares accompanied by short X-ray bursts while others are characterized by flares having relatively long-enduring X-radiation.

These data have been discussed _in extenso_ in a paper now being prepared.

FIGURE CAPTIONS

Figures 1-9. Summary of solar soft x-ray flux. For each data-interval the maximum observed flux and minimum observed flux are plotted and joined by a vertical line. Data intervals shorter than 8 min have been omitted. The flux scale is logarithmic. The abscissa is divided according to "Bartels days."

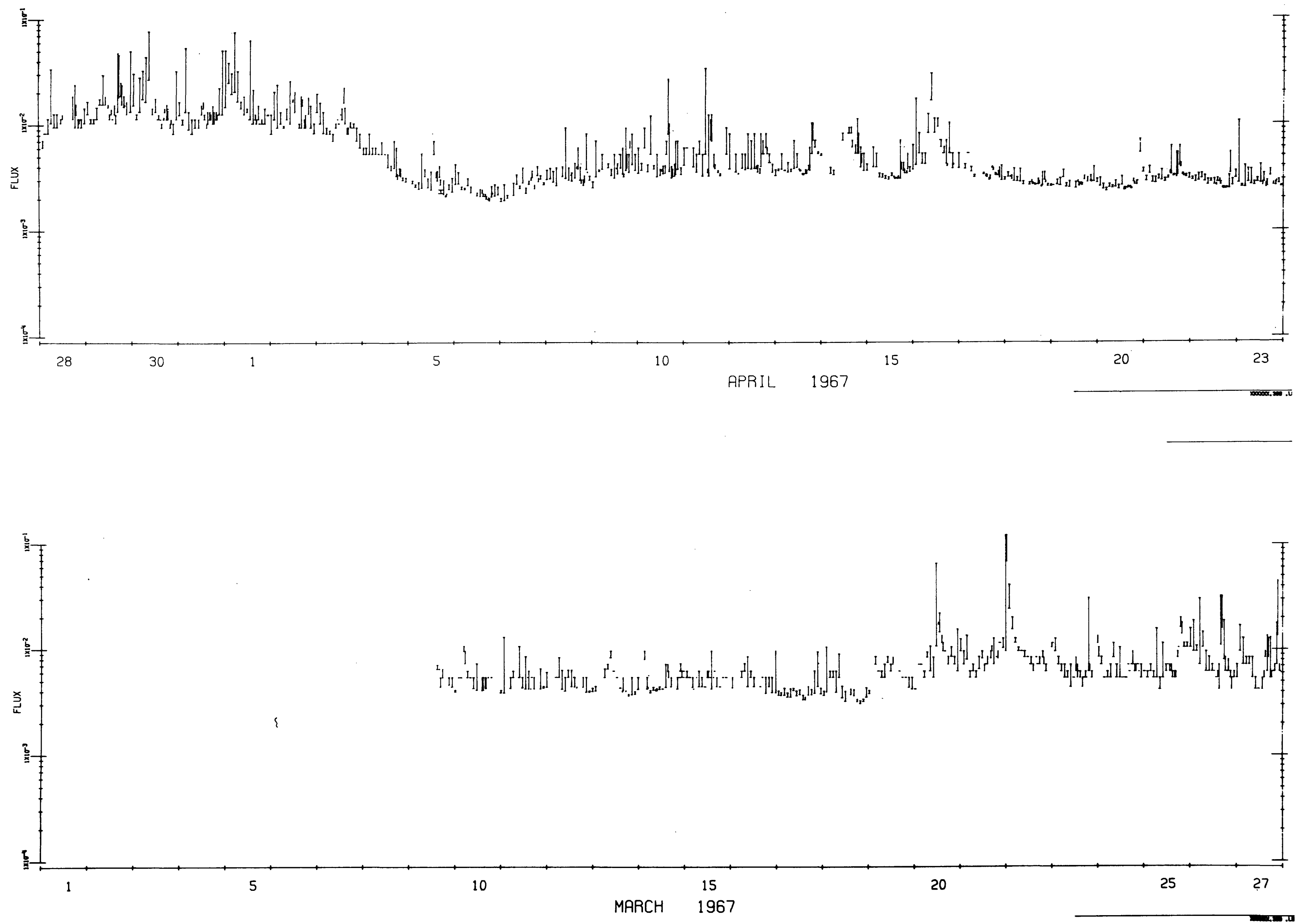
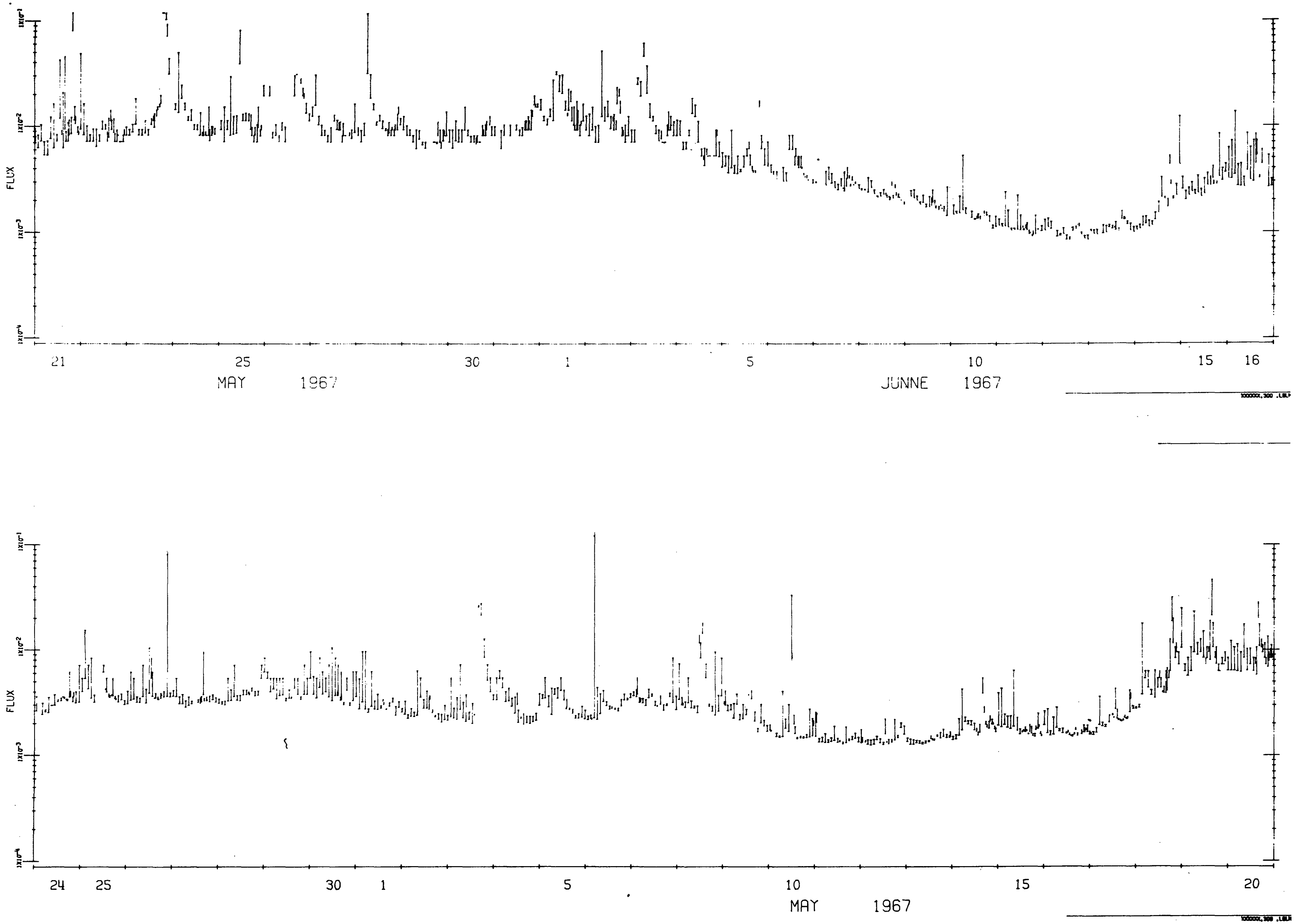
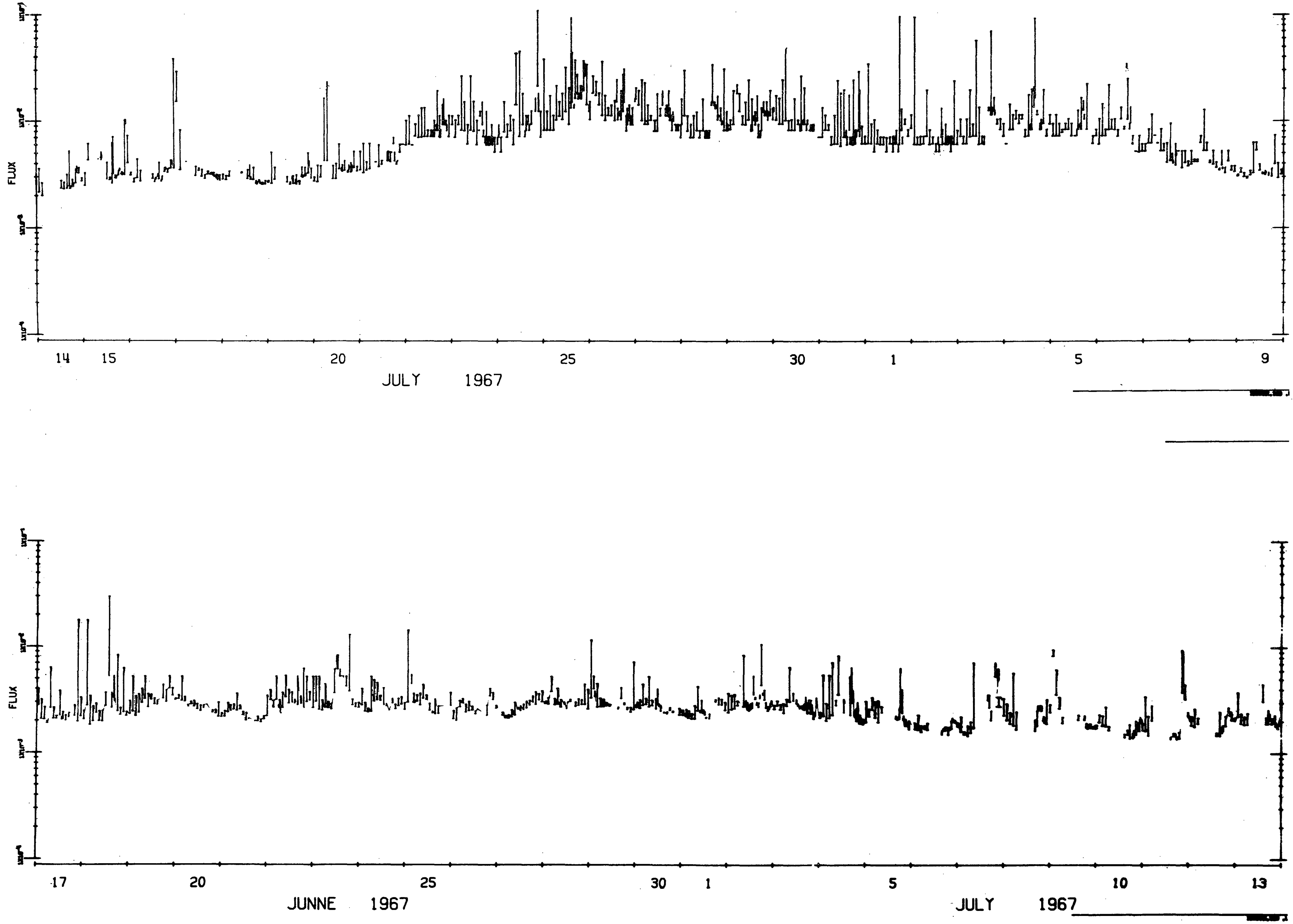

FLUX
1X10⁻¹
1X10⁻²
1X10⁻³
1X10⁻⁴
28
30
1
5
10
15
20
23
APRIL 1967
1
5
10
15
20
25
27
MARCH 1967

Figure 1



FLUX
21
25
30
1
5
10
15
16
MAY 1967
JUNNE 1967
FLUX
24
25
30
1
5
10
15
20
MAY 1967

Figure 2


FLUX
14
15
20
25
30
1
5
9
JULY 1967
FLUX
17
20
25
30
1
5
10
13
JUNNE 1967
JULY 1967
Figure 3

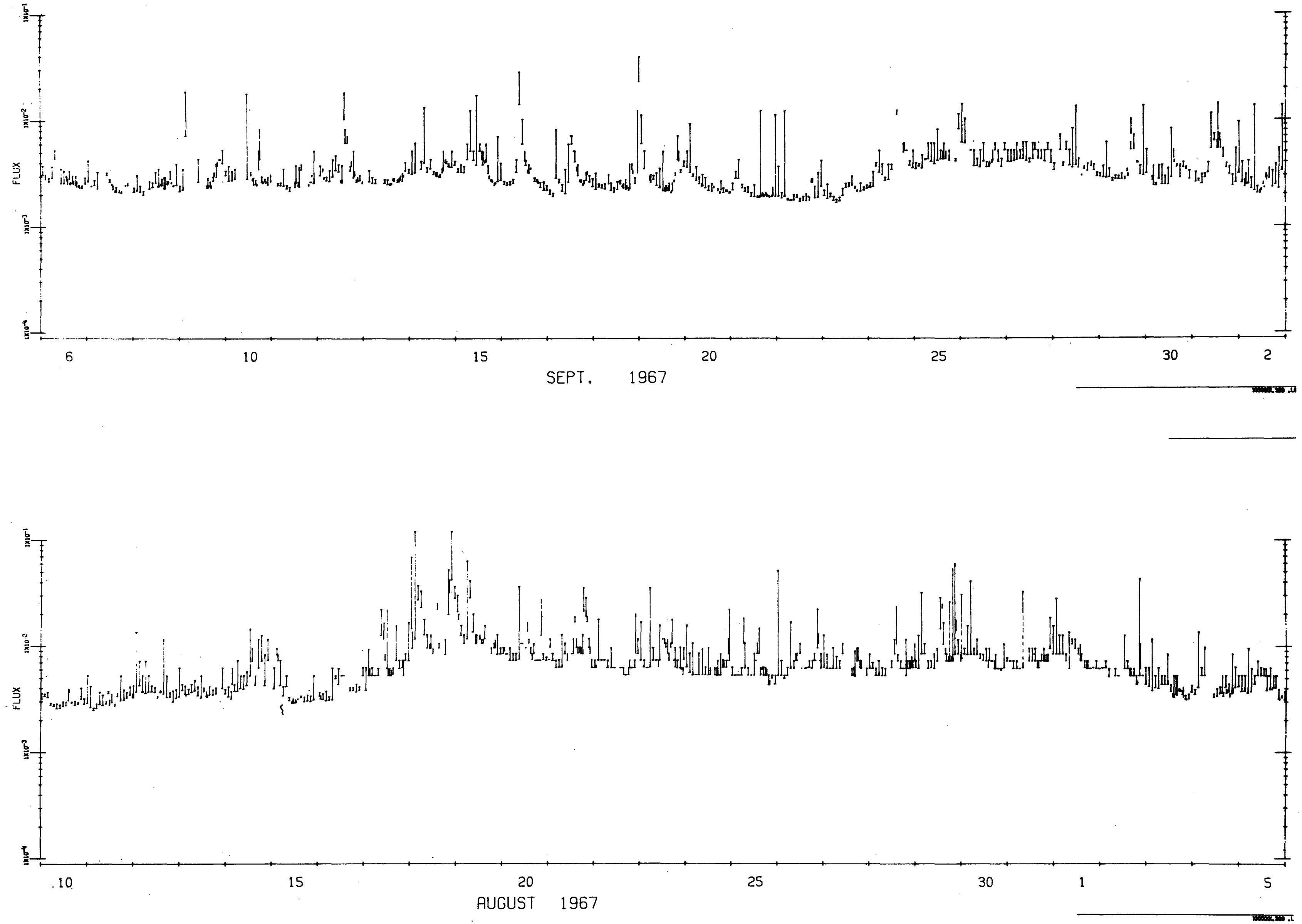

FLUX
6
10
15
20
25
30
2
SEPT. 1967
FLUX
10
15
20
25
30
1
5
AUGUST 1967

Figure 4

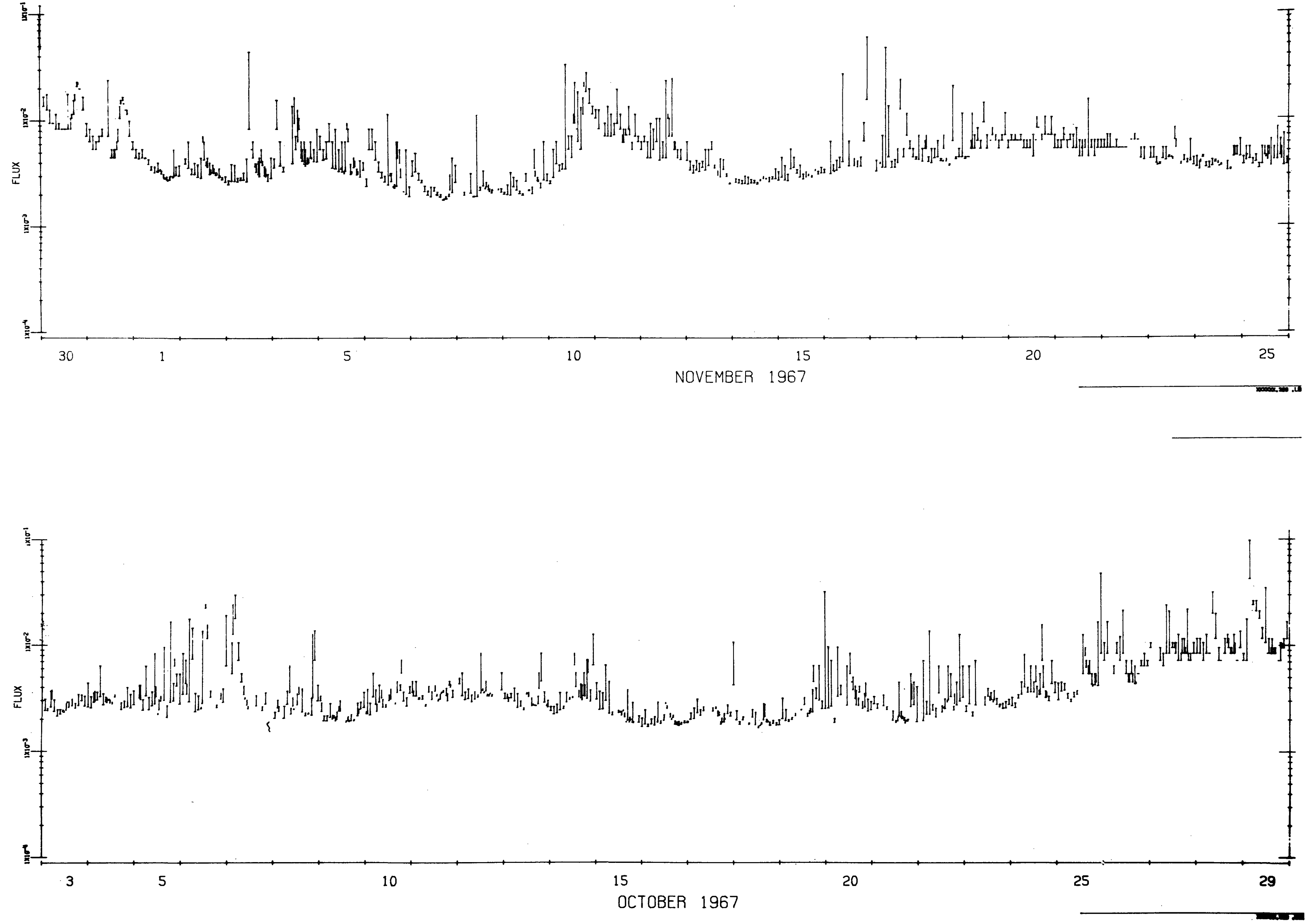
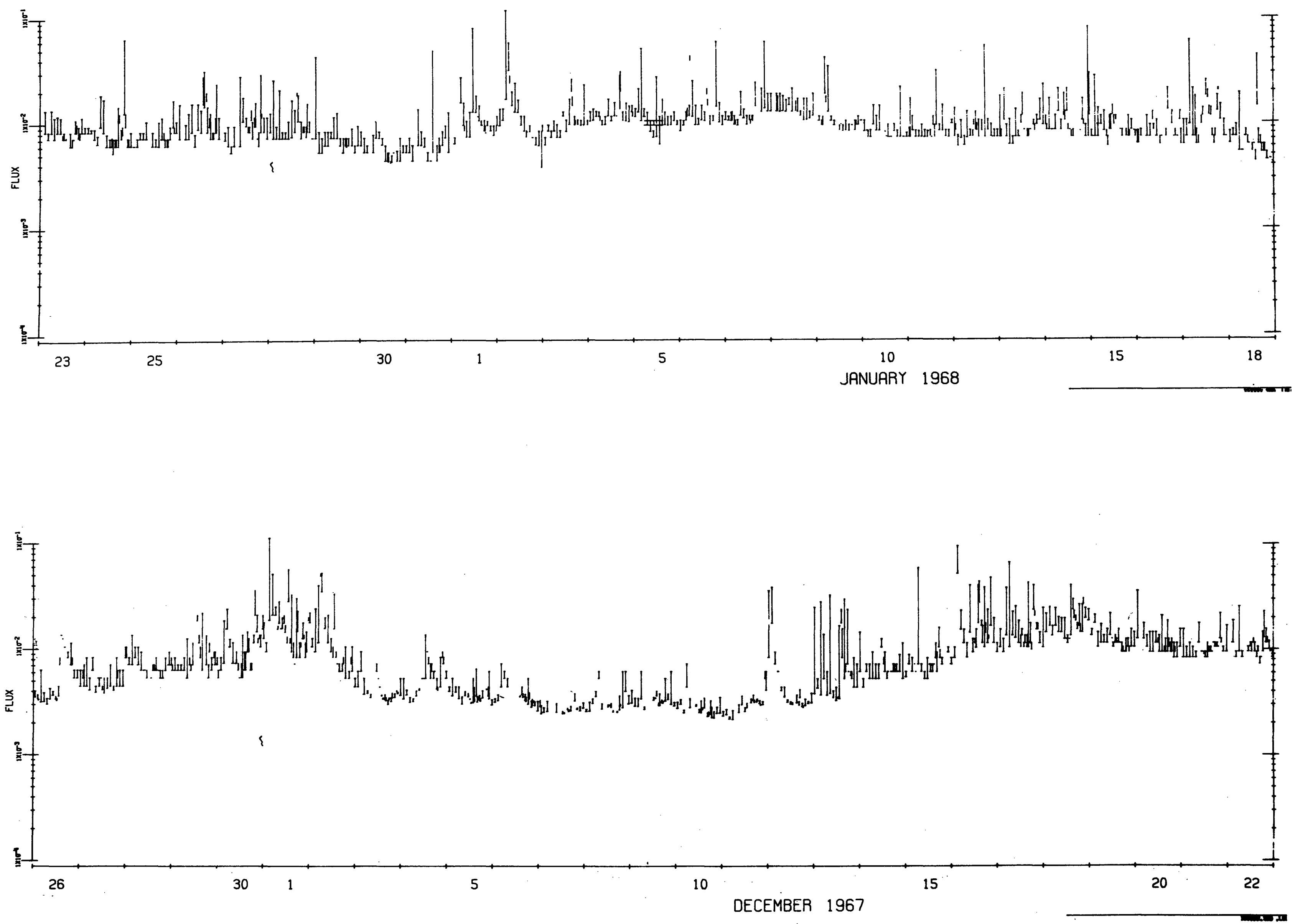

FLUX
30
1
5
10
15
20
25
NOVEMBER 1967
FLUX
3
5
10
15
20
25
29
OCTOBER 1967

Figure 5



1X10⁻¹
1X10⁻²
1X10⁻³
1X10⁻⁴
FLUX
23
25
30
1
5
10
15
18
JANUARY 1968
26
30
1
5
10
15
20
22
DECEMBER 1967

Figure 6

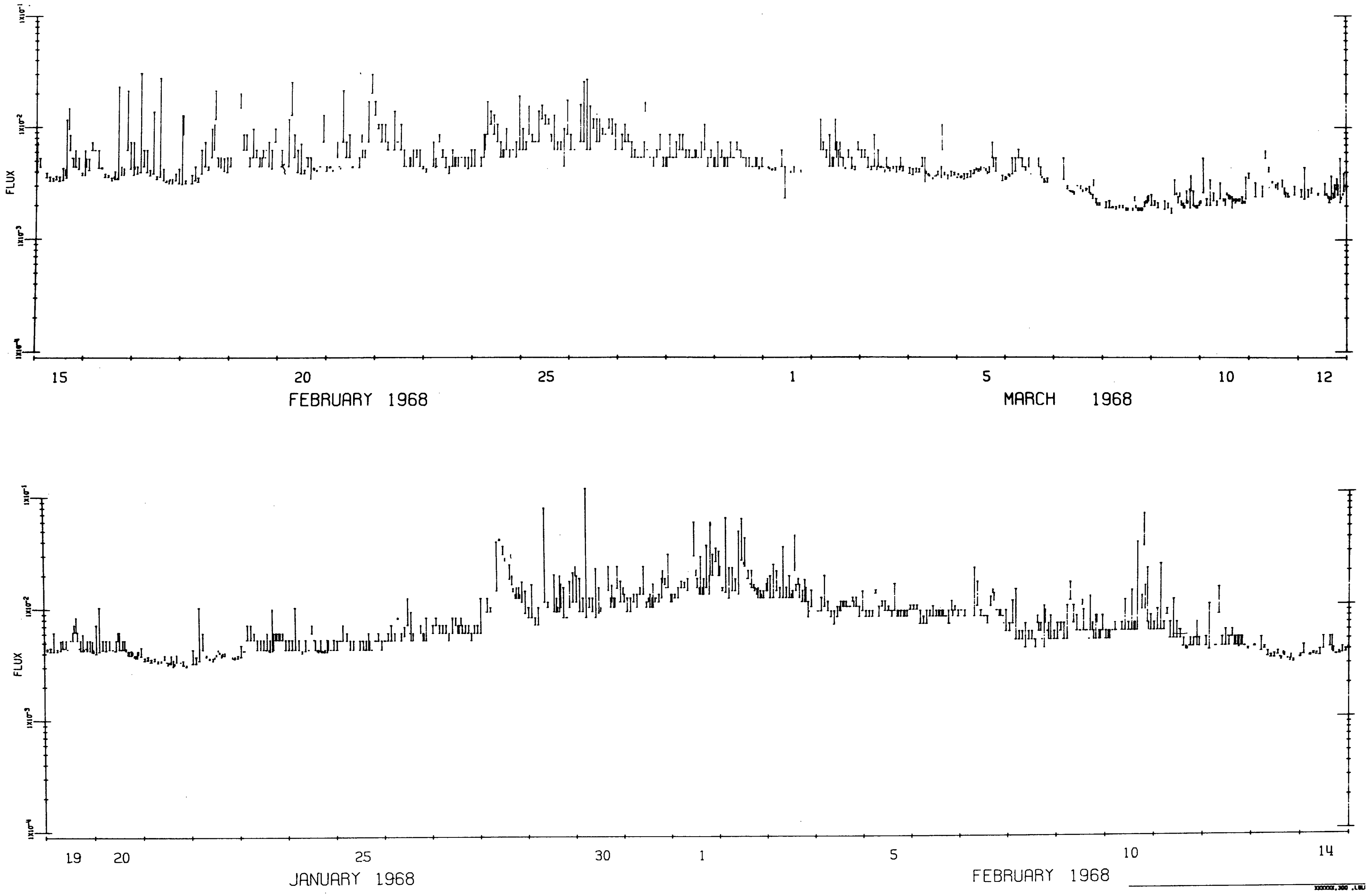

FLUX
1X10-1
1X10-2
1X10-3
1X10-4
15
20
25
1
5
10
12
FEBRUARY 1968
MARCH 1968
19
20
25
30
1
5
10
14
JANUARY 1968
FEBRUARY 1968

Figure 7

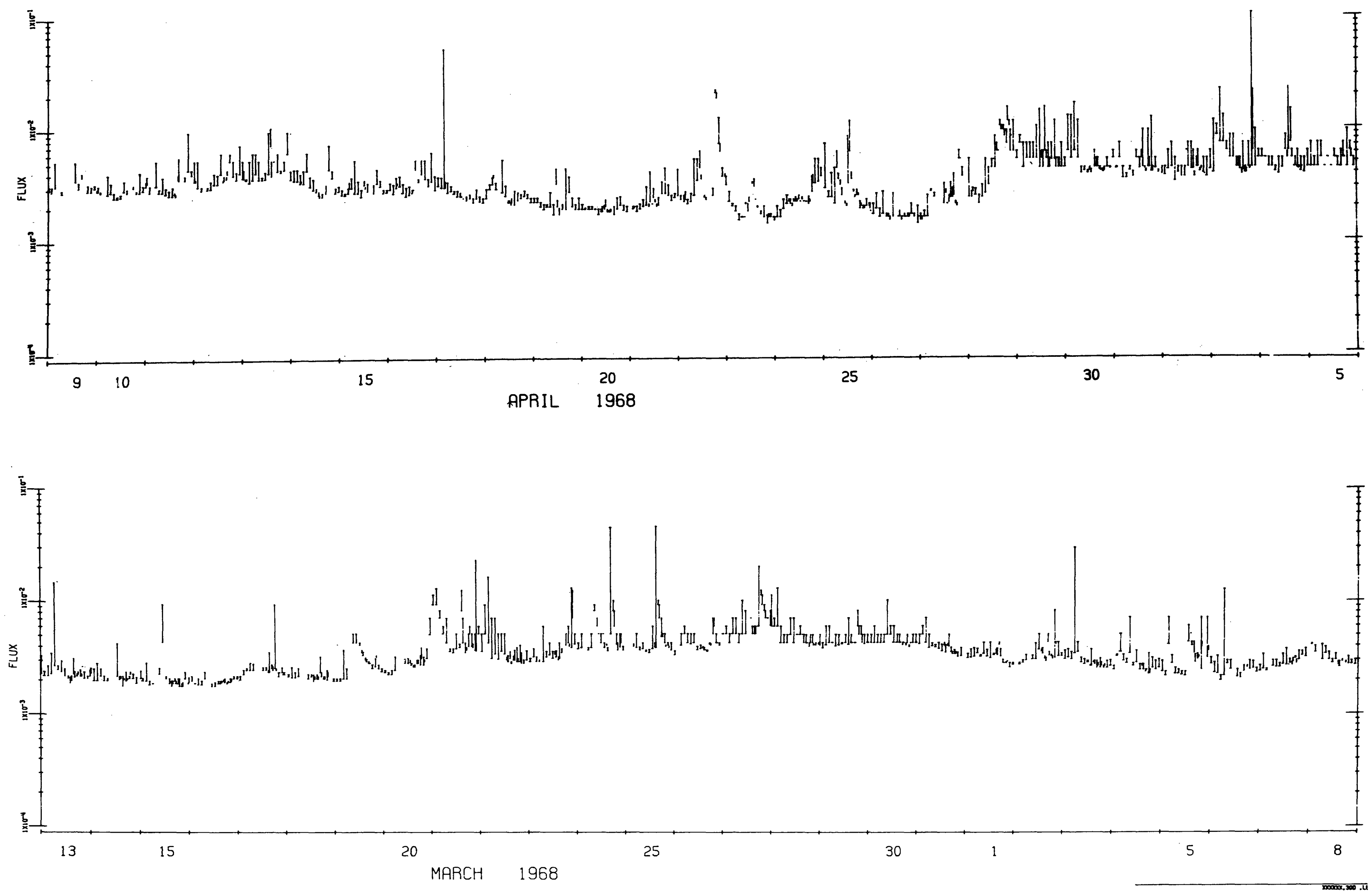

1X10⁻¹
1X10⁻²
1X10⁻³
1X10⁻⁴
FLUX
9
10
15
20
25
30
5
APRIL 1968
13
15
20
25
30
1
5
8
MARCH 1968

Figure 8

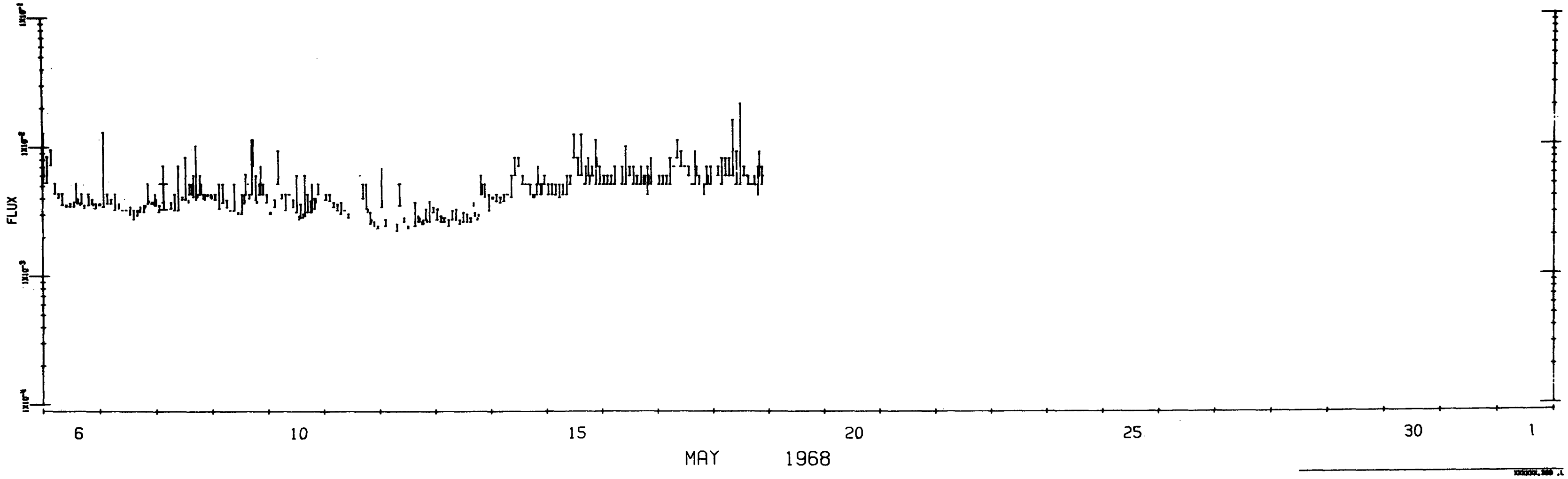


Figure 9

SOFT SOLAR X-RAYS AND SOLAR ACTIVITY

III. Relationship of 8-12 Å Solar X-Ray Background to Other Indices of Solar Activity

March 10, 1967 - April 30, 1968

Summary

For this study we have defined a daily soft X-ray background flux level as being the lowest flux recorded during ach day, and have designated it as the "daily base level" $E_B(8,12)$ ergs $cm^{-2}sec^{-1}$, as measured at the earth. This definition is dictated by the extreme sensitivity of soft X-radiation to minor activity on the sun. Since even sub-flare-associated enhancements may disturb the observed flux levels for up to a half-hour and more, and since subflaring may be nearly continuous at some times, we are obliged to seek a a background flux that may only be fleetingly observable. In practice, the base-level was measured only between the Universal hours 0600-2200, for two reasons: (1) the other indices of solar activity which were used in this study were based upon data gathered between 0500-2000 UT, generally; (2) occasionally the base level is reached at around 2400 UT, and thus a measurement obtained then would be applied to two dates without respect to changes that might take place at later times.

The other indices of solar activity used in this study are listed in Table I. Except for the plage index, all were taken from the Solar-Geophysical Data Bulletins, and all corrections published in the Bulletins were applied to the data. In addition, the radio fluxes were reduced to values as observed from the earth, uncorrected for eccentricity of the earth's orbit. The plage index used is prepared at the McMath-Hulbert Observatory from daily Calcium K spectroheliograms. It is the sum of the areas of calcium plages (in millionths of a solar hemisphere) weighted individually by their intensity excess above background chromospheric intensity, $\Sigma A_j \times I_j$, and is an indicator of the total excess flux in the Ca II K line due to all visible plages.

The daily indices for the interval March 10, 1967, through April 30, 1968, are portrayed graphically in Figures 1 through 16. In those diagrams, the data are displayed in 27-day blocks, based upon "Bartels days," and separate ordinate scales are supplied for each index as indicated on the left-hand side of the figures. The daily plage indices have been scaled down by multiplying them by 0.01. (In Figures 4 through 16, data for the first date in each diagram were erroneously deleted by the computer.)

TABLE I

CORRELATION COEFFICIENTS FOR THE INTERVAL
MARCH 10, 1967 - APRIL 30, 1968

Data Pair	Correlation Coefficient
8800 MHz / $E_B(8,12)$	0.828
4995 MHz / $E_B(8,12)$	0.784
2800 MHz / $E_B(8,12)$	0.886
2695 MHz / $E_B(8,12)$	0.863
1415 MHz / $E_B(8,12)$	0.779
606 MHz / $E_B(8,12)$	0.657
Rz / $E_B(8,12)$	0.698
Σ A x I / $E_B(8,12)$	0.726
2800 MHz / Rz	0.832
Σ A x I / 2800 MHz	0.825
Rz / Σ A x I	0.739

Correlation coefficients have been calculated from the 14 months of data and are listed in Table I. The correlations of soft X-ray background with the radio indices are in good agreement with those obtained by Wende and Van Allen for the 2-12 Å flux as observed on Mariner V during a three-month interval in 1967. We have plotted the observed relationship between daily 2800 MHz flux and base-level X-ray flux in Figure 17. This figure shows that the high correlation that was obtained depends heavily upon data points measured at lower levels of solar activity. It is not clear whether the scatter of points at higher activity levels is an indication that in many instances the true base-level of X-rays was not seen, or whether the scatter is a real one.

Although the time-base of 14 months in our analysis is only about 0.1 of a solar cycle, we attempted to determine whether the data showed any indication of an evolution of the statistical relationships between indices. An indication of a secular change might, for example, suggest whether long-term changes in the total coronal emission measure occur. Accordingly, we divided our data into four partially-overlapping time intervals and calculated linear least-squares fits to pairs of the indices. The form of the regression was

$$y \text{ (any index)} = a + b \cdot E_B(8,12) \qquad (1)$$

The coefficients a and b for the four time intervals are given in Table II. We also show some of the results graphically in Figures 18 and 19.

TABLE II

COEFFICIENTS OF LEAST-SQUARES FITS TO PAIRS OF DAILY SOLAR INDICES

Data Pair		Time Interval: Mar. 10, 1967- July 31, 1967	June 1, 1967- Oct. 31, 1967	Aug. 1, 1967- Dec. 31, 1967	Nov. 1, 1967- Apr. 30, 1968
8800 MHz / $E_B(8,12)$	a =	263	271	286	268
	b =	9057	8102	7394	11890
4995 MHz / $E_B(8,12)$	a =	130	141	156	158
	b =	11080	10140	10240	13570
2800 MHz / $E_B(8,12)$	a =	96.6	98.5	106	99.8
	b =	9822	9514	8652	11390
2695 MHz / $E_B(8,12)$	a =	94.4	96.2	99.4	98.7
	b =	9346	8561	9193	11120
1415 MHz / $E_B(8,12)$	a =	60.8	63.9	70.8	66.6
	b =	4893	4056	4126	6727
606 MHz / $E_B(8,12)$	a =	51.5	54.2	56.4	55.5
	b =	2001	1300	1565	3202
Rz / $E_B(8,12)$	a =	33.4	45.1	55.9	54.7
	b =	11240	10420	9771	10580
$\sum A \times I$ / $E_B(8,12)$	a =	13020	14030	16540	13400
	b =	2.03×10^6	1.80×10^6	1.47×10^6	2.36×10^6

These regressions appear to show a slight trend which is consistent within the different pairs of indices, but which must be viewed with considerable caution. While there is fairly good agreement among the regressions for the 1967 data, the data for the time interval November 1, 1967, through April 30, 1968, suggest that, at the higher solar activity levels as indicated by, for example, the 2800 MHz flux, the background X-ray base level was below what might have been expected on the basis of the sun's performance in 1967. We can think of three explanations for this: (1) The ion chamber lost sensitivity in early 1968. However, in-flight calibrations show no electrical deterioration, and data obtained into 1969 do not indicate that filling gas was being lost from the ion chamber. (2) The true base level was being measured in 1968 because of a decline in total flare rate, and the true base level was not always obtained in 1967 becasue of the high rate of flaring when great active centers were present on the sun. (3) The observed effect is reflecting conditions on the sun associated with the dramatic decline in rate of flaring after mid-February, 1968.

There are also statistical reasons for caution about inferring evolutionary trends from the regressions. The linear form that was chosen is only an approximation to the true relationships (see, e.g., Figure 17). Further, the scatter of data points at higher levels of activity introduces an error into each coefficient a and b.

Auto-correlation curves have been calculated for $E_B(8,12)$, R_Z, $\Sigma A_j \times I_j$, and the 2800 MHz daily flux, see Figures 20 through 23. While the latter three indices show a negative minimum in their auto-correlations at lags near 14 days, the $E_B(8,12)$ auto-correlation does not dip to negative values but shows a small positive minimum near a lag of 16 days. One possible interpretation of this is that the X-radiation arises from levels high enough in the corona to be easily detected even when the underlying plage is approximately one day's rotation beyond the sun's limb. As regards the relative amplitudes of the maximum near 25 days and the minimum near 42 days, the X-ray curve behaves most nearly like that for the plage index, emphasizing the close association of soft X-ray emission with Ca II K structure which is revealed by direct X-ray photography. Again, however, the positions of the maxima and minima in these two curves suggest a high atmospheric level for the X-ray source volume.

Cross-correlation analyses have been carried out for lags between minus and plus two solar rotations. These are displayed in Figures 24 through 29. The sense of the lags is given in the figure captions.

These cross-correlations reproduce for the solar X-radiation the familiar influence of sunspots upon the extent and lifetime of their associated plage regions, in the sense that the more extensive spot groups, which strongly contribute to R_Z, are usually associated with larger, brighter, and longer-lasting plages (see Figures 25, 27, and 29), and are also thus associated with the most prominent X-ray source volumes. It is tempting to infer, from the amplitudes of the lagged peaks at ± 28 days in the cross-correlation of X-rays with the 2800 MHz flux (Figure 24), that the development curve of X-ray emission from evolving active centers tends to have a phase lag with respect to the development curve for the 2800 MHz radiation. However this effect, if real, is small.

FIGURE CAPTIONS

Figures 1-16. These diagrams graphically portray the daily variations of solar activity indices during the interval March 10, 1967 to April 30, 1968. The abscissa is divided according to "Bartels days." Separate ordinate scales are given for each quantity; all scales are linear. Generally the scales are such that the X-ray data appear as the lowest curve and the 606 MHz daily flux appears as the highest curve. (Beginning with Figure 4, data for the first date of each graph was accidentally omitted.) Radio fluxes are given in units of 10^{-22} watts m^{-2} Hz^{-1}.

Figure 17. The daily base level of soft X-ray flux is here plotted against the daily 2800 MHz flux level. The radio flux density is given in units of 10^{-22} watts m^{-2} Hz^{-1}.

Figure 18. Least-squares linear fits to segments of 14 months of data are shown. Here, the X-ray base level is compared with the daily McMath-Hulbert plage index.

Figure 19. Least-squares linear fits to segments of the 14 months of data are shown. Here, the X-ray base level is compared with the daily 2800 MHz flux.

Figures 20-23. Auto-correlation curves for daily solar activity indices and for the soft X-ray base level.

Figure 24. Cross-correlation of soft X-ray base level with daily 2800 MHz flux. Negative lags correspond to placing X-ray data upon <u>later</u> dates of the 2800 MHz data set.

Figure 25. Cross-correlation of soft X-ray base level with R_Z. Negative lags corresponding to placing X-ray data upon <u>later</u> dates of the R_Z data set.

Figure 26. Cross-correlation of soft X-ray base level with plage index. Negative lags correspond to placing X-ray data upon <u>later</u> dates of the Σ A x I data set.

Figure 27. Cross-correlation of 2800 MHz daily flux with R_Z. Negative lags correspond to placing 2800 MHz data upon <u>later</u> dates of the R_Z data sets.

Figure 28. Cross-correlation of the 2800 MHz daily flux with plage index. Negative lags correspond to placing 2800 MHz data upon <u>later</u> dates of the Σ A x I data set. This curve is normalized at zero lag. The maximum occurs at a lag K = -1 day.

Figure 29. Cross-correlation of plage index with R_Z. Negative lags correspond to placing $\sum$ A x I data upon later dates of the R_Z data set.

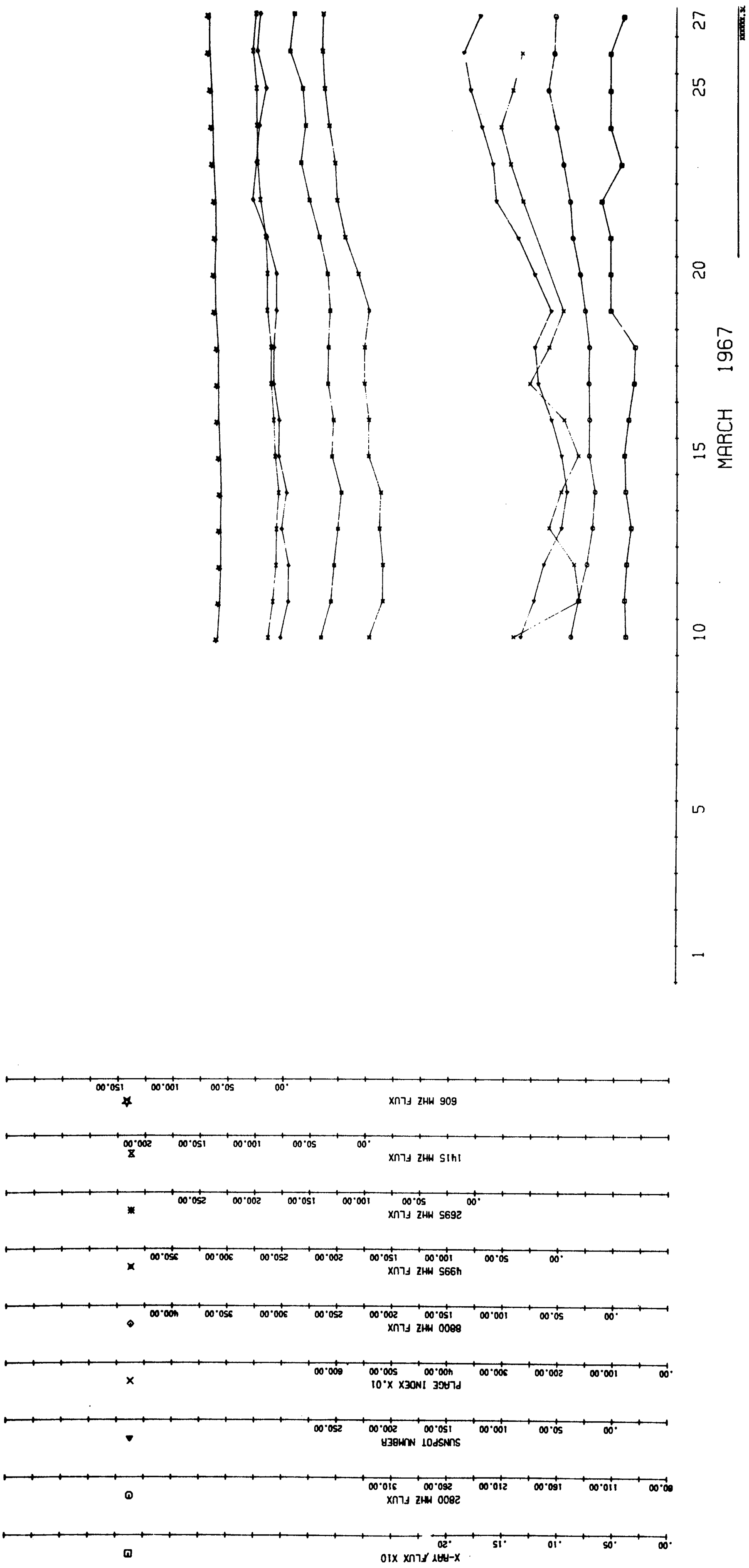

MARCH 1967
1
5
10
15
20
25
27
606 MHZ FLUX
1415 MHZ FLUX
2695 MHZ FLUX
4995 MHZ FLUX
8800 MHZ FLUX
PLAGE INDEX X.01
SUNSPOT NUMBER
2800 MHZ FLUX
X-RAY FLUX X10

Figure 1

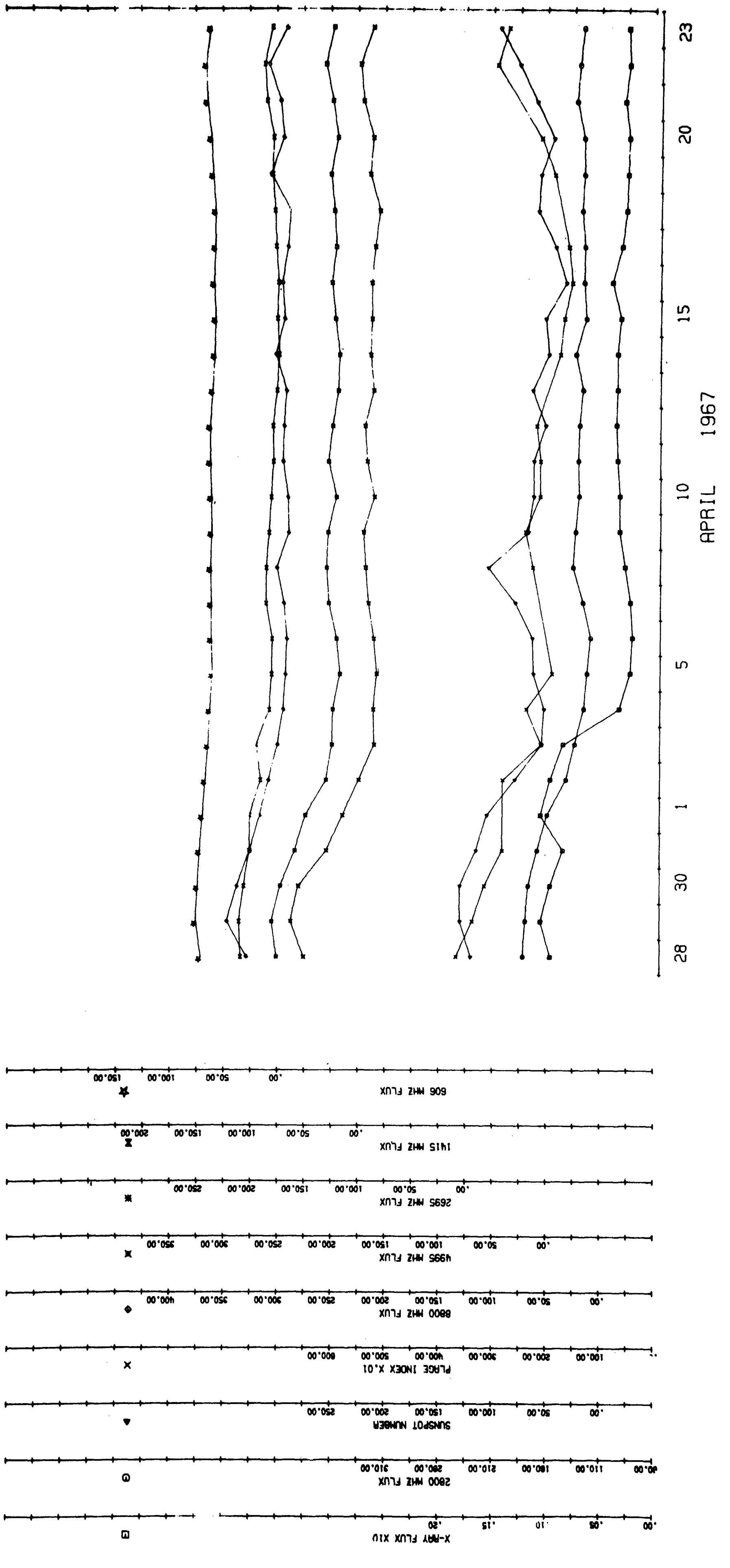

APRIL 1967
28
30
1
5
10
15
20
23
606 MHZ FLUX
1415 MHZ FLUX
2695 MHZ FLUX
4995 MHZ FLUX
8800 MHZ FLUX
PLAGE INDEX X.01
SUNSPOT NUMBER
2800 MHZ FLUX
X-RAY FLUX X10

Figure 2

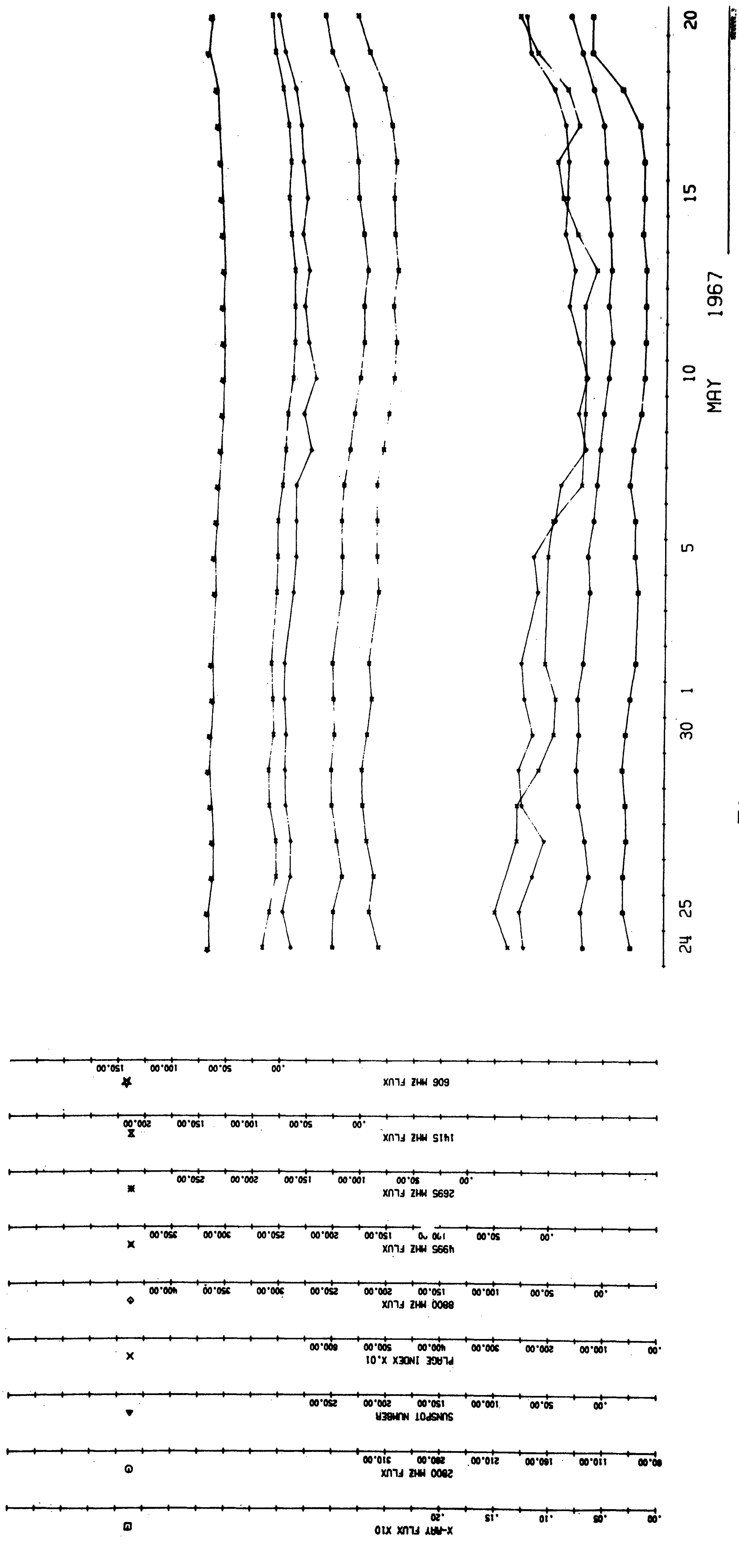

24 25 30 1 5 10 15 20
MAY 1967
X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
FLARE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX

Figure 3

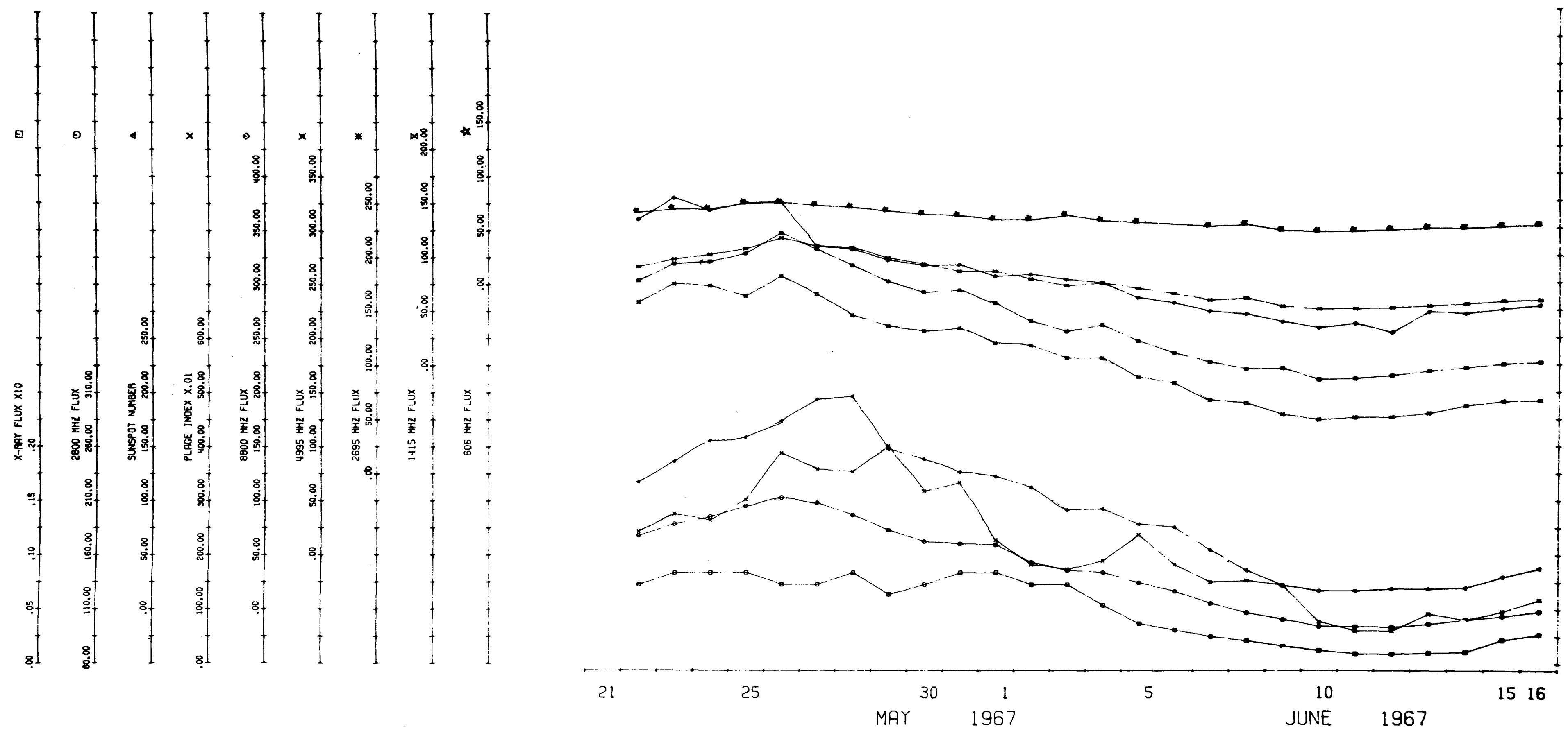
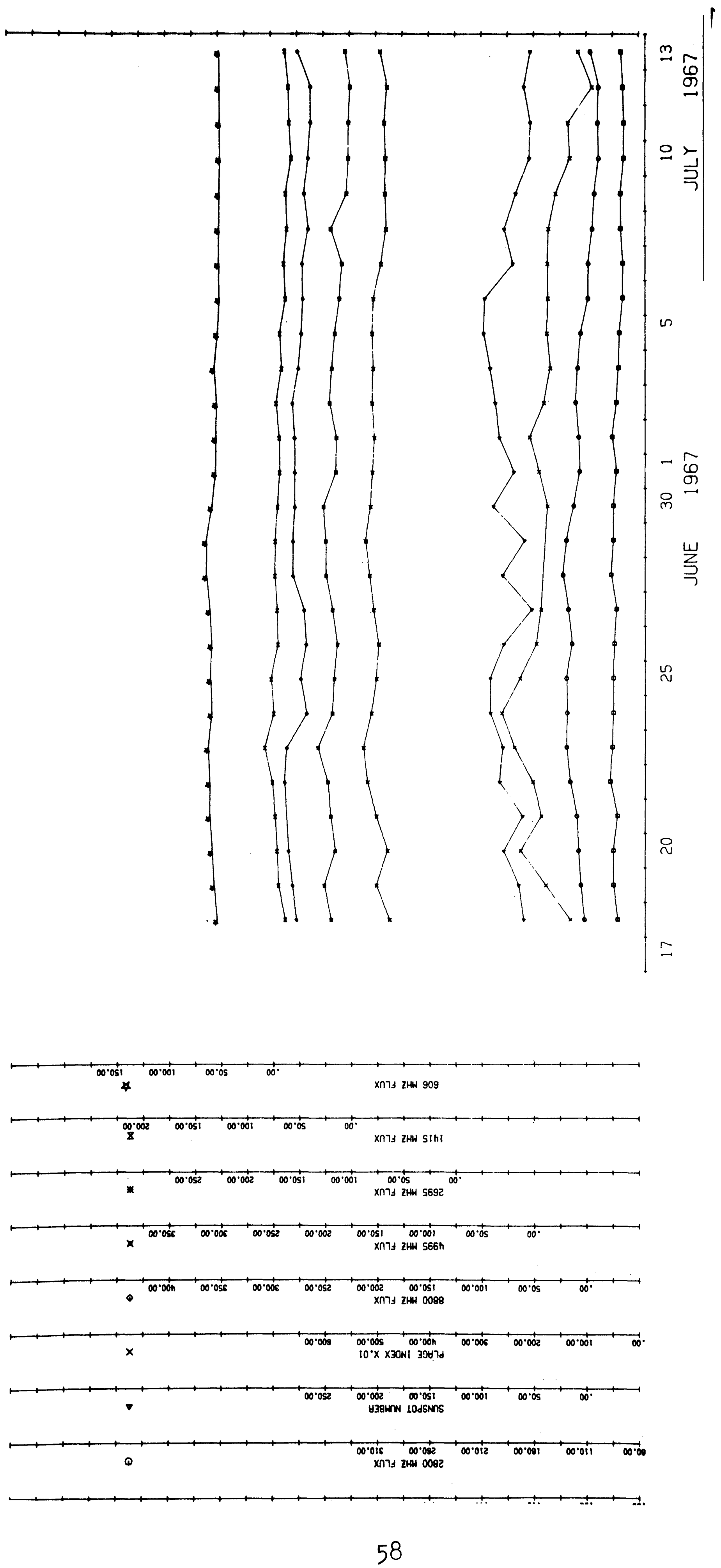
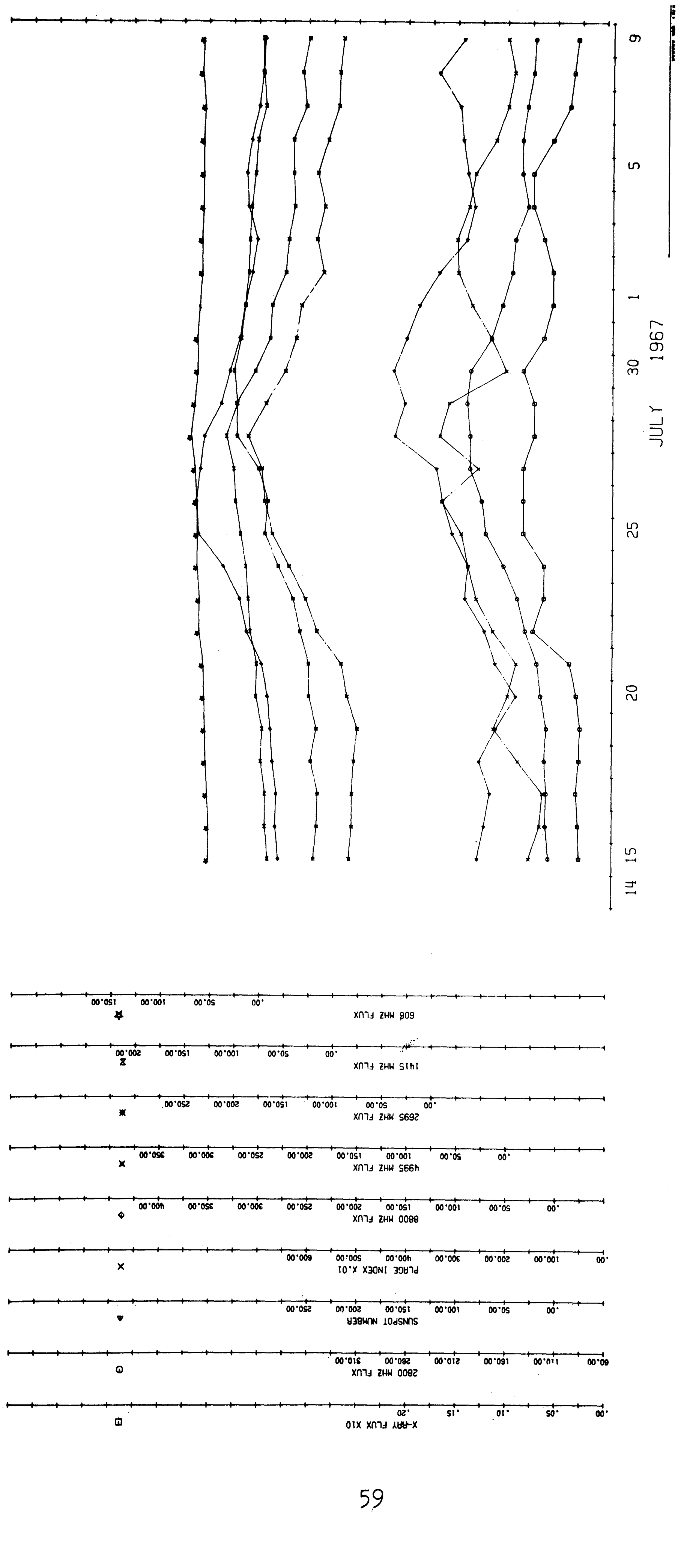

X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX
21
25
30
1
5
10
15 16
MAY 1967
JUNE 1967

Figure 4



17
20
25
30
1
5
10
13
JUNE 1967
JULY 1967
606 MHZ FLUX
1415 MHZ FLUX
2695 MHZ FLUX
4995 MHZ FLUX
8800 MHZ FLUX
PLAGE INDEX X.01
SUNSPOT NUMBER
2800 MHZ FLUX

Figure 5



JULY 1967
14
15
20
25
30
1
5
9
608 MHZ FLUX
1415 MHZ FLUX
2695 MHZ FLUX
4995 MHZ FLUX
8800 MHZ FLUX
PLAGE INDEX X.01
SUNSPOT NUMBER
2800 MHZ FLUX
X-RAY FLUX X10

Figure 6

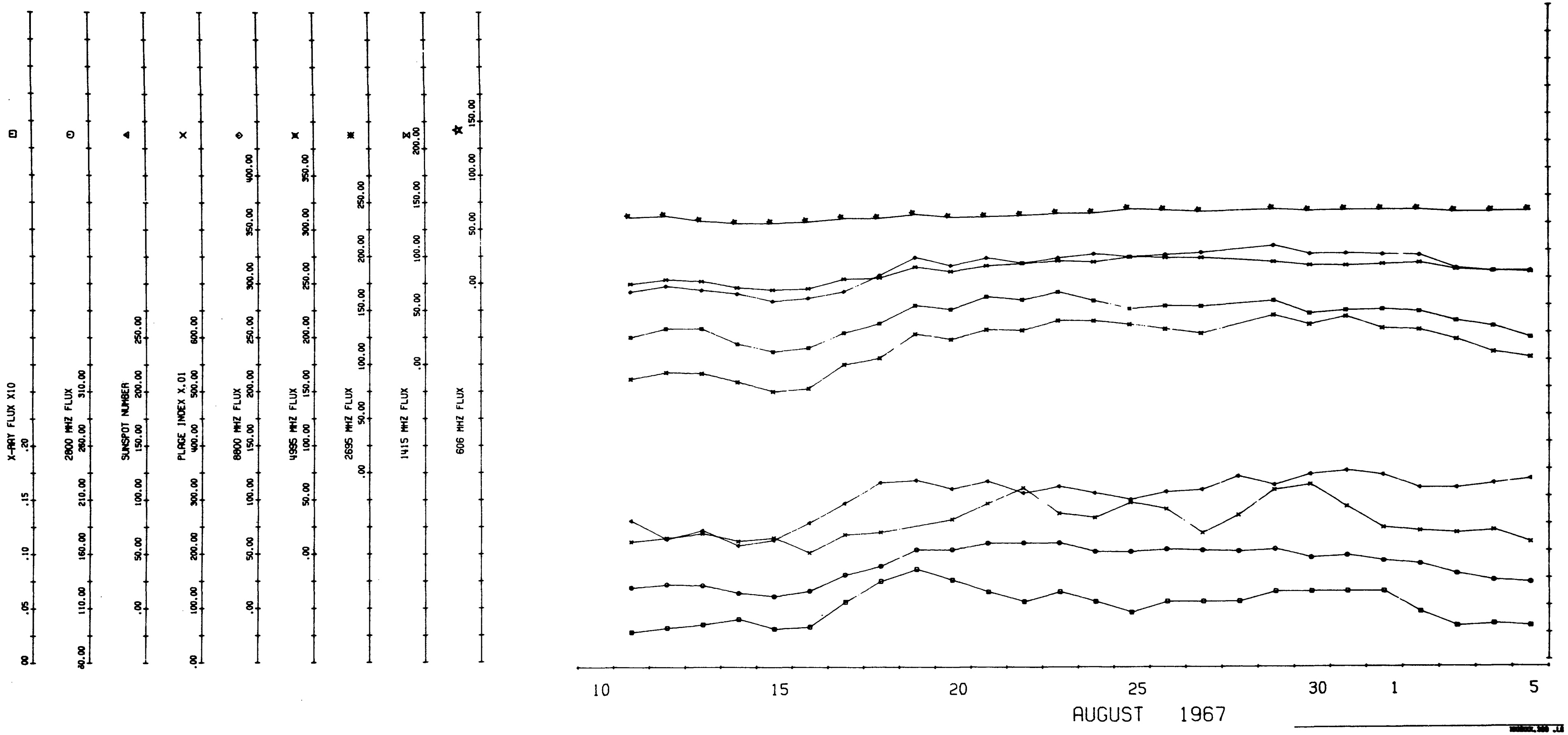

X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX
10
15
20
25
30
1
5
AUGUST 1967

Figure 7

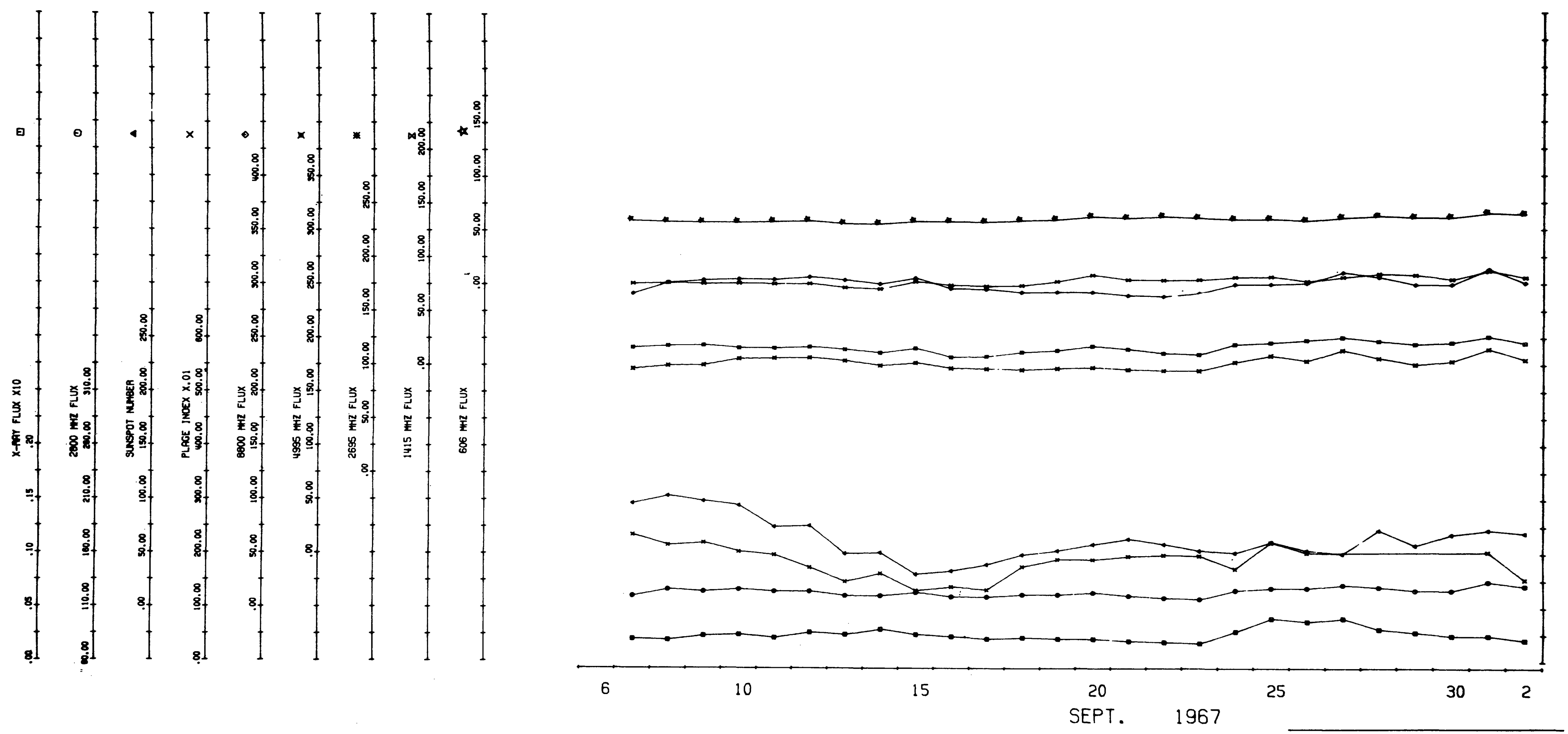

X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX
6
10
15
20
25
30
2
SEPT. 1967

Figure 8

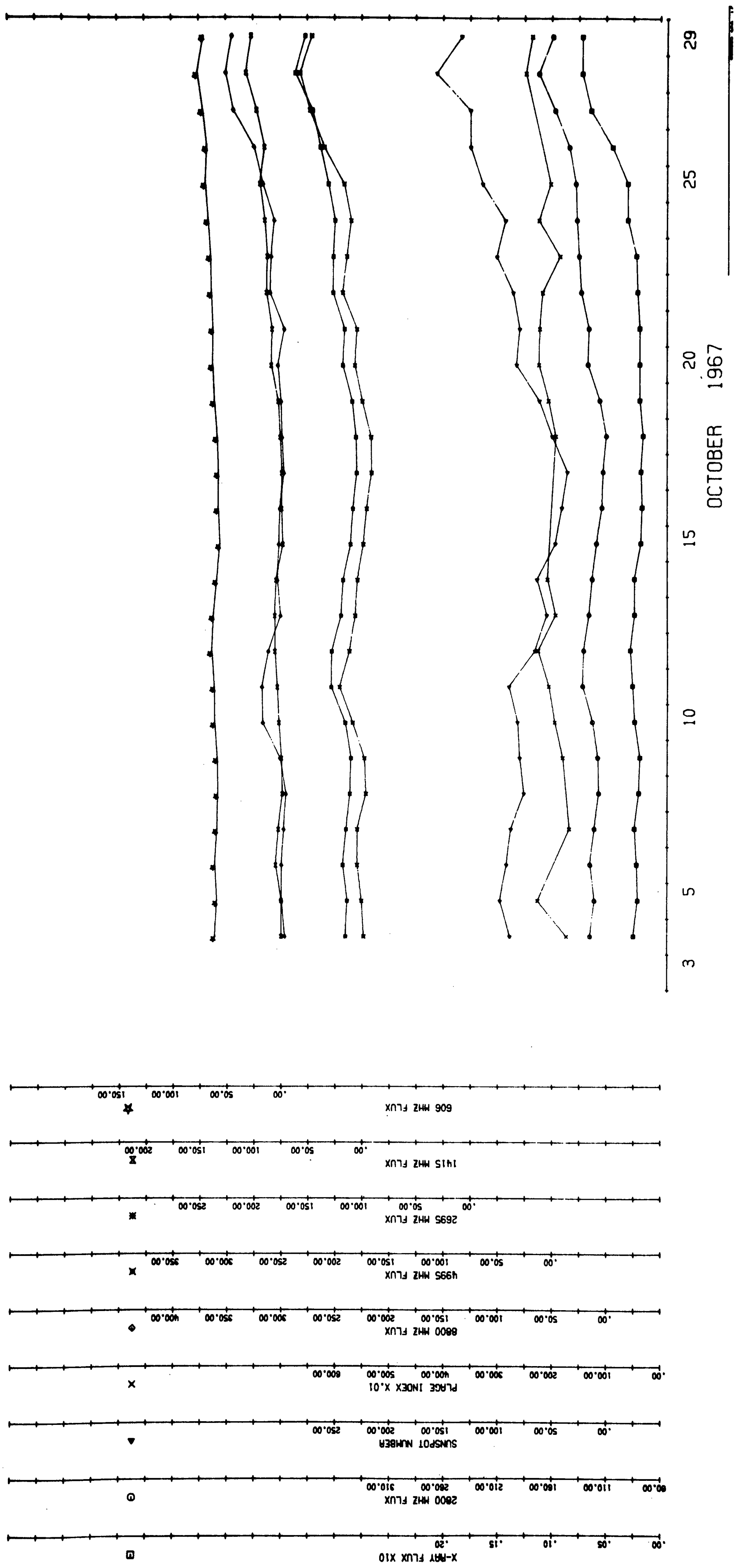

3
5
10
15
20
25
29
OCTOBER 1967
X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX

Figure 9

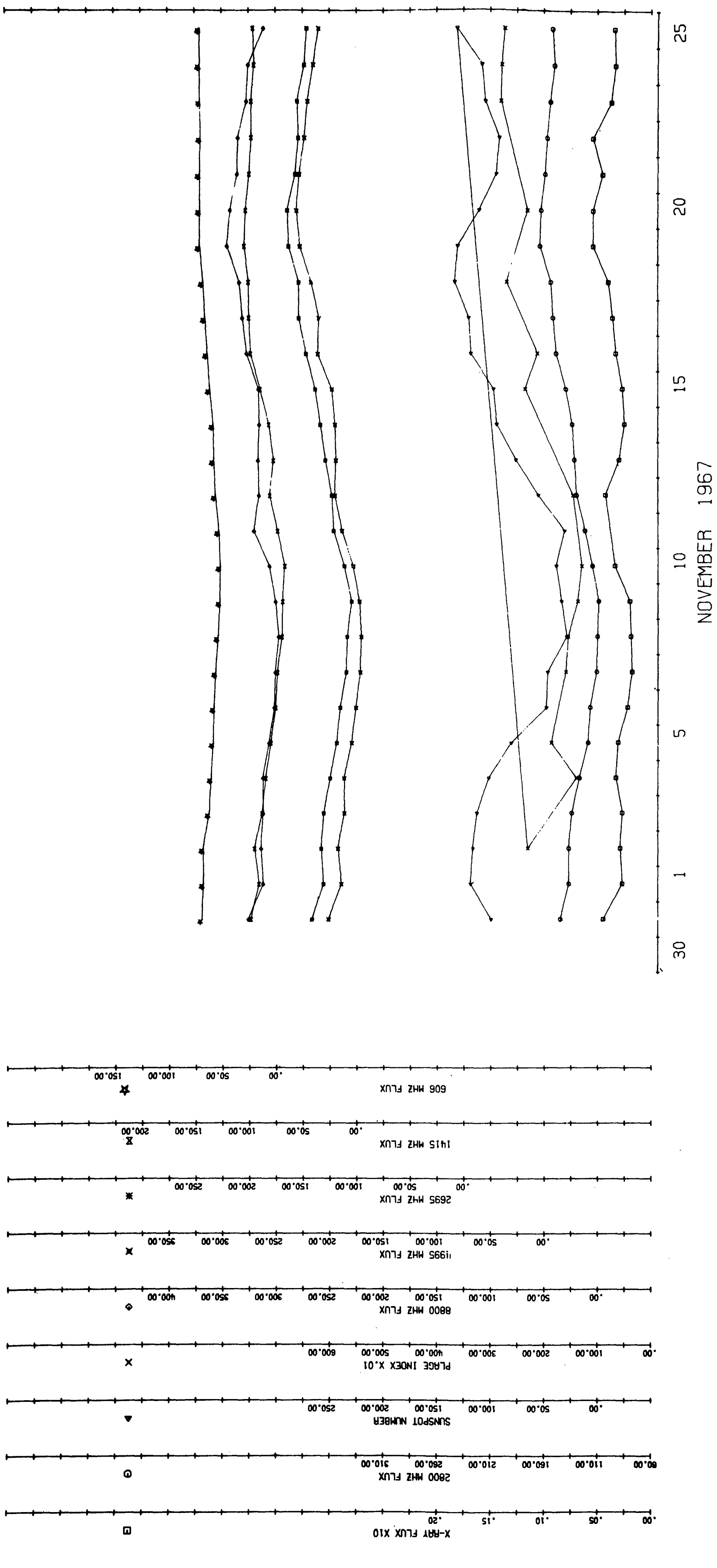

NOVEMBER 1967
X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
1995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX

Figure 10

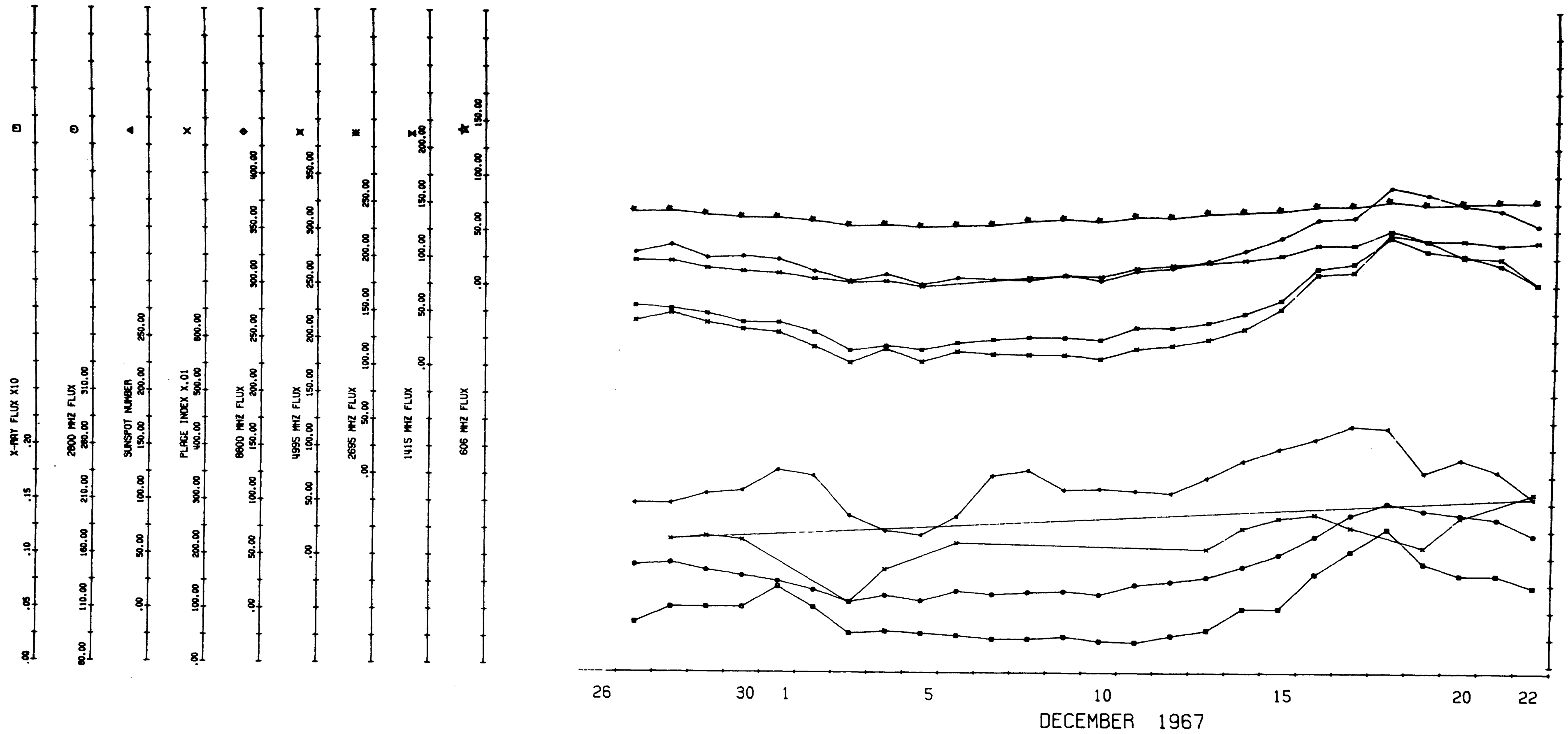

X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX
26
30
1
5
10
15
20
22
DECEMBER 1967

Figure 11

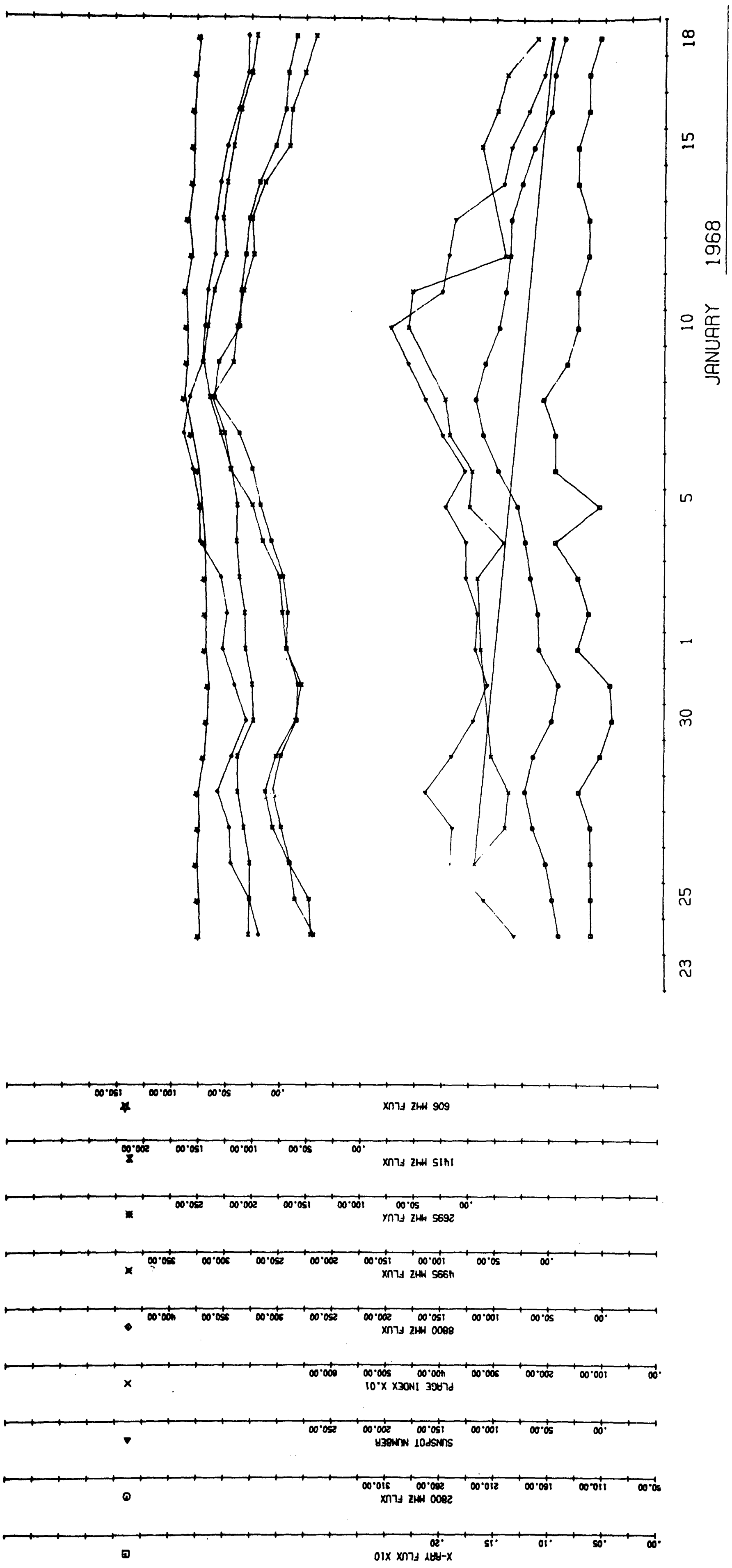

JANUARY 1968
606 MHZ FLUX
1415 MHZ FLUX
2695 MHZ FLUX
4995 MHZ FLUX
8800 MHZ FLUX
PLAGE INDEX X.01
SUNSPOT NUMBER
2800 MHZ FLUX
X-RAY FLUX X10

Figure 12

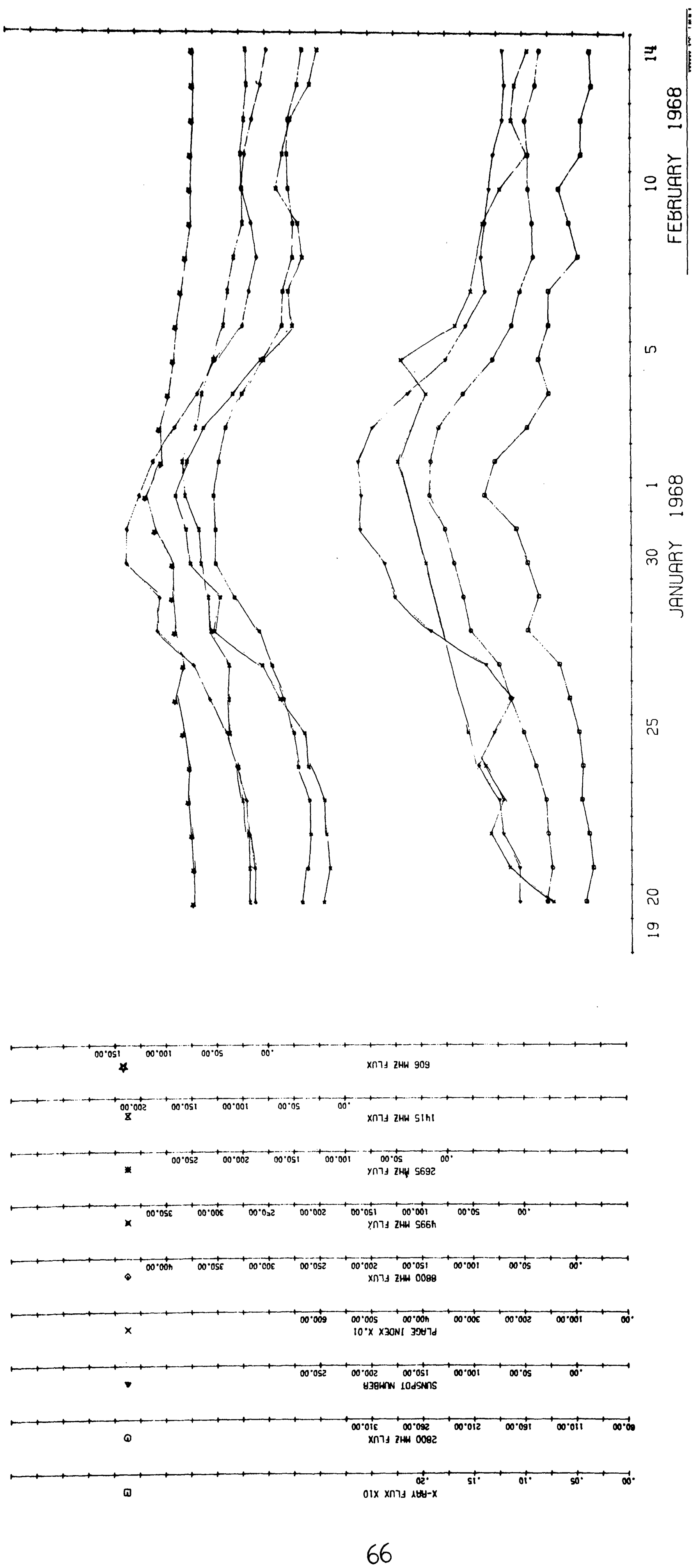

19
20
25
30
1
5
10
14
JANUARY 1968
FEBRUARY 1968
606 MHZ FLUX
1415 MHZ FLUX
2695 MHZ FLUX
4995 MHZ FLUX
8800 MHZ FLUX
PLAGE INDEX X.01
SUNSPOT NUMBER
2800 MHZ FLUX
X-RAY FLUX X10

Figure 13

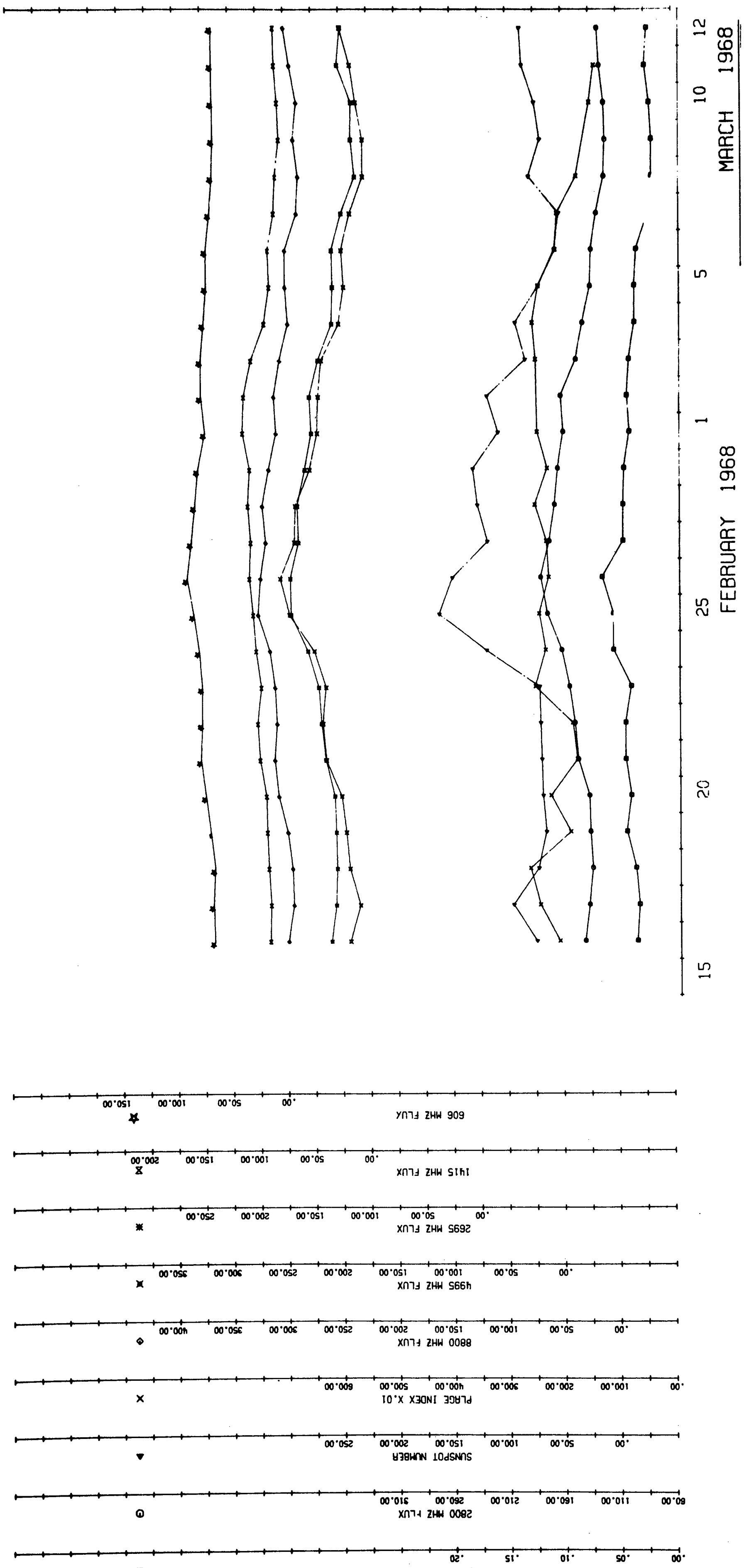

15
20
25
FEBRUARY 1968
1
5
10
12
MARCH 1968
X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX

Figure 14

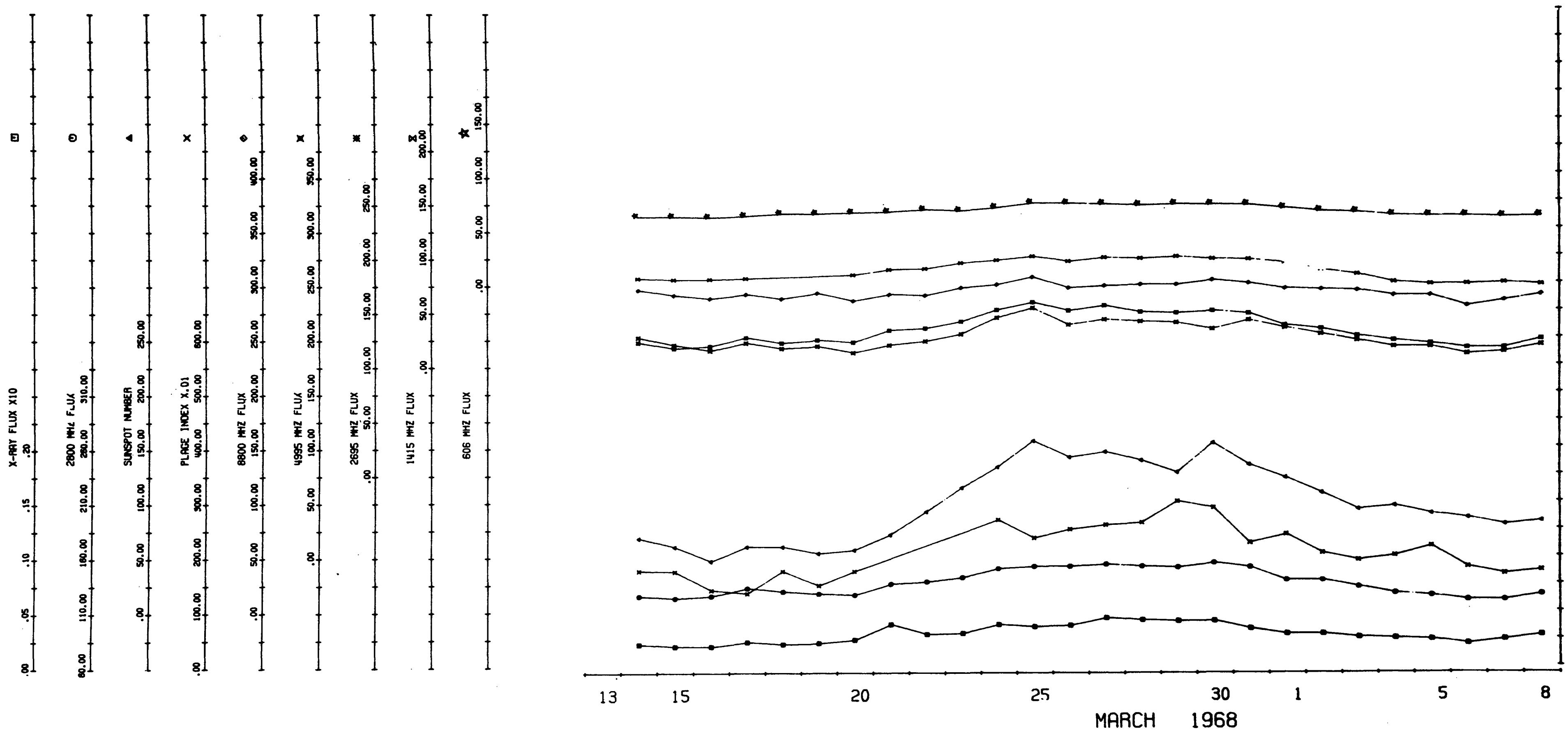

X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX
13
15
20
25
30
1
5
8
MARCH 1968

Figure 15

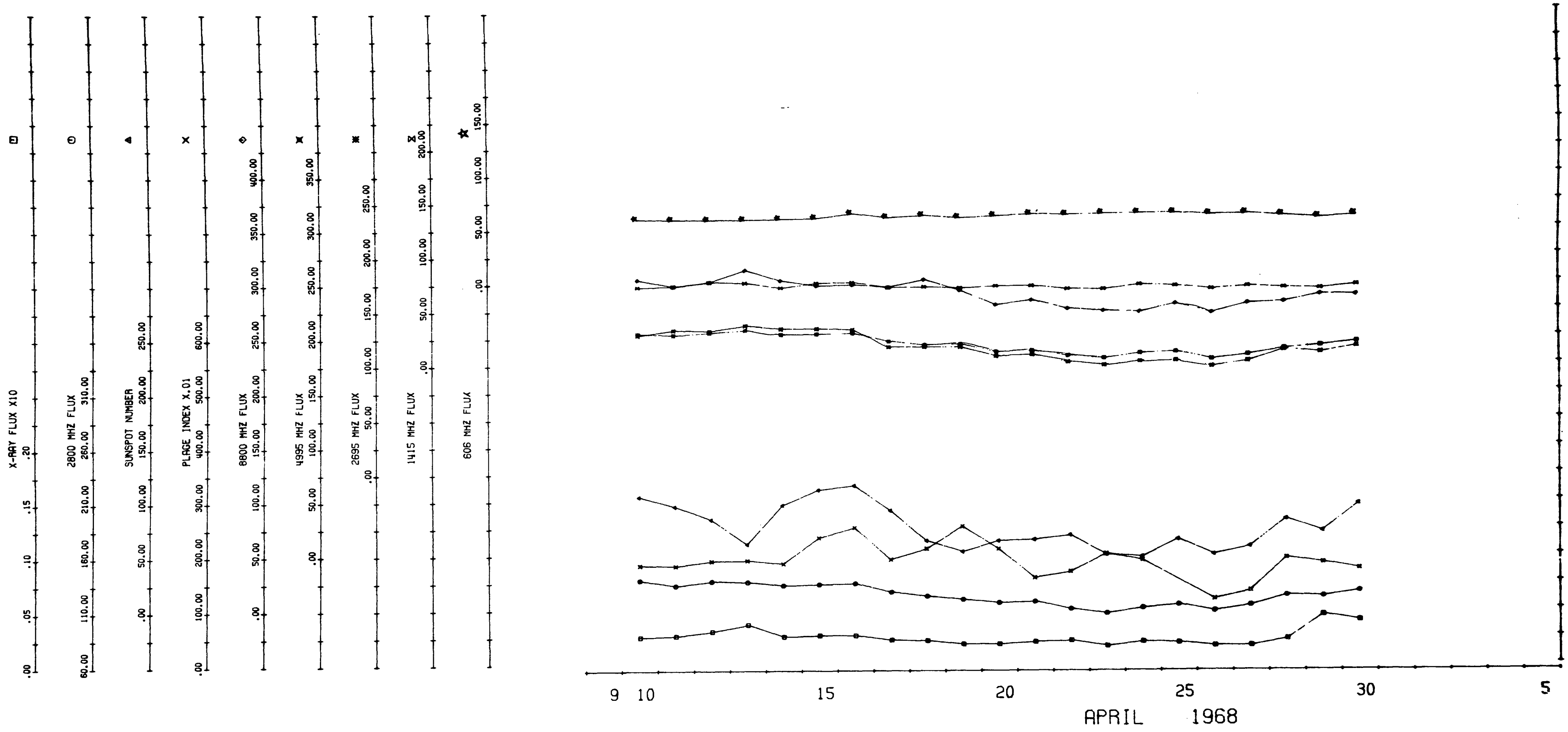
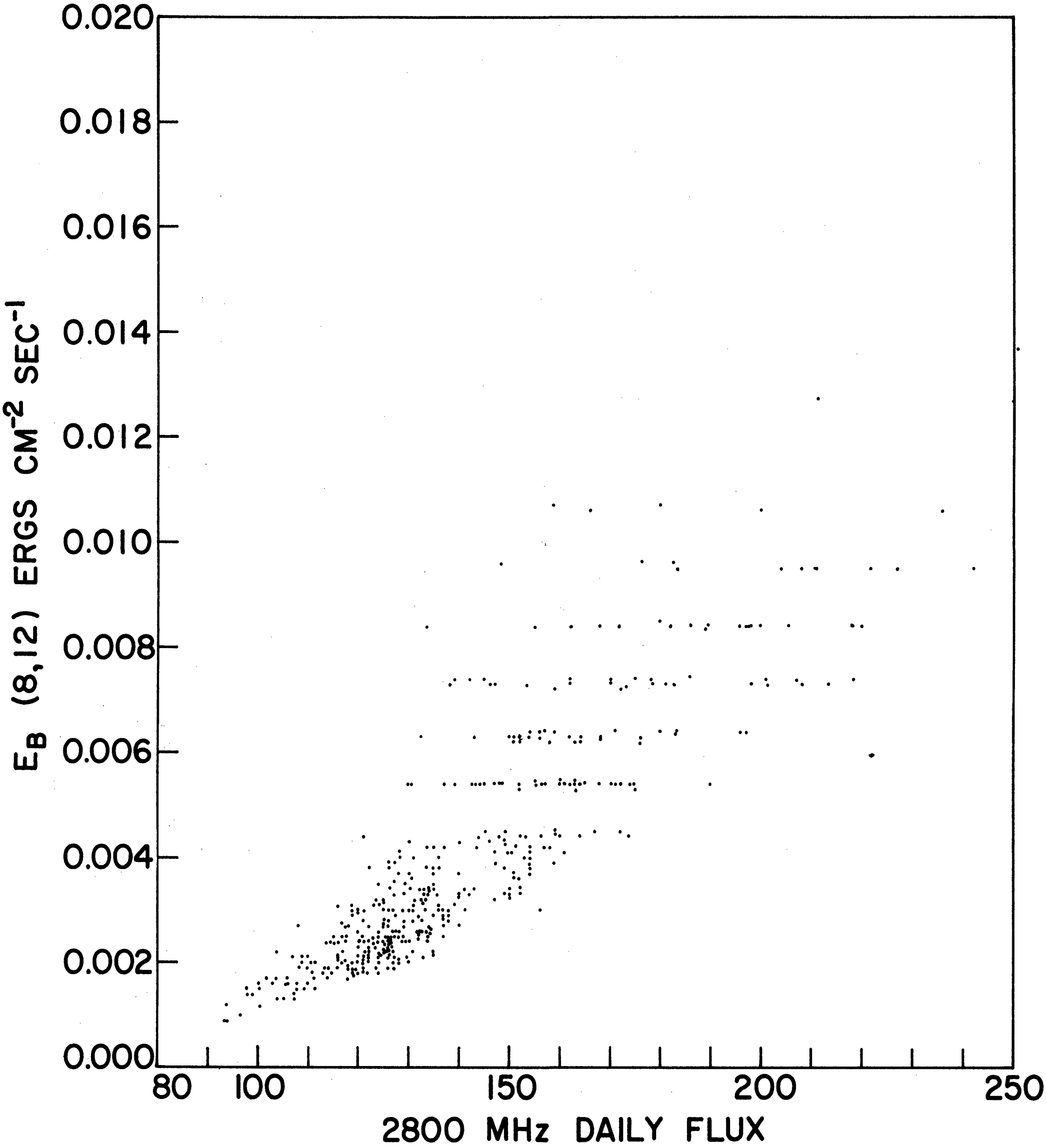

X-RAY FLUX X10
2800 MHZ FLUX
SUNSPOT NUMBER
PLAGE INDEX X.01
8800 MHZ FLUX
4995 MHZ FLUX
2695 MHZ FLUX
1415 MHZ FLUX
606 MHZ FLUX
9 10 15 20 25 30 5
APRIL 1968

Figure 16



0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
E_B (8,12) ERGS CM^{-2} SEC^{-1}
80
100
150
200
250
2800 MHz DAILY FLUX

Figure 17

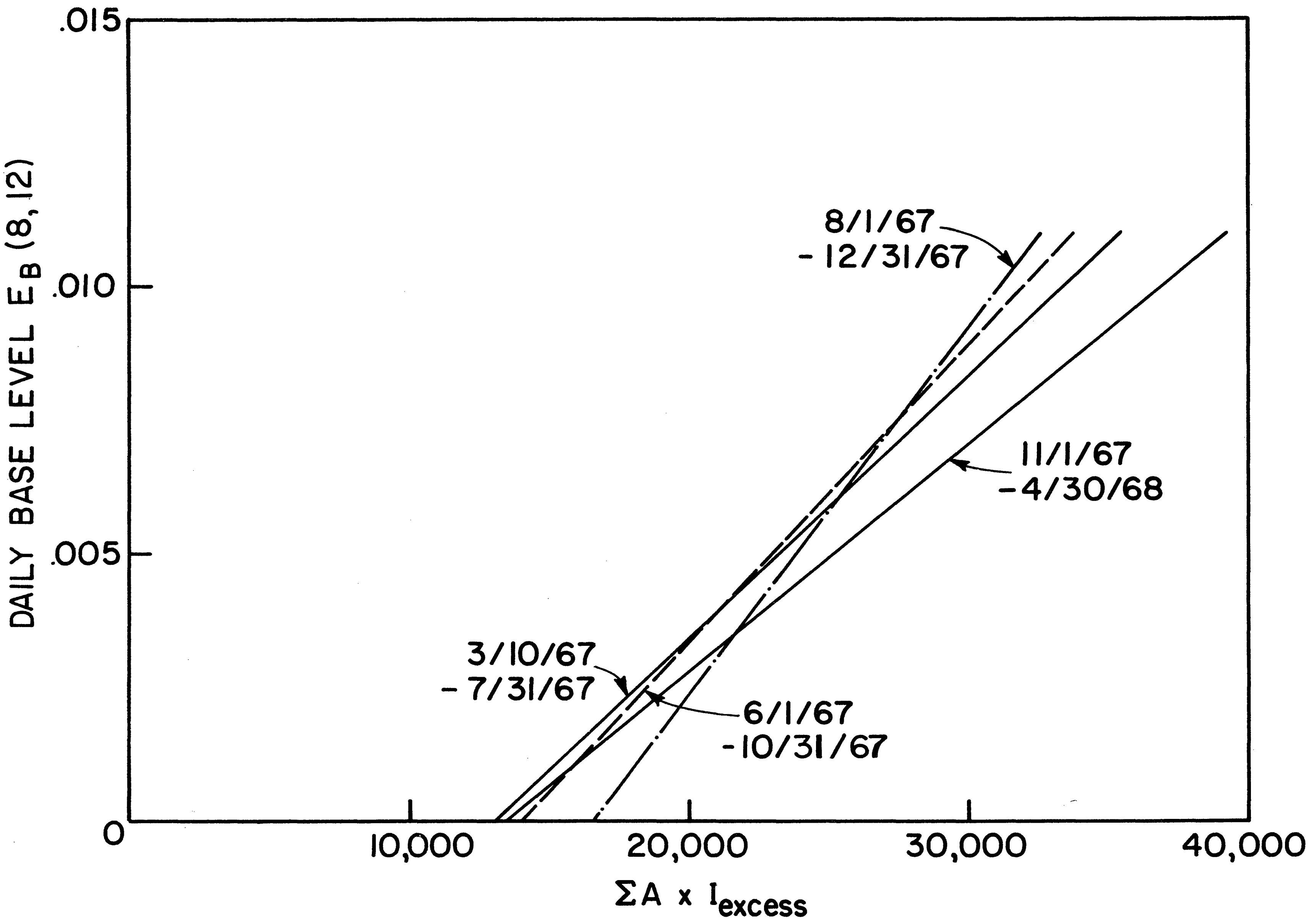
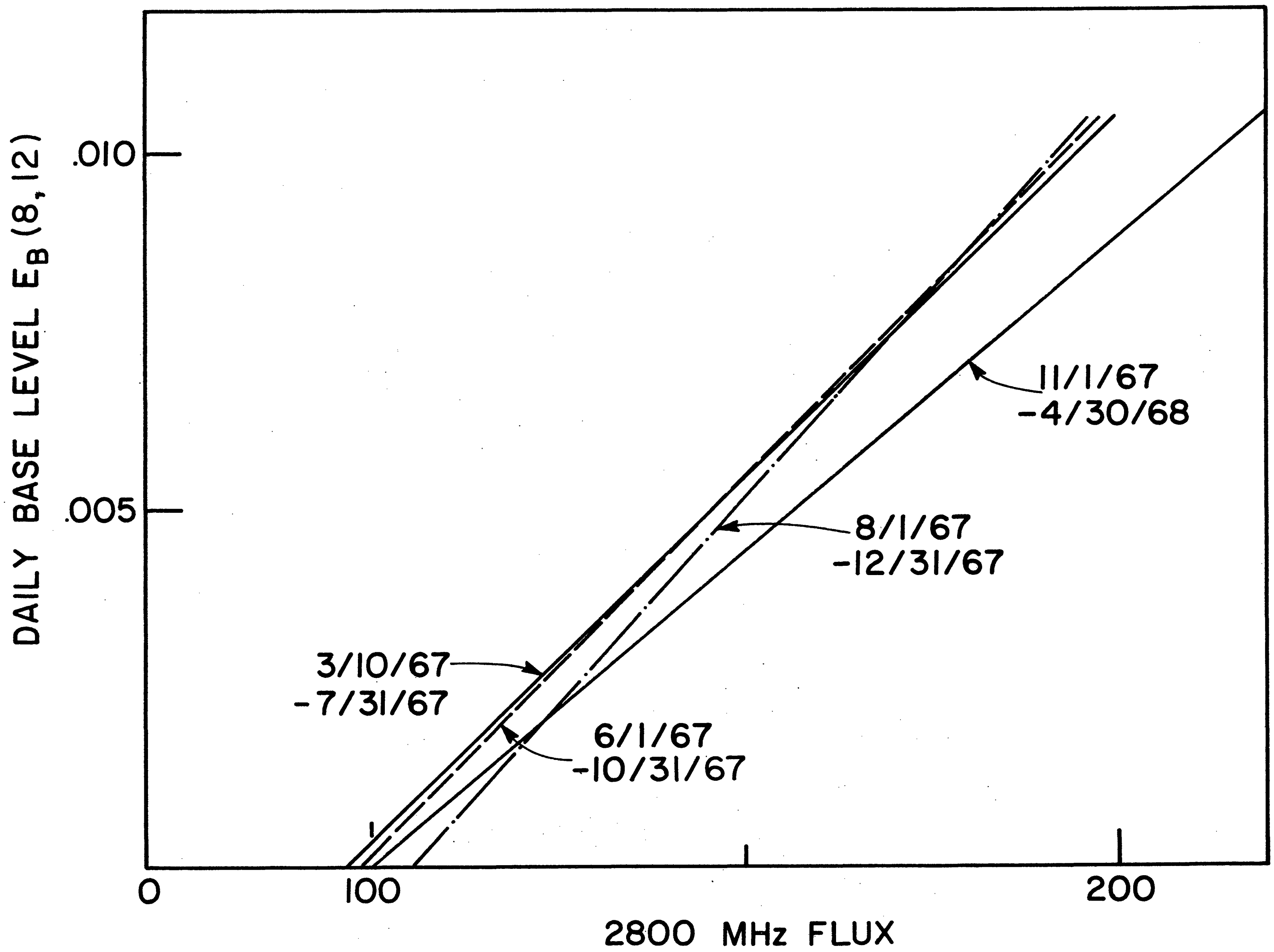

.015
.010
.005
0
DAILY BASE LEVEL E_B (8, 12)
10,000
20,000
30,000
40,000
$\Sigma A \times I_{excess}$
8/1/67
- 12/31/67
11/1/67
-4/30/68
3/10/67
- 7/31/67
6/1/67
-10/31/67

Figure 18



DAILY BASE LEVEL E_B (8, 12)
.010
.005
0
100
200
2800 MHz FLUX
3/10/67
-7/31/67
6/1/67
-10/31/67
8/1/67
-12/31/67
11/1/67
-4/30/68

Figure 19

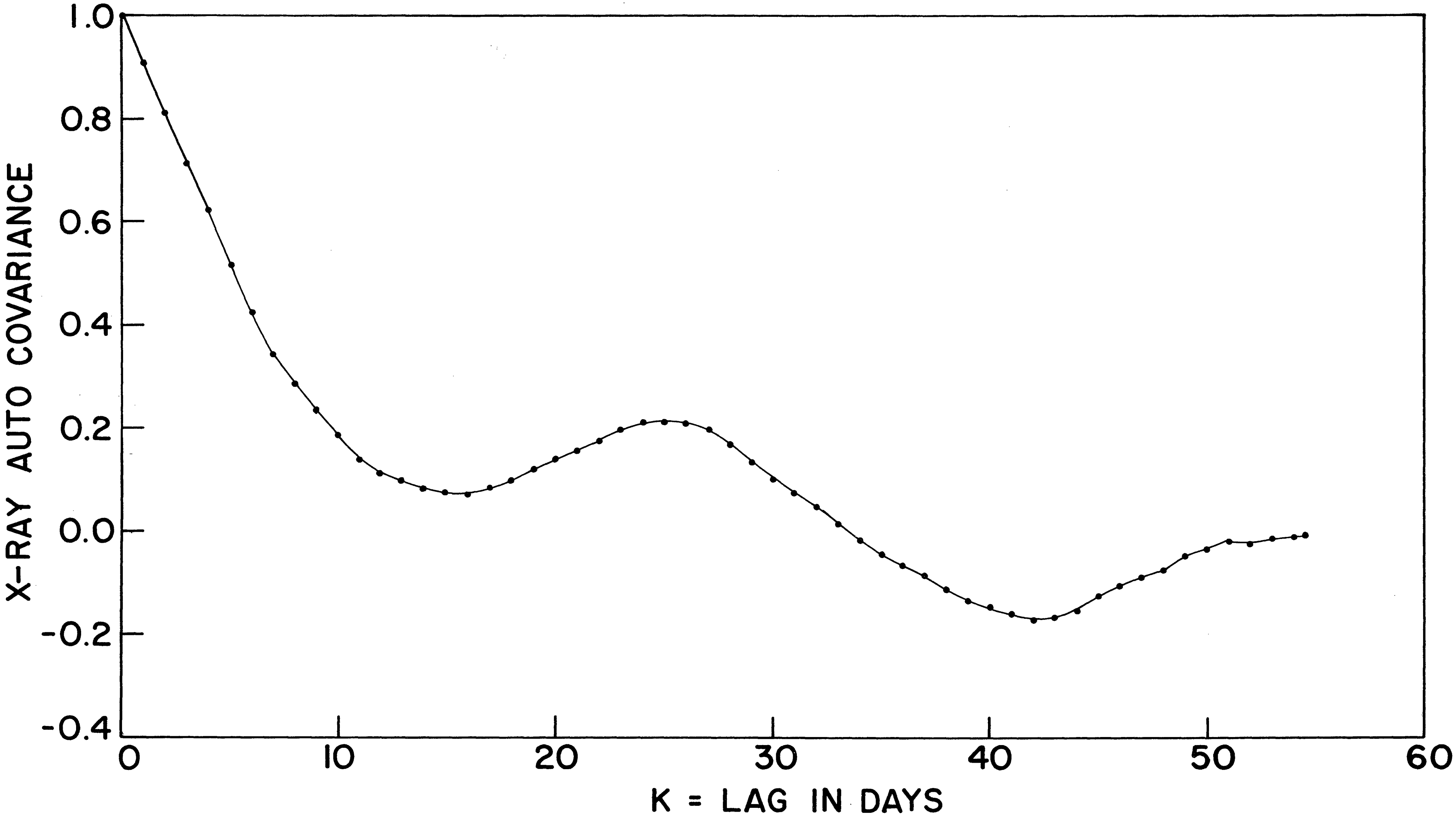
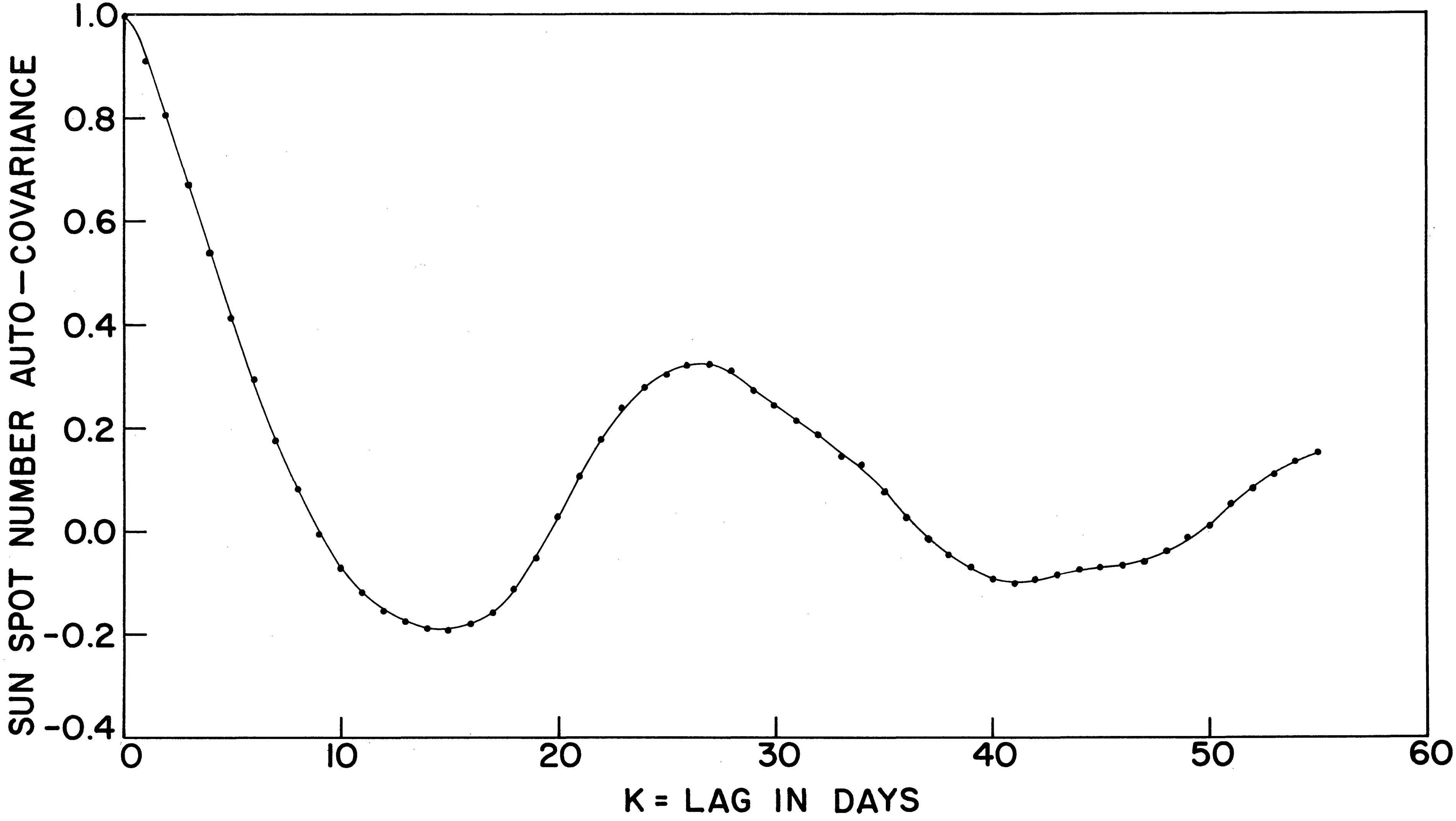

1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
X-RAY AUTO COVARIANCE
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 20



SUN SPOT NUMBER AUTO-COVARIANCE
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 21

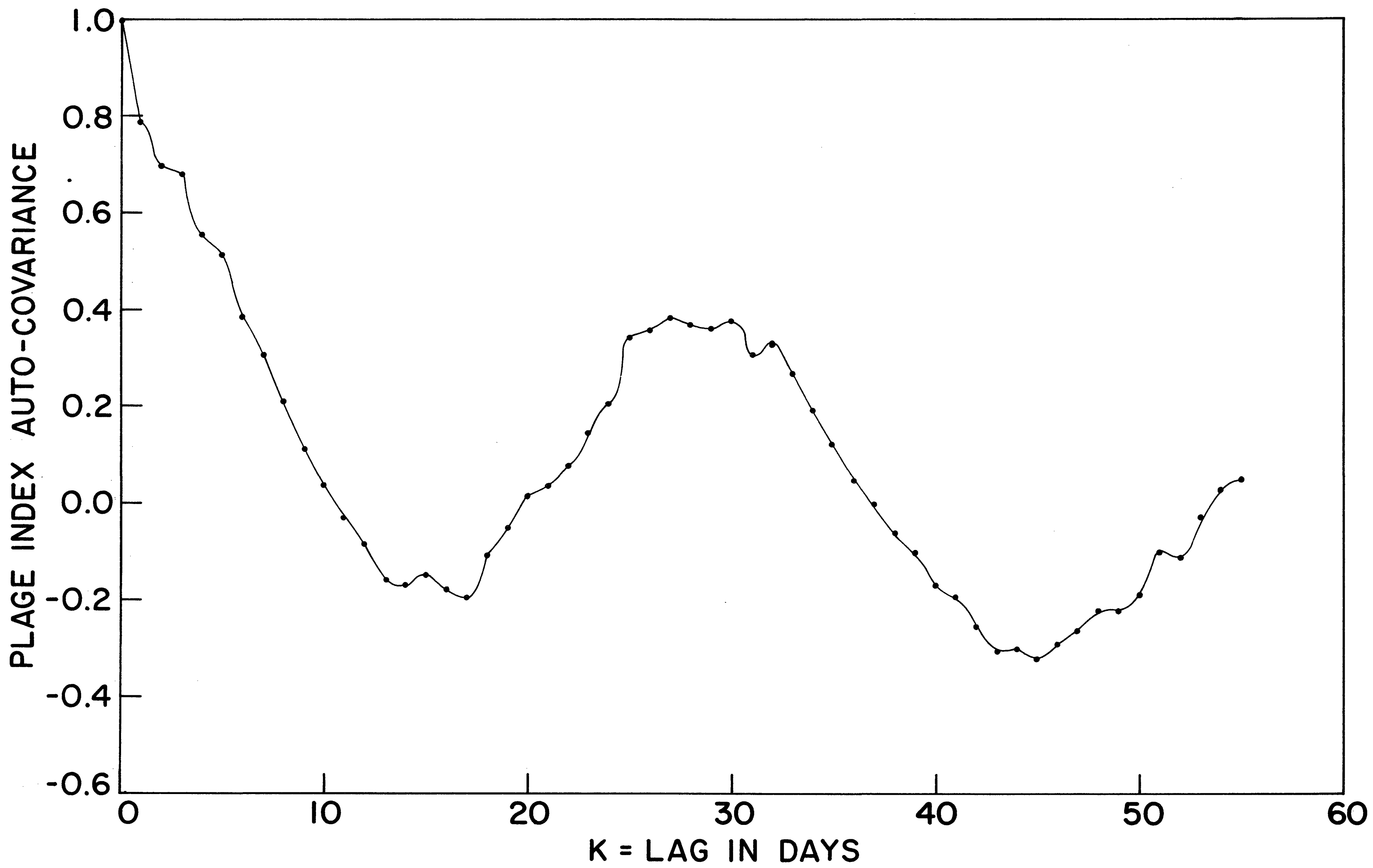

1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
PLAGE INDEX AUTO-COVARIANCE
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 22

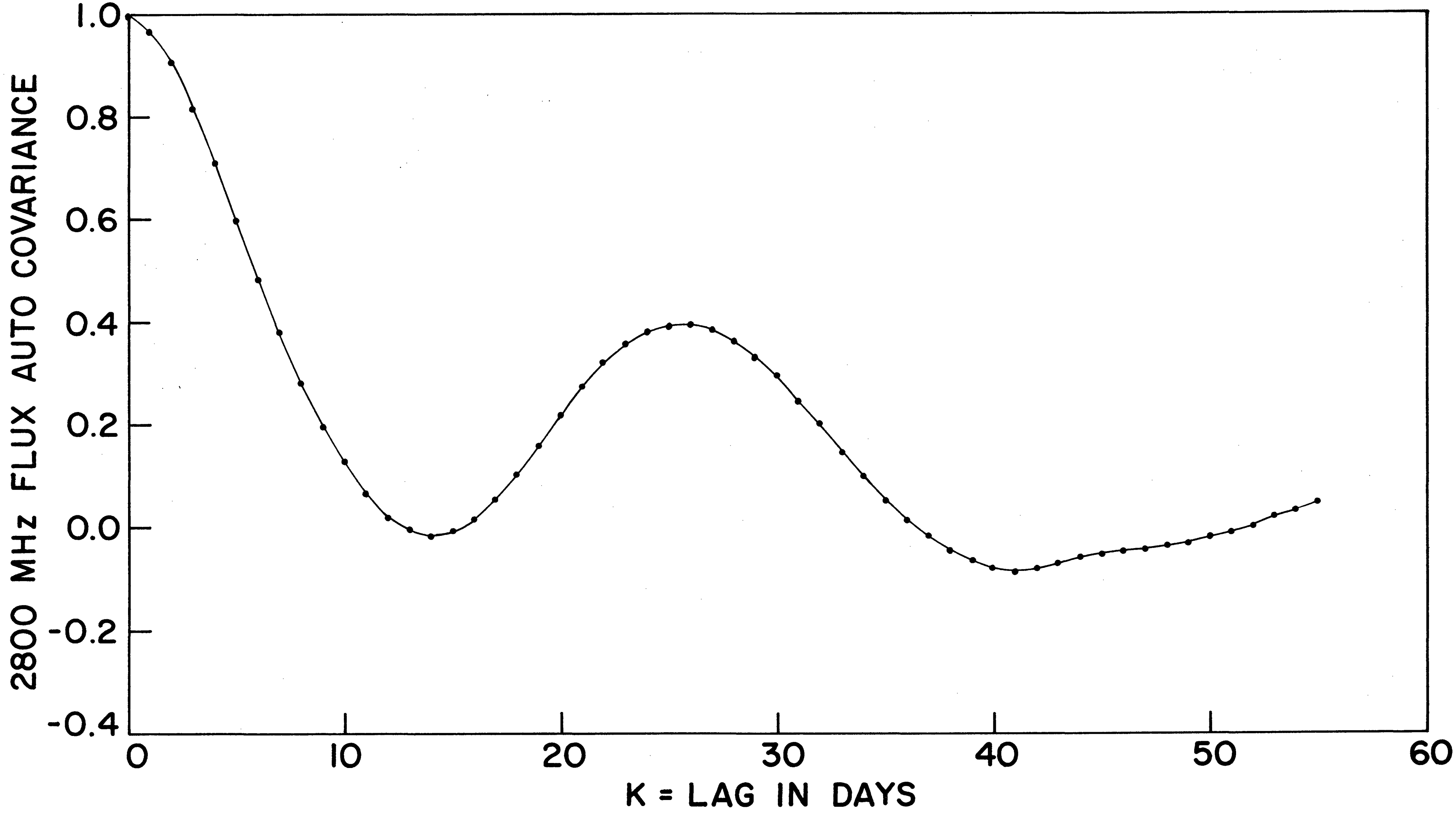

2800 MHz FLUX AUTO COVARIANCE
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 23

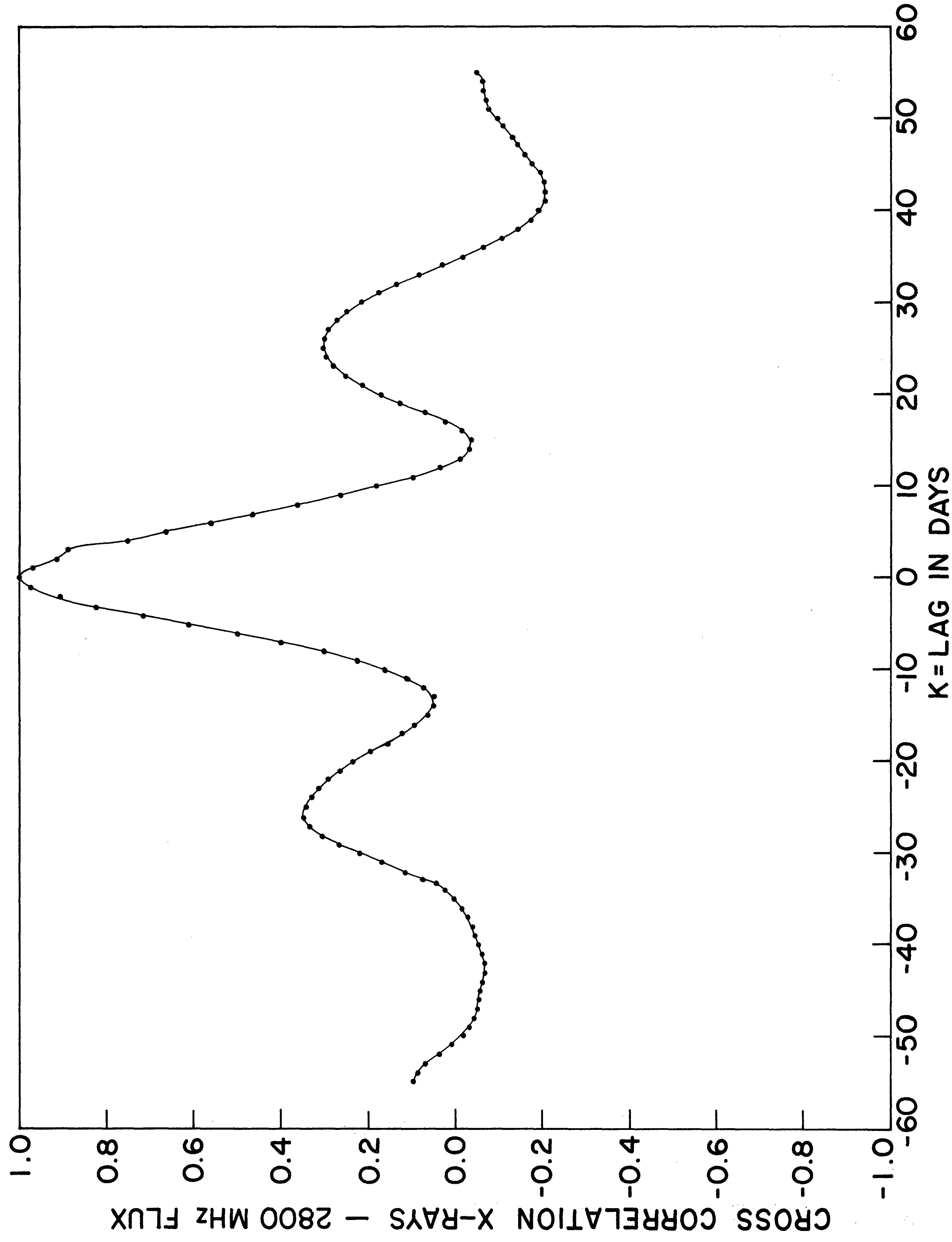

CROSS CORRELATION X-RAYS — 2800 MHz FLUX
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 24

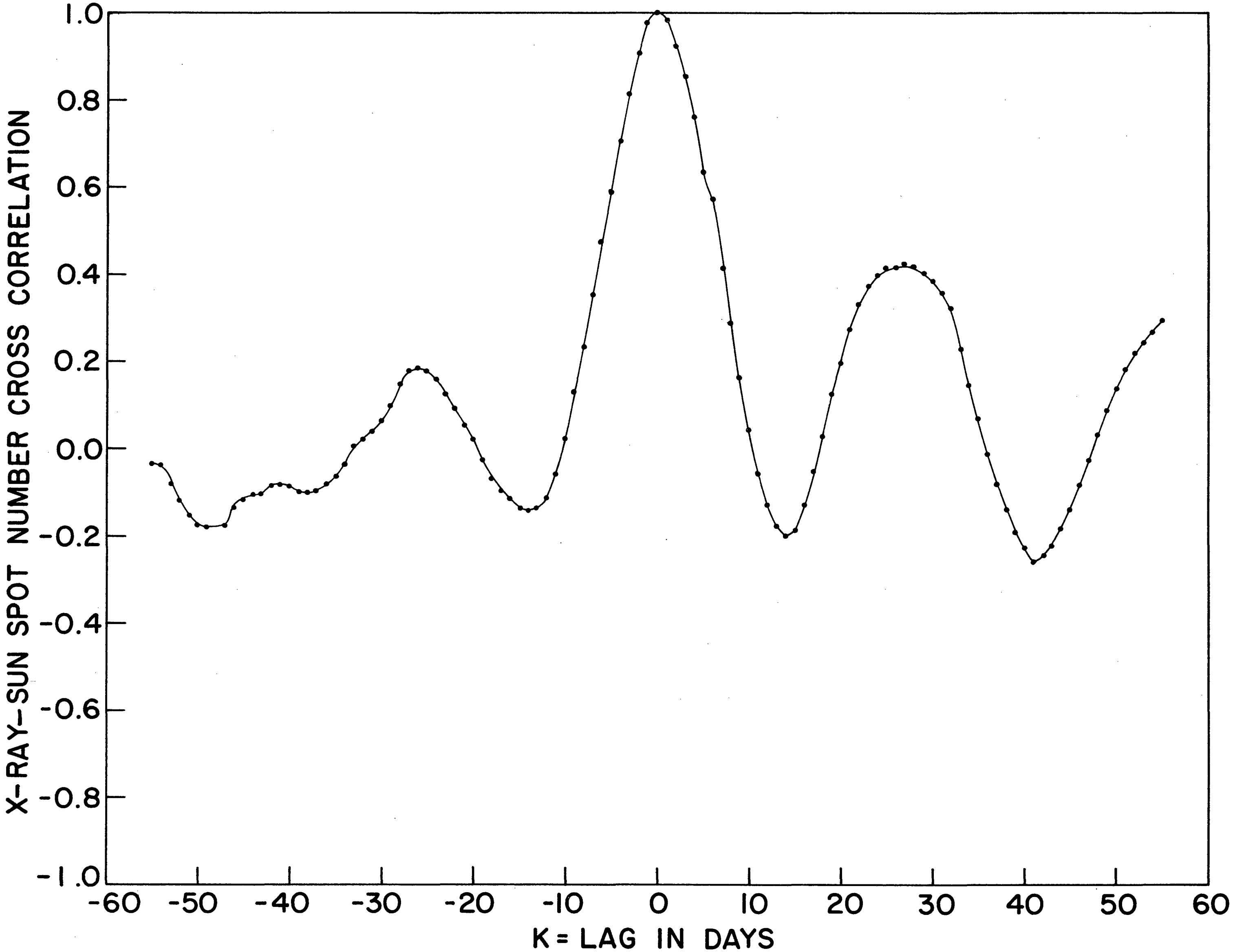

X-RAY-SUN SPOT NUMBER CROSS CORRELATION
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 25

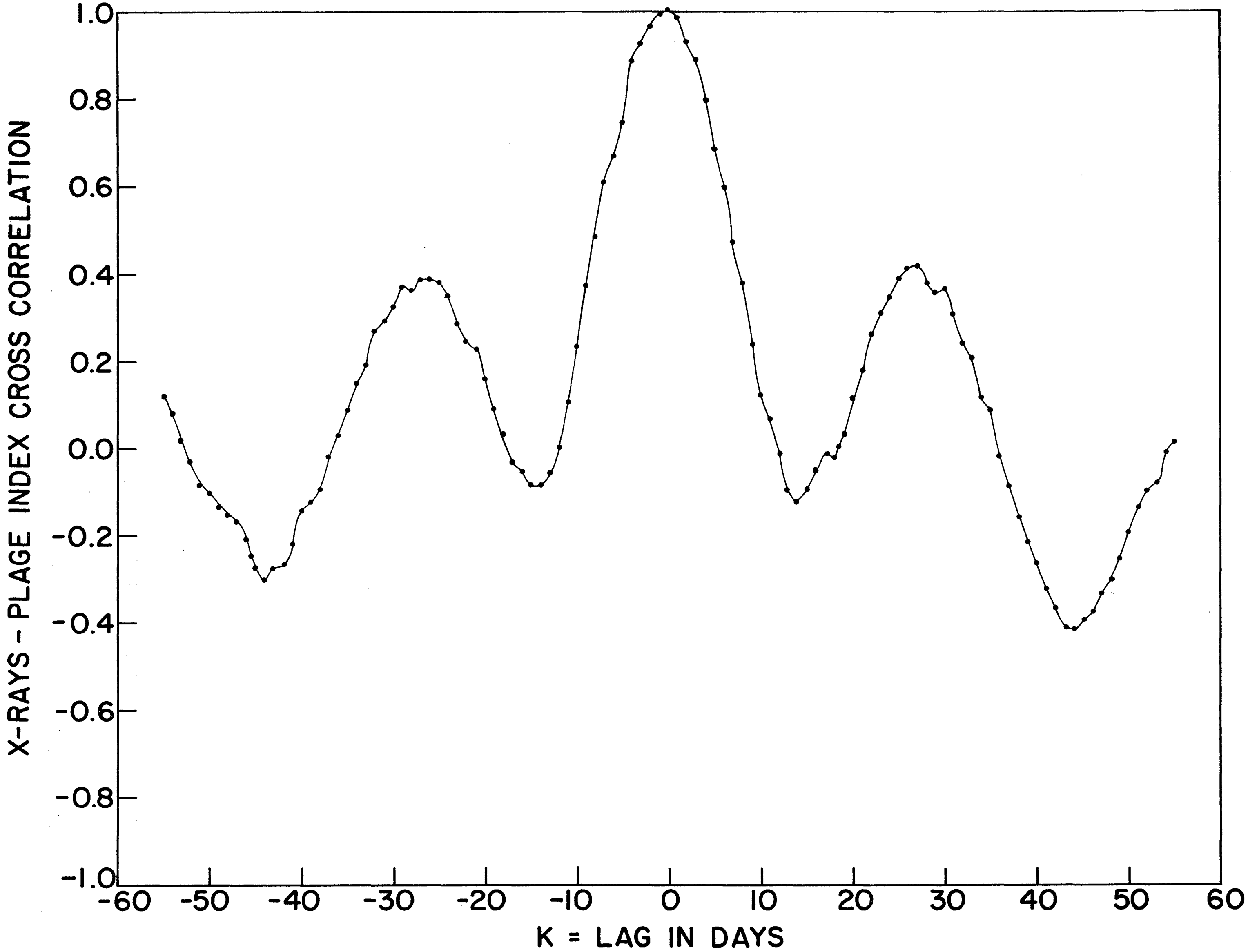

X-RAYS - PLAGE INDEX CROSS CORRELATION
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 26

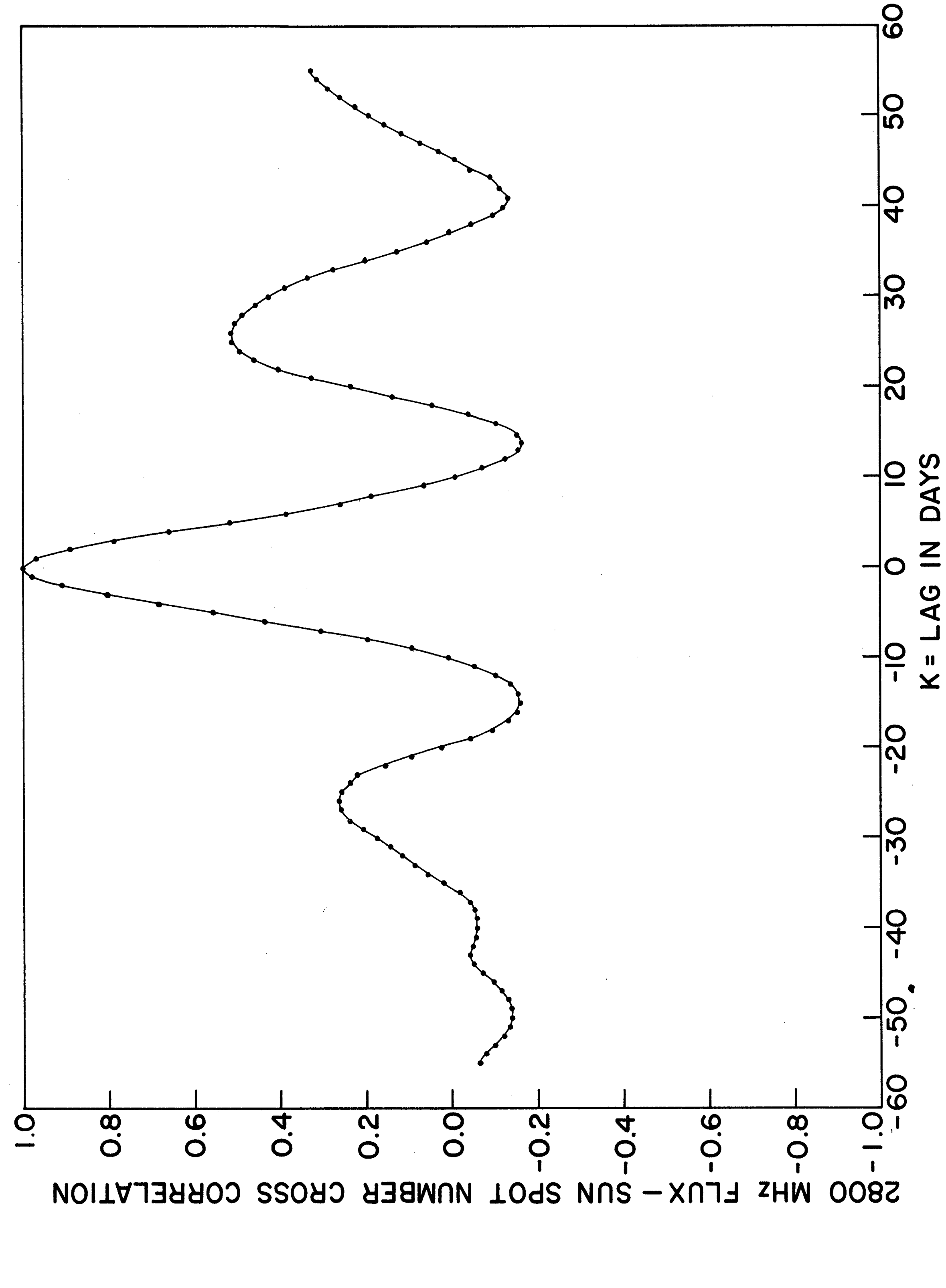

2800 MHz FLUX – SUN SPOT NUMBER CROSS CORRELATION
K = LAG IN DAYS
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60

Figure 27

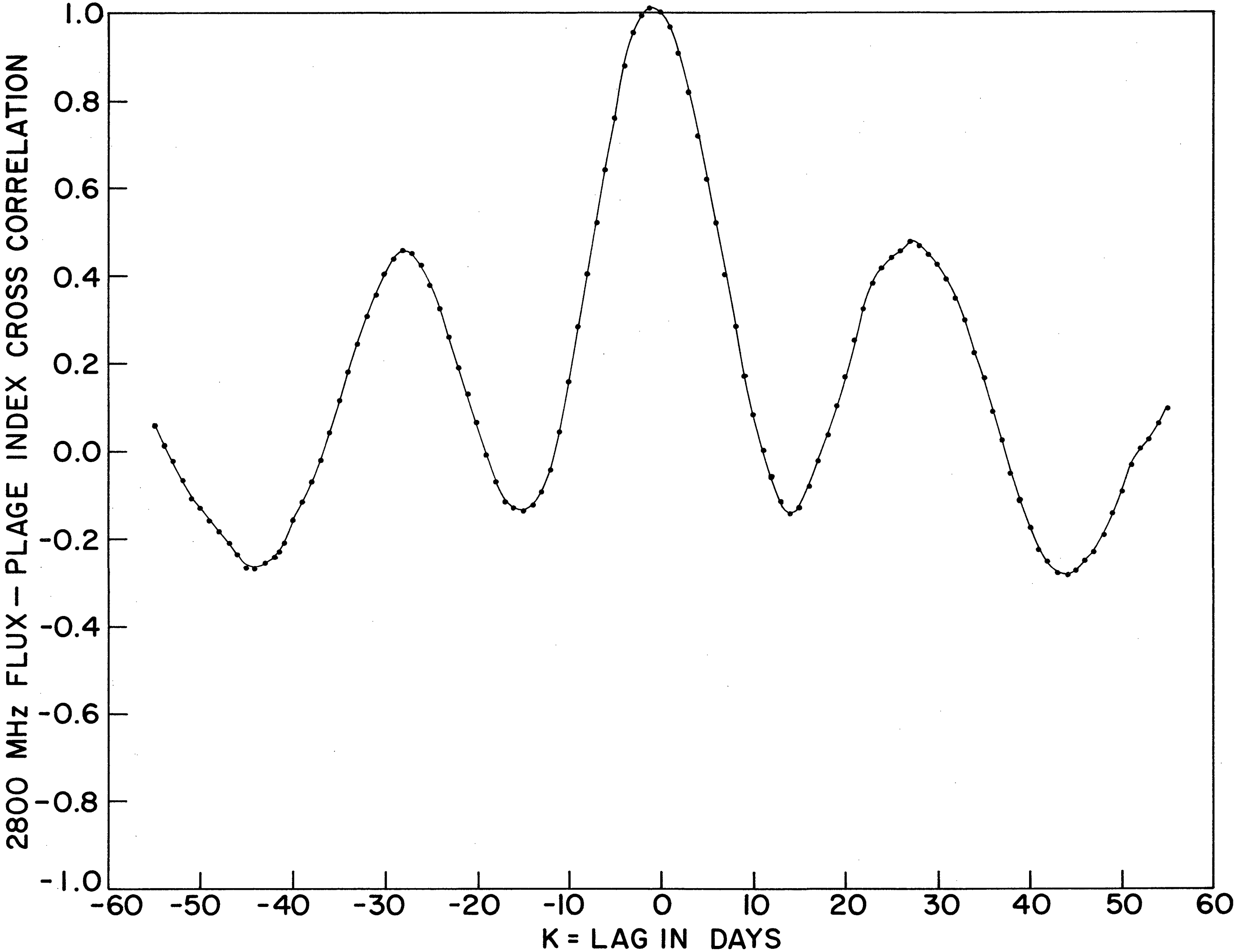

2800 MHz FLUX – PLAGE INDEX CROSS CORRELATION
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
K = LAG IN DAYS

Figure 28

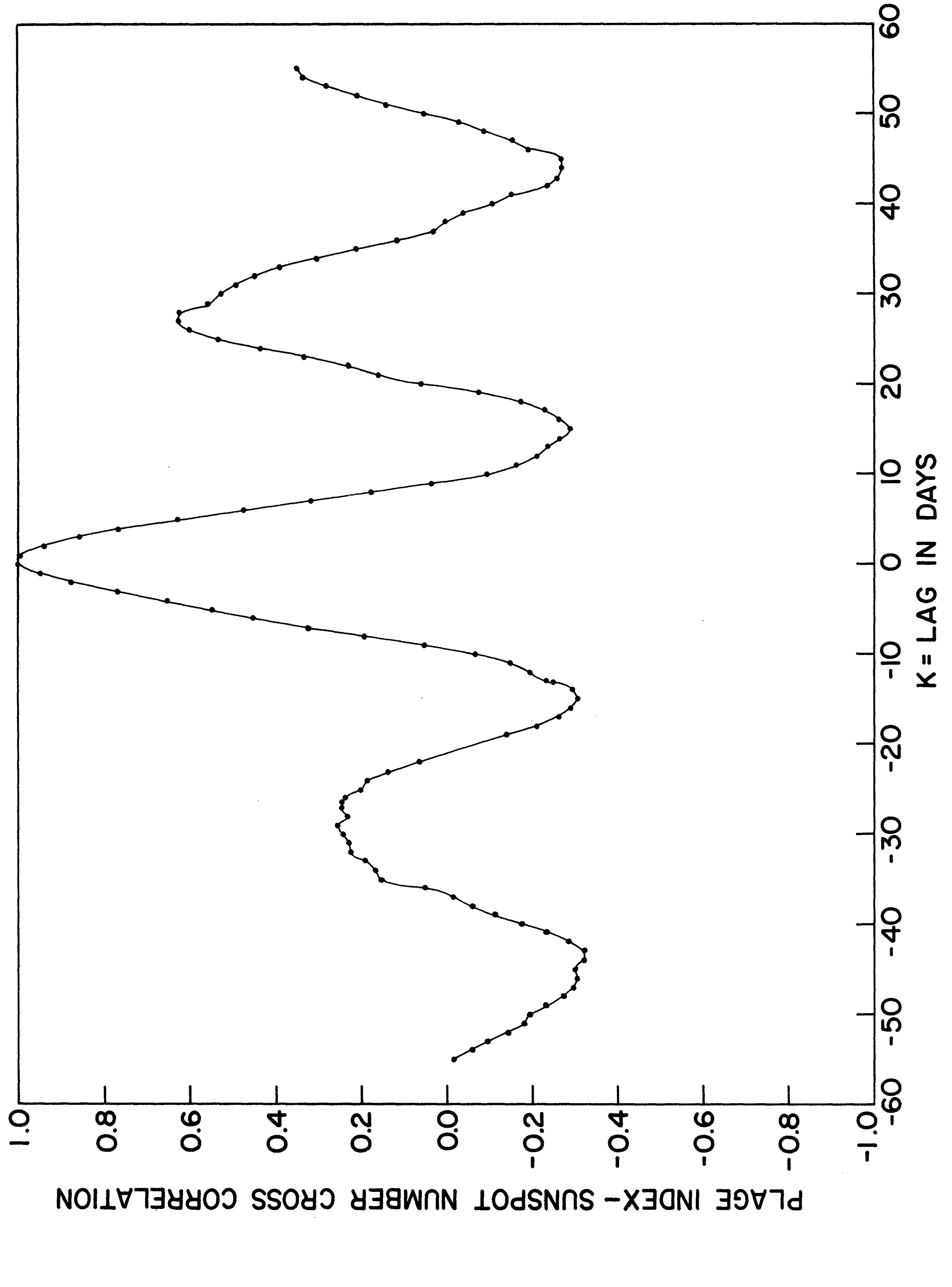

PLAGE INDEX – SUNSPOT NUMBER CROSS CORRELATION
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
K = LAG IN DAYS

Figure 29

SOFT SOLAR X-RAYS AND SOLAR ACTIVITY

IV. Loop Prominences with Soft X-Ray Emission

I. Introduction

Great systems of loop prominences are closely associated with major flares. They were first identified as flare-associated structures by Dodson (1961). Bruzek (1964), in a classical observational study, investigated the flare/loop-prominence relationship and described the loops as a "prolonged flare process which, slowly decaying, propagates into the solar corona."

The major loop systems which Bruzek described appear within sporadic coronal condensations following the onset of great flares. The flares are themselves found to be the sites of emission of Type IV radiation and are often productive of subsequent PCA effect. Jeffries and Orral (1965a, 1965b) suggested that the loop prominences have their origin in the thermalization of fast particles which are guided along magnetic field lines. In their view and in Kleczek's (1964), at least a significant fraction of the loop prominence material is delivered to the system in the form of protons of keV and higher energies. The delivery of these particles onto the loops, if it occurs, is unobservable at visual wavelengths, but the process may be expected to be observable in the X-ray region of the solar spectrum.

Olson and Lykoudis (1967) have considered an alternative model for production of loop systems based upon a condensation process. In their hypothesis, plasma confined to the coronal condensation is compressed and subsequently loses energy by radiation and by conduction, becoming visible in Hα as loops. Because no material is added to the system it is unlikely that this mechanism can give rise to a major loop system, since the observations require that the loops contain more mass than is available from the coronal condensation (Kleczek, 1964). Olson and Lykoudis concluded that loops produced by their mechanism would comprise small systems $h \lesssim 30{,}000$ km, and that these would be insignificant emitters of X-radiation.

We have obtained excellent records of the solar soft X-ray flux between 8 and 12 Å covering the period March 9, 1967, to June 28, 1968 (Teske, 1969). These records were examined for soft X-radiation that may have been associated with major systems of loop prominences, with the aim of understanding something further about the processes which give rise to those structures.

II. The Data

Major systems of loops are rare phenomena: Bruzek (1964) assembled twenty-nine cases of major systems at the limb during a seven-year period November, 1956-September, 1963, without commenting upon the completeness of his list.

A list was made by us of the twenty-six loop systems reported at the solar limb by Sacramento Peak (in Geophysics and Space Data Bulletin: GSDB) during the interval March 10, 1967-December 31, 1967. A twenty-fifth case (May 21, 1968) was added to the list because of its reported magnitude: the loop tops extended to 0.08 solar radii from the limb. Seven additional cases of flares accompanied by loops were culled from the Quarterly Bulletin on Solar Activity (QB) for the same time period. A reasonably prominent soft X-ray enhancement was found to accompany only ten of the thirty-three events in the catalog (Table I), although several others may have been associated with very weak soft X-ray enhancements of amplitude $\Delta E(8,12) \leq 0.005$ ergs $cm^{-2}sec^{-1}$ at the earth. In our opinion, weak X-ray enhancements are easily confused by sub-flaring activity and with fluctuations in the background flux, and so these have not been studied.

Our flare patrol films are not especially suited to the examination of loop prominence images. Where possible we have examined them to confirm the identifications. Our impression is that the majority of the "loops" reported in GSDB are indeed loop-like configurations but are not the major systems described by Bruzek. Thus the low fractional association of reported "loops" with soft X-radiation may have no meaning with respect to the great systems. We reserve comment as to whether the majority of the reported "loops" may be identified with phenomena generated by the Olson-Lykoudis mechanism (1967).

Optical (Hα) data available to us permit the reasonable identification of four of the ten "yes" cases of Table I as major loop systems (Table II). These four events are discussed below. In Section III we will consider those features of our observations which are relevant to the compression model and to the injection model.

TABLE I

REPORTED Hα LOOPS

Date	Time, UT	Source	Position	Soft X-Ray Enhancement
3/18/67	1510-1530	GSDB	N10 W90	No
3/20/67	1322-1542	GSDB	N26 E90	Yes
3/21/67	2022-2034	GSDB	N16 E90	Possible
3/22/67	0022	QB	N24 E68	Yes
3/27/67	0441	QB	N24 W14	Weak
4/ 2/67	0407	QB	N24 W86	No
4/ 2/67	2054-2159	GSDB	N18 W90	No
4/14/67	1532-2035	GSDB	S21 W90	Yes
5/18/67	1927-1958	GSDB	N26 E90	Moderate
5/18/67	1934	QB	N25 E80	Moderate
6/ 1/67	1214E-2040U	GSDB	N24 W90	Yes*
8/ 4/67	1526-1603D	GSDB	N30 W90	Moderate, short-lived
8/ 6/67	1400-1442	GSDB	S24 E90	No
8/18/67	2044-2129	GSDB	N24 E90	Yes
8/23/67	0515	QB	N23 E36	No
9/24/67	1444-1652	GSDB	N13 E90	Possible?
9/24/67	2152-2242	GSDB	N20 E90	No
9/26/67	1846U-2014	GSDB	S23 W90	Weak
10/ 3/67	0943	QB	S20 W83	No
10/19/67	1920-2014	GSDB	N14 E90	Possible
10/27/67	1434-1645	GSDB	S15 E90	No
10/27/67	1758-1830	GSDB	S17 E90	No
10/27/67	1946-2036	GSDB	S13 E90	No
10/27/67	2232-2310	GSDB	S16 E90	No
10/29/67	2128U-2235D	GSDB	N10 W90	Yes
10/29/67	2347	QB	N10 W90	Yes
10/30/67	1654E-2400D	GSDB	N10 W90	Yes*
10/31/67	1912-2352D	GSDB	N12 W90	Yes*
11/ 3/67	1415-1442	GSDB	N20 W90	Possible
11/ 4/67	1635-1811	GSDB	N17 W90	No
11/10/67	1338-2342	GSDB	S25 W90	Possible?
12/ 2/67	0810	QB	N21 W90	Possible
12/ 2/67	1426-1702	GSDB	S28 W90	Possible
12/ 4/67	1302	QB	S19 W90	Yes
5/21/68	2050-2440D	GSDB	N16 E90	Yes*

*Optically identified as major loop system.

TABLE II

LOOP PROMINENCES FOUND TO HAVE A SIGNIFICANT SOFT X-RAY ENHANCEMENT

Date	X-Rays Begin (UT)	X-Rays End (UT)	X-Ray Peak Flux $\Delta E(8,12)$ ergs $cm^{-2} sec^{-1}$	Hα Loops First Visible (UT)	Comments
6/ 1/67	0700	1500	0.022	Unknown	
10/30/67	<1740	>2400	0.015	1850	
10/31/67	1550	>2500	0.013	1912	
5/21/68	<2020	>2400	>0.016	2041	Poor Hα data

A. OCTOBER 30 AND 31, 1967

Data relating to the time-period October 30 (12^h UT) to October 31 (24^h UT) are presented in Figure 1. We have associated the two prolonged X-ray enhancements on each day with large systems of loop prominences seen at the solar west limb. Hα filtroheliograms of these systems are shown in Figure 2. These were very kindly made available by Dr. Hyder at Sacramento Peak (Figure 2a and 2b, October 31) and by Mr. Miller at Lockheed California Company (Figure 2c, October 30).

Hyder (1969) estimates that the top of the system on October 30 had reached an apparent altitude $h \sim 1.2 \times 10^5$ km by 23^h15^m UT, while on October 31 the loop tops appear to have reached a projected altitude $h \sim 4 \times 10^4$ km by 19^h24^m UT. From a consideration of the probable location of the flares which may have initiated these phenomena (Teske 1970) we have deduced actual heights of the loop tops $h \gtrsim 10^5$ km. These systems thus rank among the largest studied by Bruzek (1964).

Neither of these systems was associated with Type IV radiation, an observation to be compared with Bruzek's (1964), in which only four out of twenty-seven cases of loops at the limb were accompanied by recognized Type IV (two cases occurred prior to Type IV's recognition). However, the phenomena seen in October, 1967, appear to be ranked with major loop systems on basis of morphology and magnitude. There is no evidence for an X-ray burst associated with an initiatory flare for either loop event (Teske, 1970), and so the soft X-rays being observed were very likely entirely associated with the loop systems themselves.

The first loops on October 30 were seen on McMath-Hulbert films at 18^h50^m, about 35 min before soft X-ray maximum. On October 31, Sacramento Peak saw visible loops beginning at about 19^h12^m, perhaps 15 min after the (approximate) maximum X-ray flux. The time of appearance of a loop system is probably an observational artifact, since the systems grow in height from low mounds (Bruzek, 1964), and these times correspond in our present observations to the times of first recognition of the prominences as a system of loops. The differences in time of loop recognition and time of X-ray maximum may be reconciled if we assume (i) that on October 31 the system had to rise to a considerable altitude ($h \sim 60,000$ km, Teske, 1970) before becoming visible from the earth and (ii) the X-ray source is located at altitudes above the limb and thus above the Hα source. According to Bruzek, loop systems require $> 1^h$ to grow to 60,000 km altitude. Thus, on October 31, recognizable but smaller Hα loops may have been invisibly present "below" the solar limb, prior to X-ray maximum.

The active center with which these two loop systems were associated (McMath region No. 9034) became exceedingly active active on October 29, while it was on the west limb. An importance 2b flare which began at 2347 UT on the 29th may have been associated with a system of loops, according to the Quarterly Bulletin on Solar Activity. Our satellite data show the flare X-ray burst and a lingering strong enhancement of soft X-ray flux following the flare; the flux declined slowly over an interval of 6-8 hr, from an initial post-flare level comparable to the levels observed with the other two October loop systems. The flare itself was accompanied by strong cm-λ radiation and by a strong post-burst phase lasting more than 3 hr. No Type IV was reported. Thus this active center produced, during a 48-hr interval, three systems of loop-type prominences, none of them associated with reportable Type IV radiation.

We have not studied the loops of October 29. We have no optical data concerning them other than the comment in the Quarterly Bulletin. It is noteworthy that the loops were reported by Sacramento Peak as beginning before the importance 2b flare (Table I). Thus the loops may have had their origin in an earlier event, perhaps a subflare which began at 2037 UT. Our X-ray data do not indicate any major enhancement in the interval 2042-2129 UT, however, and the cm-λ burst at 2036 UT was very minor.

B. JUNE 1, 1967

Data relating to the phenomena of June 1 are shown in Figure 3. Superposed upon the extended X-ray enhancement which began at 07^h00^m are many short X-ray bursts which are associated with flares on the visible disk. The X-ray background remains above normal until at least 15^h00^m.

Sacramento Peak reported loops at the west limb, in the position of plage #8818, at the beginning of observations at 12^h14^m. The McMath-Hulbert flare-patrol films record their presence at the beginning of observations at 11^h03^m. We have no data which provide the time of first visibility on the sun.

Evidence for an initiatory flare has been discussed by Teske (1970). It is likely that the X-ray rise after 07^h00^m is associated with the flare and the radio burst. Further, the maximum X-ray flux recorded at around 09^h00^m may be to a slight extent contaminated by subflaring activity near that time. It is unlikely, though, that the maximum seen in soft X-rays represents only the X-rays of the initiatory flare, because it occurs 110 min after the peak of the cm-λ burst. It is unfortunate that swept-frequency observations at meter-λ were not being made around the time of the flare.

C. MAY 21, 1968

"Loops" were reported by Sacramento Peak Observatory on the northeast limb beginning at 20^h50^m, eventually extending to 0.08 ($h \sim 6 \times 10^4$ km) above the limb. These thus rank with average loop heights recorded by Bruzek (1964). Our flare patrol film, which ceased at 20^h56^m, indicate structures that resemble a great loop system as early as 20^h41^m. The assembled data for this event are in Figure 4.

A subflare on the northeast limb may be associated with the formation of the loop system. If so, its importance rating is perhaps incorrect. A Type II burst following the flare is suggestive of a significant magnitude for the event, while the cm-λ burst amplitudes (~ 20 flux units) would argue otherwise. As on October 30 and 31, 1967, no Type IV radiation was reported.

It is likely that the X-ray enhancement between 20^h20^m and 21^h00^m is primarily a burst component associated with the subflare. The burst is more prolonged than is usual for a subflare, although the rate of decay of the burst is essentially flare-like. The low level of enhancement after 22^h00^m demonstrates that this loop prominence system was not as productive of X-radiation as were the others previously discussed. The Hα data available to us do not indicate that the system was morphologically different from other major loop systems, although these data are of poor quality.

D. X-RAY ENERGIES OF THESE EVENTS

We have estimated the peak emission rates and time-integrated soft X-ray energy of three of the events (Table III). That given for the June 1, 1967, loops is surely an overestimate because of the detection of some flare burst X-rays but is not too large by more than a factor of two. Thomas (1970) has analyzed the response of the Michigan ion chamber to various spectral distributions—both line and continuous—and concluded that the relative errors of quoted fluxes do not exceed 30% for the spectral distributions that may be reasonably expected even if time-variations of spectrum occur. He has also concluded that systematic sources of error (calibration, primarily) do not lead to errors in quoted energies exceeding a factor of three, and that the true systematic errors may be less than that.

TABLE III

SOFT X-RAY EMISSION RATES, ENERGIES, RISE, AND DECAY TIMES FOR THREE MAJOR LOOP SYSTEMS

Date	X-Ray Peak Flux at Sun (ergs sec^{-1})	$\int \Delta E(8,12)\,dt$(ergs)	e-folding times Rise (Minutes)	Decay (Minutes)
6/ 1/67	6.2×10^{25}	1.5×10^{30}	-	-
10/30/67	4.2×10^{25}	6×10^{29}	101^m	216^m
10/31/67	3.7×10^{25}	6×10^{29}	119^m	243^m

It is surprising to find three separate events which produce such similar peak rates and total X-ray energies. Energy estimates cannot reliably be made for the May 21, 1968, loops. However, the peak rate of X-radiation and total X-ray energy for the loops on that date are very much smaller than those given in Table II. The following discussion (Section III) will consider the loop systems of October 30 and 31 at length. These were the largest loops that were identified optically, and were among the strongest soft X-ray emitters in Table I. They may therefore not be typical of loop systems generally; the loops of May 21, 1968 may also exemplify a morphologically similar but less energetic phenomenon.

III. Discussion

Because the Michigan ion chamber responds to a broad band of wavelength principally between 8 and 12 Å (see Thomas, 1970) it is not possible to utilize the observations directly in a deductive physical discussion. To do so would require prior information as to emission measure and temperature. Comparison of our data with solar X-ray data at 7.7 - 210 keV energies obtained in flare events by Peterson and Hudson* indicates that in flares the flux levels observed by us are almost entirely line or free-bound emissions. This is deduced from the fact that an extrapolation of the bremsstrahlung spectrum near 7.7 keV into our band-pass fails to explain our flux levels by factors of from 10 to 100. The complex interplay of variations of emission lines and continua during the course of a transient phenomenon makes it extremely difficult to extract any but rudimentary information. However, Thomas (1970) has pointed out that the relative flux levels measured are not significantly affected by spectral variations.

*We thank Drs. L. E. Peterson and H. S. Hudson of the University of California at La Jolla for an opportunity to inspect their data.

During the course of the October 30 and 31 loops, the cm-λ radio emission was weak, non-impulsive and probably thermal in origin. Thus our X-ray fluxes probably represent line emission and some free-bound continua, for which the flux levels are given by

$$E(8,12) \propto \int_V N_e^2 f(T_e)\, dV \sim N_e^2 V f(T_e) \quad (1)$$

where we assume an isothermal-isotropic emitting volume. $f(T_e)$ is a function of temperature appropriate to the thermal emission mechanism.

The X-ray flux curves observed in October, 1967 are not directly associated with the inferred flare events, but principally with the loops. We ask whether the loops might be the result of a compression that is quite separate from a flare process. In considering the Olson-Lykoudis compression model, then, we may write $(N_e V) = (N_{total})$, and

$$E(8,12) \propto \frac{N_{total}^2}{V} f(T_e) \quad (2)$$

since no material is to be added to the magnetic field lines. During the compression stage, if it occurs, the decrease in volume, V, may possibly act to provide a temporarily increased rate of line and continuum emission. There are two difficulties with the compression model, however, beyond those already cited.

The first difficulty is that the Olson-Lykoudis model predicts that the highest temperatures will be achieved while the compression is still in progress, and T_e will have declined significantly before the compression is completed. Thus, if indeed sufficient X-radiation is emitted, X-ray maximum will occur prior to the visible appearance of Hα loops in the system. This was not the case on October 30, 1967. A second difficulty is inherent in the model calculations: an expression derived by Orrall and Zirker (1961) was used to specify the volume emission coefficient; comparison of this expression with the calculations of Cox and Tucker (1969) shows it to be too small by about a factor of four in the relevant temperature range. Thus the predicted time-scale for development of visible loops in the compression-condensation model must be shortened well below the observed time-scale for the decay of the soft X-ray emission. We must therefore reject the model as incompatible with the observations.

In conjecturing that major loop systems are visible evidence for the storage of fast particles, Jeffries and Orrall (1965a,b) suggested that injection of the particles onto magnetic field lines above the flare site leads to increased density near the tops of the field loops, where the keV protons are thermalized. As density and temperature rise the region will expand rapidly and, cooling, produce the visible Hα loops. It is of interest to ask whether protons are injected on a short time-scale or over a long interval of time. Jeffries and Orrall (1965b) suggested that a continued injection may sometimes occur.

We assume first that all of the loops of a system are a consequence of a single event taking place on a short time-scale and that the protons are directly injected into the magnetic field loops.

Reasons have been cited for expecting expression (1) to be applicable to the observations under discussion, at a time when the plasma is thermalized. If there is a single injection event, we may use expression (2) in discussing a single loop subsequent to the thermalization stage and explosion at the top of the loop. At the time of the explosion, N_{total} will be constant, V increasing and T_e diminishing, leading to a decline of soft X-ray emission from that loop. On magnetic field lines threading higher altitudes, however, the plasma will not yet be thermalized, since thermalization time increases with decreasing mean ambient density. While we do not know the initial energies of the injected protons, the calculations of Jeffries and Orrall (1965a) indicate that for reasonable energies, protons injected into even very high loops within the permanent coronal condensation should be thermalized within 10 min. If, after thermalization and the conjectured explosion the plasma may be characterized by $T_e \sim 10^7$ °K and $N_e \sim 10^{11}$ cm^{-3}, we may calculate the time for the gas to cool to a temperature at which the Hα line becomes visible, using Cox and Tucker's (1969) emission coefficients. Assuming that the rate of change of internal energy of the gas is approximately

$$\frac{dE}{dt} = 3.5\, N_H k \frac{dT_e}{dt} \quad \text{ergs cm}^{-3}\text{sec}^{-1}$$

over the relevant temperature range (H and He fully ionized), we find that T_e will decline from 10^7 °K to 5×10^4 °K in 1.5×10^3 seconds by radiative processes alone. Electron conduction may also be an important cooling process. A comparison of the total time for thermalization and radiative cooling in a single loop (~ 35 min for high loops to first become visible under the assumptions made) with the soft X-ray decay time-scale for the entire system (~ 220 - 240 min) does not support a single-injection scheme.

On the other hand, if the plasma is driven to $T_e \sim 10^8$ °K during thermalization of the protons, the time-scale for radiative cooling to 5×10^4 °K is $1.8 \times 10^{15}/N_e$ seconds. The observed time-scale for X-ray decline then requires $N_e \sim 1.3 \times 10^{11}$ cm^{-3}. While this number density satisfies the optical observations (Jeffries and Orrall, 1965a), we can show that the single-injection model, if it is valid, would not produce such a high kinetic temperature.

In the single-injection model, all protons will be thermalized with ~ 10 min, and therefore before radiative losses have caused a significant decline in

T_e, if T_e is $\sim 10^8$ °K. Kleczek (1964) has measured the total volumes of loop prominences $V \geq 2 \times 10^{27}$ cm^3. Thus, an emission measure $N_e^2 V \geq 2 \times 10^{49}$ cm^{-3} may be estimated from the requirement $N_e = 1.3 \times 10^{11}$ cm^{-3}. If T_e rises to 10^8 °K, the result will be an enormous flux of hard thermal bremsstrahlung radiation, which is not observed.

The single-injection model then cannot be invoked to satisfy the soft X-ray observations if $N_e \sim 10^{11}$ cm^{-3} in the loops. We have the alternatives of (i) supposing $N_e < 10^{11}$ cm^{-3} or (ii) invoking an injection on a longer time-scale.

As to the former alternative, the X-ray decay time may be satisfied for $T_e = 10^7$ °K and $N_e = 1.2 \times 10^{10}$ cm^{-3} at the tops of the loops following thermalization. There still remains, however, the difficulty of the long time interval over which successively higher loops appear in the prominence system.

No single loop of a major system is seen to enlarge or to rise in altitude; rather the loops seem to appear at successively higher levels. Several hours after the initiating flare, loops are still appearing at high altitudes, but at a much reduced rate (Bruzek, 1964). Undoubtedly the very late appearance of higher loops is associated with longer thermalization times at the higher altitudes and with a longer radiative cooling time imposed by the lower densities. We suggest that it must also be associated with a later injection of energetic protons onto the highest loops.

The protons may be stored for long periods on magnetic field lines that rise beyond the inner corona (Jeffries and Orrall, 1965b) and delivered to lower field lines to produce the loop system. Our X-ray fluxes, which depend upon $N_e^2 V$, probably protray the delivery of the particles onto the prominence loops rather than the storage reservoir itself. It is not clear to us, however, why particles stored on field lines rising to high levels should be delivered to the lowest-lying loops of the prominence system first. An alternative to the storage model is the hypothesis that protons continue to be accelerated within the initiatory flare during the formation of the loop system. Under this hypothesis, our X-ray flux curves then show a slow initial development and slower decay of the secondary acceleration mechanism.

IV. Summary

Major systems of loop prominences appear to be productive of soft X-radiation on a long time-scale. In at least one such system, for which our identification is not entirely clear-cut, the X-ray emission was however quite weak.

We have compared observations of X-rays from two systems of loops (October 30 and 31, 1967) with two models for production of the loops. The data are not compatible with a compression-condensation model. The data are however compatible with the single-injection model provided (i) N_e in the loops is $\sim 10^{10} cm^{-3}$, an order of magnitude lower than the value derived from optical spectra. The particle-injection model may also be invoked, on the other hand, provided (ii) the delivery of protons into the prominence system takes place on a time-scale of hours. Our data cannot distinguish between these alternatives.

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FIGURE CAPTIONS

Figure 1. In this summary of solar data for October 30 and 31, 1967, the top panels depict times of beginning, maximum and ending of reported flares and the reported times of swept-frequency radio spectrum events. Below these is shown the soft X-ray flux, which is given as the energy flux integrated over the wavelength interval 8 to 12 Å as measured at the earth. In the lower half of the figure, single-frequency radio bursts are schematized according to the author's interpretation of data published in the Quarterly Bulletin of Solar Activity. Radio flux density is measured in units of 10^{-22} watts m^{-2} Hz^{-1}. The observed times of loop prominence activity are shown just above the X-ray record.

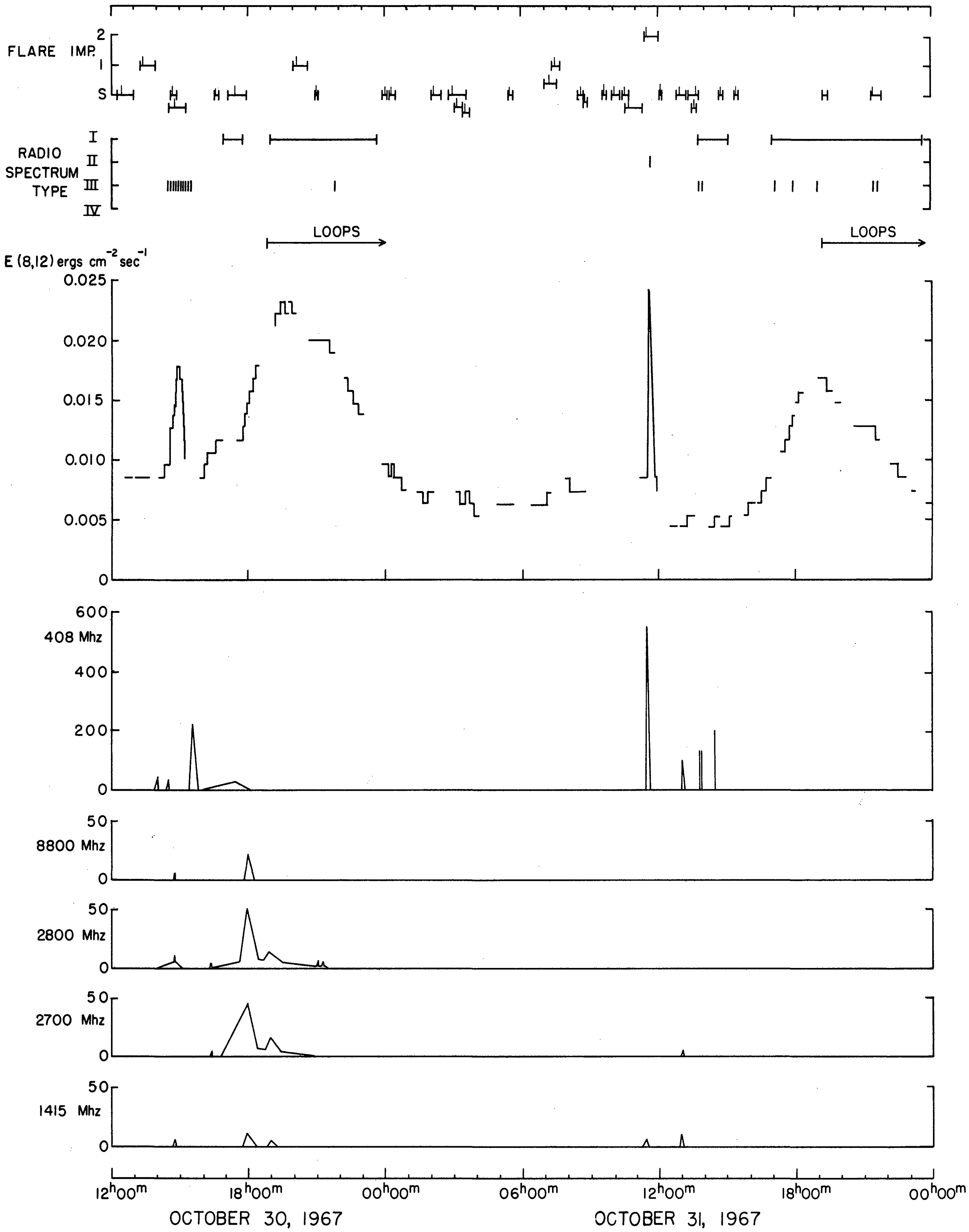
Figure 2. a. Sacramento Peak Observatory film of west limb loops, $21^h42^m53^s$ UT October 31, 1967. H-alpha.

b. Sacramento Peak Observatory film of west limb loops, $22^h34^m20^s$ UT October 31, 1967. H-alpha.

c. Lockheed Observatory flare-patrol film (H-alpha) taken at 20^h08^m UT October 30, 1967.

Figure 3. Solar data summary for June 1, 1967. The top panels depict flare occurrence and reported swept-frequency radio spectrum events. Below these we schematically show reported cm-λ and dcm-λ single-frequency bursts. At the bottom is the soft X-ray flux record. Loop prominence occurrence is shown just above the X-ray record.

Figure 4. Solar data summary for May 21, 1968. Flares, swept-frequency radio spectrum events, single-frequency bursts and X-ray fluxes are shown. Loop prominence occurrence is shown just above the X-ray flux record.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I
II
III
IV
LOOPS
LOOPS
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0.020
0.015
0.010
0.005
0
600
408 Mhz
400
200
0
50
8800 Mhz
0
50
2800 Mhz
0
50
2700 Mhz
0
50
1415 Mhz
0
12^{h}00^m
18^{h}00^m
00^{h}00^m
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OCTOBER 30, 1967
OCTOBER 31, 1967

Figure 1

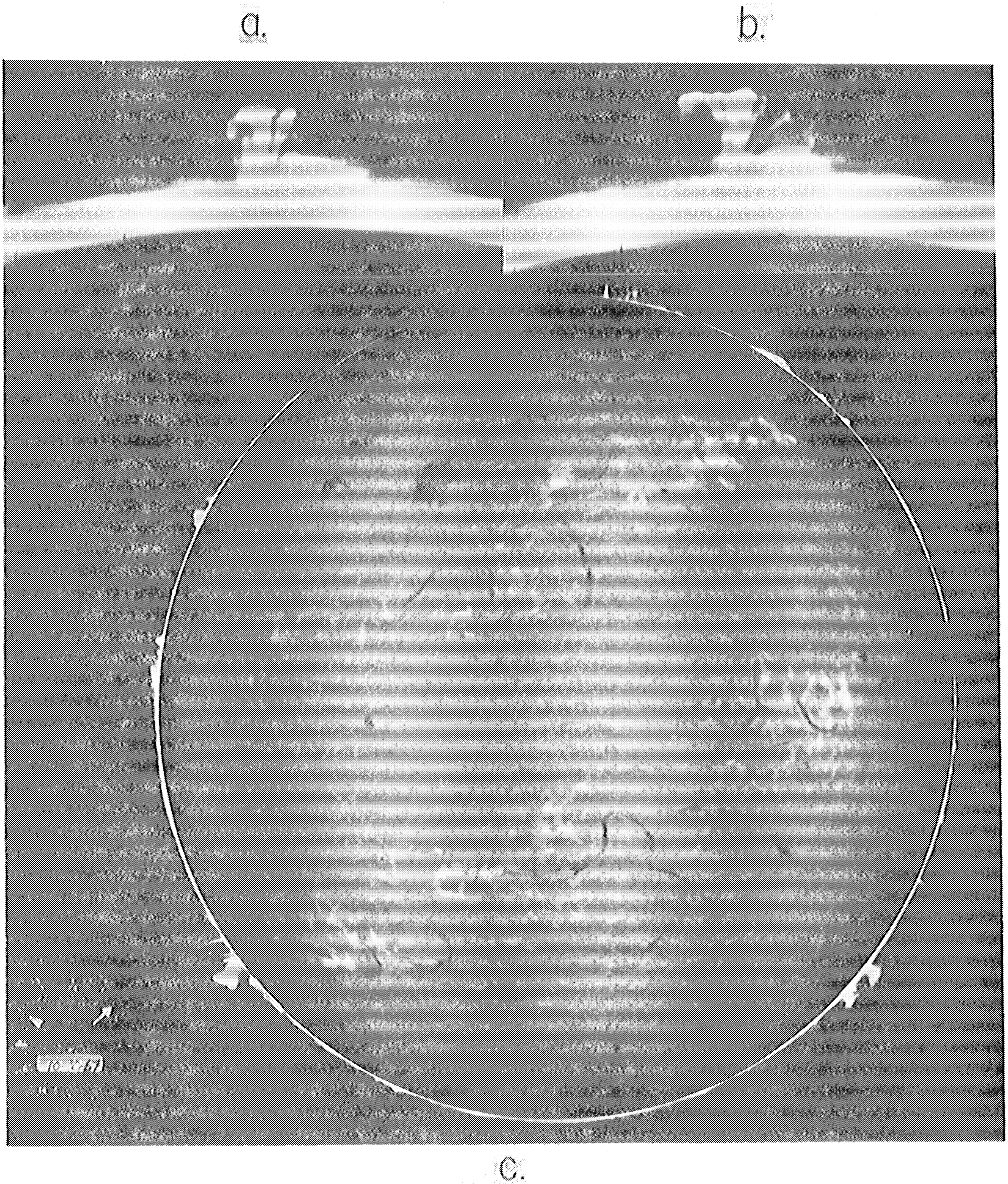
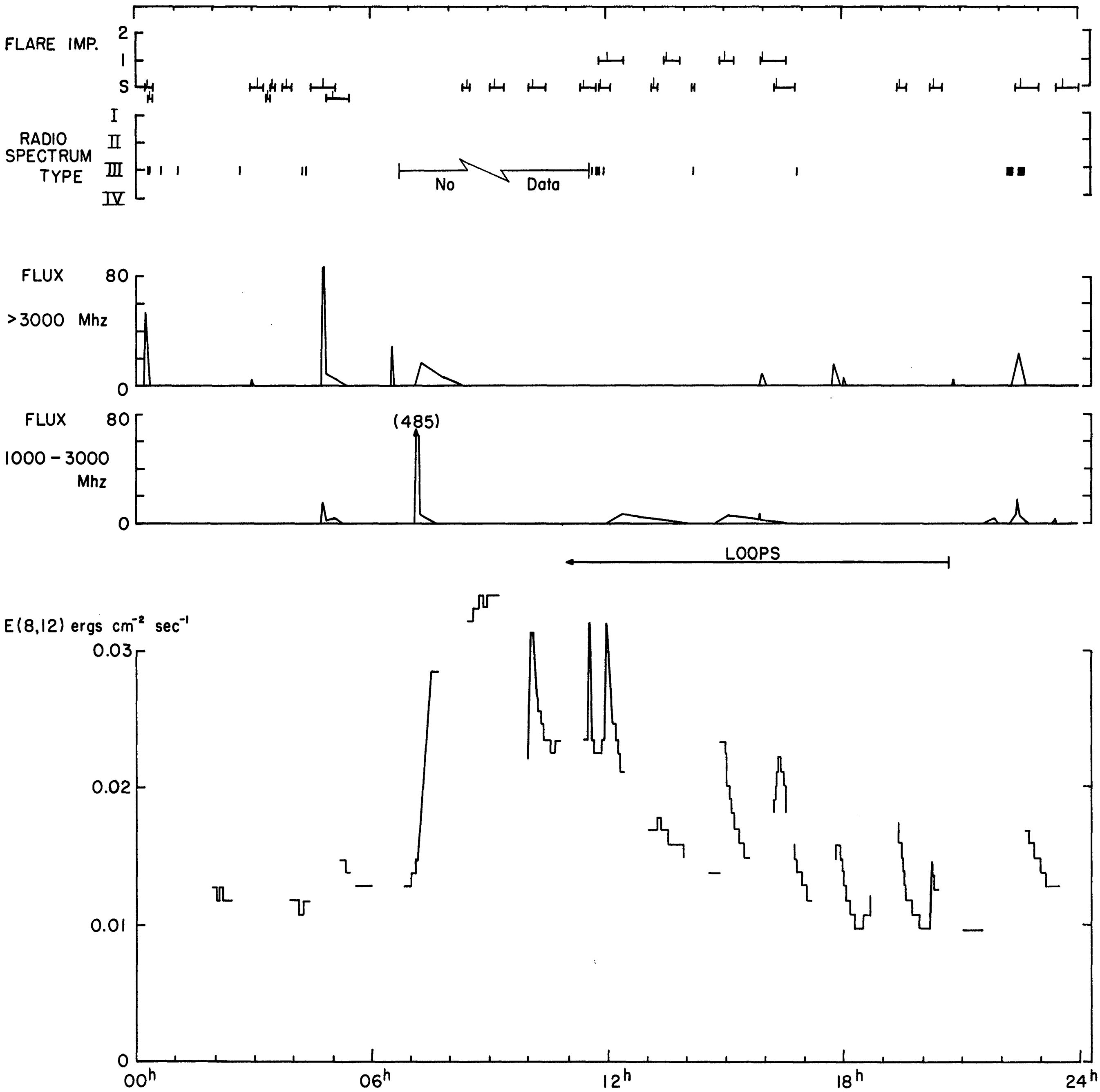


Figure 2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III
IV
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0
FLUX
80
1000 - 3000
Mhz
0
(485)
LOOPS
E(8,12) ergs cm⁻² sec⁻¹
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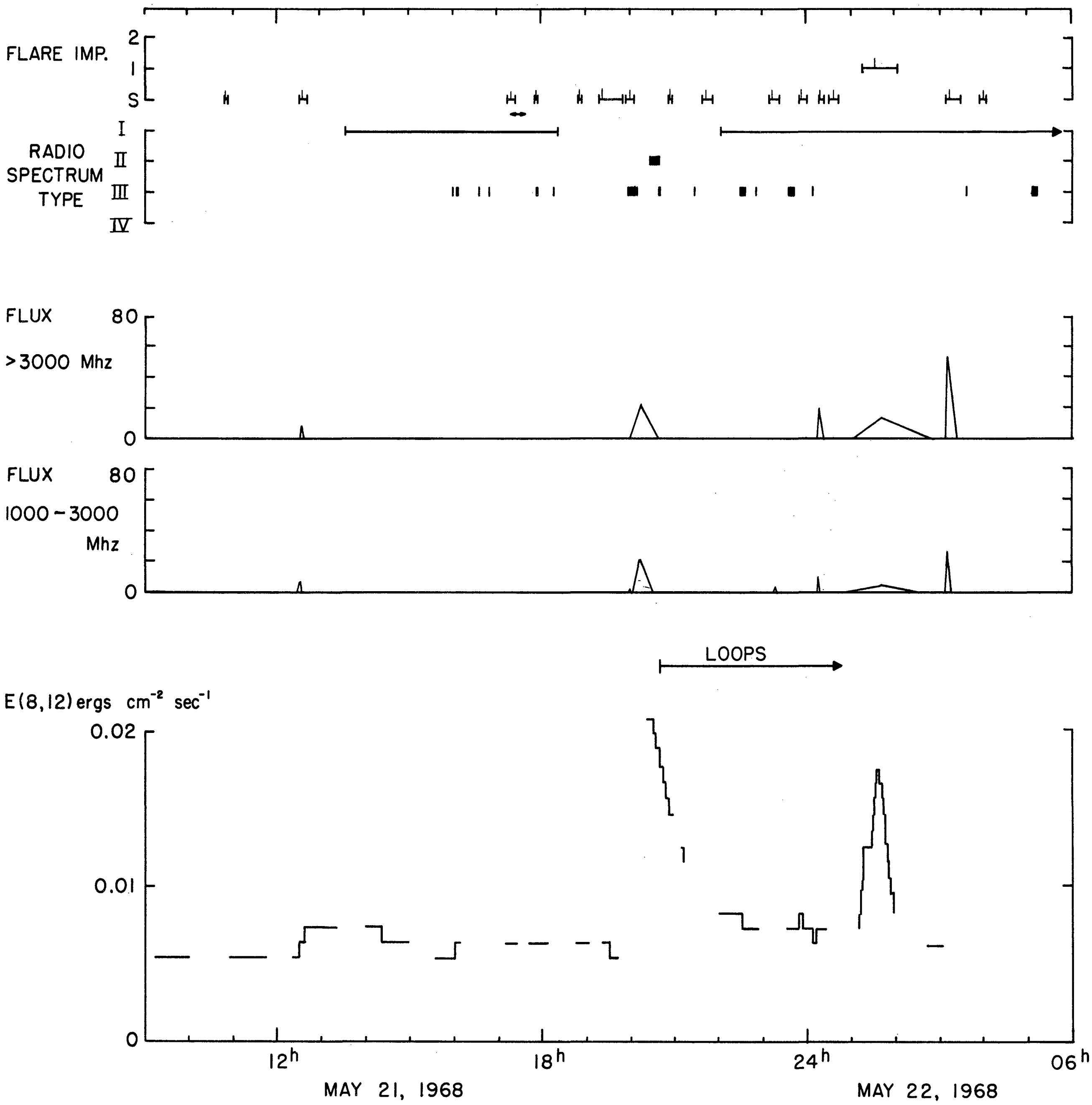
0.02
0.01
0
00h
06h
12h
18h
24h
JUNE 1, 1967

Figure 3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II
III
IV
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80
0
FLUX 1000-3000 Mhz
80
0
LOOPS
E(8,12) ergs cm-2 sec-1
0.02
0.01
0
12h
18h
24h
06h
MAY 21, 1968
MAY 22, 1968

Figure 4

SOFT SOLAR X-RAYS AND SOLAR ACTIVITY

V. Some Evidence for the Altitude of X-Ray Source Volumes in Solar Flares

Introduction

Currently, solar flare observations extending from the X-ray region of the spectrum into the longer radio wavelengths are provding information on flare structure and the physical processes within them. Interpretation of the data has left some questions open, however.

The altitude of the flare-associated hard X-ray source has been placed by some authors at solar atmospheric levels where $N_e \sim 10^9 cm^{-3}$ (Hudson, Peterson and Schwartz, 1969). Arnoldy, et al. (1968), have suggested that the microwave and hard X-ray source volumes are coextensive, and also have argued that the radio data alone may be consistent with $N_e \sim 10^{14} cm^{-3}$. Takakura and Kai (1966) present evidence in favor of a cm-λ and X-ray source volume at levels where $N_e \sim 5 \times 10^{10} cm^{-3}$, while Kiepenheuer (1964) suggested that flares occur at a level at which $N_e \sim 10^{10}$-$2 \times 10^{10} cm^{-3}$. Zirin, et al. (1969), have discussed an event in which the hard X-ray source appeared to be co-spatial with the Hα source, while Vaiana et al. (1968), interpret their June 8, 1968, flare photograph as showing that the Hα and X-ray source volumes are not coextensive Estimates of the emission measure, $\int N_e^2 \, dV$, for X-ray source regions vary from $10^{47} cm^{-3}$ (Hudson, et al., 1969) to a few times $10^{48} cm^{-3}$ (Culhane and Phillips, 1970). These are in general agreement with the sizes of cm-λ radio-emitting sources which are deduced from interferometry (Kundu, 1965), only if electron densities near $10^9 cm^{-3}$ are invoked.

There thus is as yet no clearly general agreement as to the positions and spatial organization of X-ray, cm-λ and Hα source volumes associated with flares, although these questions are being attacked by experiments—in progress and planned—which observe them with good angular resolution. It is possible, however, to investigate these problems with an experiment having no intrinsic angular resolution, if flare events taking place at and just behind the solar limb are observed. In such cases the spatial resolution is afforded by the sun' limb and by the temporal behavior of radiations that are observed, although the spatial discrimination is, of course, very crude.

This contribution represents an attempt to utilize observations of such limb events to supply some information about the relative heights of flare source volumes within the solar atmosphere.

The X-ray data which were used were gathered with the Michigan soft X-ray monitor on board the OSO-III (Teske, 1969; Thomas, 1970). This instrument observed the solar soft X-ray component between 8 and 12 Å with a time-resolution of 1.7 seconds; the whole disk was monitored without angular resolution. In the data accumulated, there are a number of events of significant X-ray amplitude which associate very poorly or not at all with visible flare phenomena. Almost always at the time of such events there was a flare-rich active center on or just behind the solar limb. We have thereby gained the impression that the OSO-III soft X-ray ion chanber at times viewed X-radiation from elevated source volumes associated with flares which occur slightly beyond the sun's limb (infra-limb flares). This impression is consistent with what is known from studies of SID phenomena (Dodson and Hedeman, 1964), with photographs of elevated X-ray source volumes above non-flaring active centers (Vaiana et al., 1968) and with current concepts of flare morphology. Because our instrument has no angular discrimination, the assignment of an otherwise unidentified X-ray enhancement to an infra-limb flare in a particular active center has great hazards unless the assignment can be based upon reliable criteria other than simply the flare-richness of the region. However, the study of correctly-identified events can supply rewarding information.

Five X-ray events which were observed during 1967 and which likely were associated with infra-limb flares were selected for study. Each is discussed individually below, in order of credibility. The assembled information suggests that the volume in which the "flare impulse" or explosion occurs may, in some flares, possibly be in the vicinity of an altitude of 10^4km, and that there is a separation of source volumes, with the soft X-ray source lying below the cm-λ source.

Observations

A. AUGUST 18, 1967, 02^h23^mUT

Several major X-ray bursts accompanied the east limb passage of McMath plage #8942. A very extensive and bright plage containing large and magnetically-complex spot groups, it appears to have been the amalgamation of several flare-rich active centers from the previous rotation. During its disk passage, plage #8942, like its parents, dominated solar activity.

The two greatest X-ray events observed by OSO-III on August 18, 1967, have the appearance of homologous events.* The second of these accompanied an imp 1n flare on the visible side of the limb, beginning at 21^h31^mUT. The first X-ray event began at 0223 UT, and we have inferred it to have been associated with an infra-limb flare in the same region.

In Figure 1 we present the X-ray and radio observations for the time of the suspected infra-limb flare. The radio data were kindly communicated to us by Dr. S. Enome at Toyokawa. During the important time interval, the Haleakala photographic flare patrol and the Ikomasan visual patrol were in operation.

*This was initially pointed out to us by Dr. Hugh Hudson.

Both observatories reported a subflare at the east limb. Dr. John Jeffries has very kindly made available to us copies of the Haleakala filtroheliograms. These show the appearance of a small flare (projected area ~ 100 millionths of the disk) from behind the east limb at 0239 UT, its maximum at 0248 UT (see Figure 2) and its disappearance at 0306 UT.

Although other flaring activity was going on in plage #8940 on the visible disk around the times of interest to us, it is difficult to associate the major radio and X-ray bursts that were observed with that visible activity if we use the timing and relative flux amplitude criteria that have been established for the soft X-rays and cm-λ bursts (Teske and Thomas, 1969). On the other hand the same criteria are also violated by the very late appearance of the limb flare and by its small area, but if we postulate that the visible limb phenomenon was a part of a larger infra-limb flare, the violations may be explained.

By intercomparing data from the Michigan soft X-ray photometer and the University of California hard X-ray counter (which also observed the event from OSO-III) we have erected criteria for judging the consistency of behavior of flare events. By these criteria for visible flares, the soft X-rays, hard X-rays and cm-λ flux for this flare are all in general agreement with one another as regards relative starting times, times of maxima and relative peak fluxes (or spectrum). Moreover, the event showed decided impulsive characteristics at those wavelengths that were observed. However, no swept-frequency m-λ events (Types II, III, or IV) were reported near the times of interest, although Sydney was observing.

In our interpretation of this event, both the region of the "flare impulse" or explosion and most or all of the X-ray and radio source volumes were above the solar limb and were visible at the earth. The magnitude of these emissions together with the late appearance, small projected area and feeble brightness of the Hα aspect suggests that only a part of a larger, lower-lying optical source was seen at visual wavelengths.

We have estimated the longitude of the flare to have been 9° (+3°,-6°) behind the solar limb by plotting the longitudes of subsequent flares, fitting them to a line of slope equal to the rate of solar rotation at the flares' mean latitude and by extrapolating the line back to the time of radio burst onset. Thus, heights down to within ~ 10^4 km above the flare were being observed. The visible part of the flare may have extended to ~ 2.0×10^4 km above its base.

B. JUNE 1, 1967, 07^h00^m UT

McMath plage region #8818 transited the disk during the latter half of May, 1967. One of the most active regions of 1967, it produced two PCA events (May 23 and May 28) and many other major flares. By May 30, flaring was most pronounced in the western part of the region so that during its west limb passage on May 31, June 1 and 2, the most active portions set behind the limb first.

On June 1 a strong soft X-ray enhancement began at 0700 UT, near the time of a major burst on 2000 MHz which was not identifiable with a visible Hα flare (see Figure 3). The X-ray background remained high until at least 1500 UT. A loop prominence system was subsequently observed on the west limb in the position angle of plage #8818 (Teske, 1970). The loop system was well developed by 1103 UT when cinematographic observations were commenced at McMath-Hulbert Observatory.

We have inferred from these observations that an infra-limb flare probably occurred in plage #8818 behind the west limb. The estimated flare longitude is W98° (±6°), so that heights down to ~ 10^4 km above the flare were being observed.

Although the radio burst on 2000 MHz was strong (485 flux units) and impulsive, the radiation at higher frequencies was weaker and less impulsive, implying an unusual radio-frequency spectrum. The accompanying soft X-ray burst, between 0700-0730 UT, was characterized by a slow rise having a less steep slope than is usually found in association with major cm-λ and dcm-λ bursts. The X-ray maximum occurred $\gtrsim$ 20 min after the 2000 MHz maximum, very long in comparison with bursts accompanying visible flares (Teske and Thomas, 1969). Our data indicate that the soft X-ray maximum may have occurred near 0900 UT, but this maximum is probably contaminated to an unknown extent by X-rays from a subflare and likely contains a component associated with the loop prominence system as well (Teske, 1970). When we take this into account, however, we find that the soft X-ray amplitude associated with the radio burst is not in disaccord with the 3100 MHz burst amplitude (Teske and Thomas, 1969).

Our interpretation of these observations, the relatively slow X-ray rise and its delayed maximum which eventually reached a flux level appropriate to the cm-λ amplitude, is that the 2000 MHz source lay at atmospheric levels above the soft X-ray source, which then rose or expanded until a major fraction, at least, was visible from earth. The impulsive volume of the 2000 MHz source lay at altitudes $\gtrsim 10^4$ km, a conclusion that is consistent with the electron density model of the solar atmosphere. The inferred expansion or upward propagation of the soft X-ray source volume may be connected with the subsequent formation of the system of loop prominences.

C. OCTOBER 30, 1967

During its transit of the western side of the solar disk, McMath plage region #9034 developed into a richly-flaring active center; the incumbent spot group was classified as δ on October 26 (and was not classified again until very close to the limb on October 29, when it was described as β). The increasing pace of visible flaring activity after October 25 was culminated by a flare of importance 2 on October 29 which was associated with a major cm-λ impulsive burst followed by a strong, long-enduring post-burst phase and reported loop prominences.

Two long-lived soft X-ray enhancements were observed on October 30 and 31, during and after west limb passage of the region. Both events were accompanied by the appearance of major loop prominence systems (Teske, 1970).

The soft X-ray, radio and optical data for the two days are summarized in Figure 4. In the figure, the decline in X-ray background is caused by the disappearance of region #9034 behind the sun's limb. The shorter X-ray bursts accompanied flares in other active centers on the visible disk.

We first discuss the October 30 event.

The imp 1n flare in #9034 on October 30 (1317-1320-1407 UT) apparently was unaccompanied by a strong soft X-ray burst or radio burst. (In flares, generally, a reportable cm-λ burst is accompanied by a detectable soft X-ray burst, although a weak X-ray burst is not necessarily accompanied by a reportable cm-λ burst. In the mode of operation of our photometer during October 30 and 31, X-ray bursts of small amplitude $-\Delta E(8,12) \leq 0.001$ ergs $cm^{-2}sec^{-1}$- would not have been recorded. Such small X-ray bursts are not usually accompanied by reportable cm-λ events.) The McMath flare patrol films start at 1401 UT and show an active prominence at the limb position of #9034. Activity in the region continued sporadically during the day on our films with small surges, the development of a small eruptive prominence and muted brightenings at the limb. None of these suggest themselves as obvious sources for the prolonged slow rise in X-ray flux that began at about 1600 UT. An ADF reported by Sacramento Peak Observatory (N24 E42) between 1654 UT and 2400 UT is in the wrong disk position to have produced the X-rays, which were observed to come from the west limb by an angularly-resolving experiment on board OSO-IV (Kreiger, 1969).

However, Sacramento Peak reported possible very faint loops at the position of #9034 between 1654E UT and 1746U UT and bright loops seen edgewise between 2019E UT and 2400D UT. The loops were not present on exposures made at 1813 UT. The system can be seen faintly on McMath flare patrol films beginning at 1850 UT and developed slowly until the end of observations at 1956 UT. Dr. Charles Hyder has kindly re-examined the Sacramento Peak films and reports that the loop system was faint (~0.1 chromospheric intensity in Hα) when first seen when clouds cleared after 2019 UT, and that the loops extended to an altitude of 1.0×10^5 km by 2201 UT reaching, 1.2×10^5 km by 2315 UT (Hyder, 1969).

Lockheed Observatory reported a flare in #9034 at (1959-2008-2035 UT). Figure 5c reproduces the Lockheed Hα frame exposed at 2008 UT showing the reported flare extending from the northwest limb in the disk field of the photograph and the feature which is identified as the loop prominence system in the limb field of the photograph. Mr. Samuel Miller very kindly made the photograph available to us. The flare in Figure 5c occurred after the loop prominence system was already well-developed.

Loop prominences are usually associated with the late phases of flares of imp 2 and 3 (Bruzek, 1964) especially with those that produce Type IV radiation (Dodson, 1961), although Bruzek's list shows that loop systems at the limb are seldom accompanied by Type IV (Bruzek, 1964). The absence of Type IV emission in the present case (see below) does not strongly militate against an inference that a major flare occurred just behind the limb, while the major system of loop prominences would appear to be sufficient evidence for this inference. No definitive optical evidence, other than the loop system, can be cited.

At 1725 UT a low bright mound was seen on our Hα flare patrol films in the limb position of plage #9034. It became relatively prominent at 1737 UT, reached a maximum height and brightness at 1759 UT when two small surges developed, and had subsided by 1850 UT when the first evidence for the loops could be seen. We do not regard this evidence as definitive. The major cm-λ burst began at 1737+ UT and reached a peak (~50 flux units on 2800 MHz) at ~1754 UT. During this interval—1724 to 1824 UT—the X-rays displayed a slow monotonic rise. Such a relationship between the cm-λ burst component and soft X-rays is not at all like that developed for visible flares (Teske and Thomas, 1969). The radio bursts and X-rays thus cannot easily be associated with the visible subflare that occurred in plage #9041 near these times (1707-1724-1754 UT).

Type III bursts were occurring sporadically in the interval 1429-1530 UT, somewhat earlier than the times of interest. Type I and continuum were reported throughout the interval 1330-2340 UT. Type IV was not reported, and the Fort Davis records were generously re-examined by Dr. Maxwell, who again reported no evidence of any kind for Type IV (Maxwell, 1969). Thus there is no indirect evidence for an acceleration event that would have produced an impulsive component.

It seems to us likely that the bulk of the soft X-radiation observed in this event and that on October 31 was associated with the loop prominenece systems (Teske, 1970). We note that the cm-λ burst, if it had accompanied a flare on the visible disk, would be expected to be associated with a soft X-ray burst of amplitude $\Delta E(8,12) \sim 0.03 - 0.04$ ergs $cm^{-2} sec^{-1}$, and in reasonable time-association (Teske and Thomas, 1969). Because no X-ray burst was seen with the cm-λ burst, the X-ray source volume associated with the cm-λ source may have been at atmospheric levels below the cm-λ source and partially or wholly hidden by the sun's limb.

In summary, we infer on the evidence of the loop prominences and the cm-λ event the occurrence of a major infra-limb flare on October 30, beginning prior to 1850 UT and perhaps as early as 1737 UT, when the cm-λ burst began. The absence of a sharp increase in soft X-ray flux at the time of the 1737 UT radio burst suggests a separation of source volumes, with the soft X-ray source volume being the lower. We have estimated, again by plotting flare longitudes and extrapolating, that the inferred flare occurred 9° (+2°, -7°) behind the limb, giving a sagittal height of $\sim 10^4$ km. If we speculate that the loop prominences are evidence for an acceleration event, and that an impulsive phase must have taken place, then the impulsive volume lay below the 10^4 km level. The absence of Type II and Type IV emissions are arrayed against this speculation, however, although it is unusual for loops at the limb to be associated with Type IV (Bruzek, 1964). Yet we note the previously-discussed event of August 18, 1967, had an impulsive component without giving rise to Type II, III, or IV radiations.

D. OCTOBER 31, 1967

A loop prominence system was observed optically on October 31 at the northwest limb position of plage #9034, and a slow X-ray event like that of the previous day was again recorded in time-association with the optical event (Figure 4). We infer from the occurrence of the loops that a major infra-limb flare took place, beginning prior to 1912 UT, when the first faint tops of the loop system were seen (Hyder, 1969).

The loop system extended to 20,000-30,000 km altitude above the limb by 1916 UT and to 40,000 km by 1924 UT, reaching maximum brightness by 1945-1955 UT (Hyder, 1969). We estimate that the inferred flare took place 23° (+7°, -9°) behind the limb, giving a sagittal height of $\sim 6 \times 10^4$ km. Thus the loop system probably extended to $\sim 10^5$ km above the flare region by 1924 UT. The system, like its predecessor on the day before, thus ranks among the tallest loop systems discussed by Bruzek (1964). Hα filtroheliograms taken at Sacramento Peak have been communicated to us by Dr. Hyder, and are reproduced in Figures 5a and 5b.

No Type III or Type IV radiation was observed on October 31 that might be connected with this event. There was no impulsive part to the cm-λ burst. A weak cm-λ event that was in progress near 1300 UT (Figure 4) may be associated with subflaring activity on the visible disk. The long-lived but weak 2700 MHz burst which began just after 1700 UT has no identifiable optical counterpart and may be associated in some way with the inferred flare.

Generally, flares accompanied by major systems of loop prominences are major flares of large area which give rise to strong cm-λ radiation and to strong X-radiation. We speculate that on October 31, 1967, such a flare did occur, and that the weak or absent X-radiation and weak cm-λ radiation stipulates that the bulk of the X-ray and cm-λ sources lay below an atmospheric level of $\sim 6 \times 10^5$ km. Subsequent to the main flare onset an expansion or outward propagation of the soft X-ray source volume may have taken place that shifted the soft X-ray source to levels above the limb that made it visible from the earth. Alternatively we may speculate that the active volume incorporating the loop prominences became a source of soft X-radiation after the main flare phase. Since a motion of the X-ray source is unlikely, we prefer the latter interpretation (Teske, 1970).

E. JULY 11, 1967, 20^h35^m UT

On July 11, 1967 there occurred a weak, slow X-ray enhancement in association with a small cm-λ burst and a Type IV dkm-λ event. The data are summarized in Figure 6. During the time interval of interest no significant activity was visible in our Hα flare-patrol records on the disk or on the limb. Because of the intervention of satellite night, we do not know if the X-ray event had an impulsive component. There was no X-ray activity seen during the previous daylight pass, 1917-1948 UT. Although for our observations we have no optical or other data to aid in ascription of the phenomena to an infra-limb flare in any region, the importance of the occurrence of Type IV and soft X-rays in close association without a visible flare has captured our attention. There were then no regions behind the east limb that had been flare-prolific during their previous apparition nor that would be flare-productive after their east limb passage in July. There are, however, two candidates that were then behind the west limb that might have produced a major flare.

1. Plage #8871 (Latitude N28)

This region (CMP July 1.3) with its incumbent large α spot rounded the northwest limb on July 8. While it was visible on the disk, only a few subflares were seen prior to July 5, when its pace of flaring picked up and continued moderately high until west limb passage. These flares were of imp 1 and 1-. After July 5 the spot was bifurcated and diminished, although the trailing part of the plage grew in brightness. The flares took place preferentially in a part of the plage preceding the α spot which rounded the limb on the 7th and within the newly-developing trailing part of the plage which rounded the limb on the 8th. By July 7, all flares were occurring in the trailing region, an observation that may however be due to the extreme limbward position of the large α spot. In its next apparition at the east limb on July 21 the region was bright and extensive, incorporating a large and magnetically complex spot group. This daughter plage, designated #8905, dominated solar activity during late July and early August. At its subsequent east limb appearance on August 18, the region was designated #8942 and gave rise to the first event studied in this communication.

If a flare in this region did act to produce the observed Type IV and X-radiation, it must have taken place roughly 40° behind the west limb, and the emitting structures have to have risen $\sim 2.5 \times 10^5$ km to become at least partially visible to the earth. While this rather extreme, such structures have been observed at radio frequencies (Kundu, 1965). Selection of this region to explain the observations then requires that the observed Type IV and X-rays arise in a volume containing relativistic electrons that extends a significant fraction of a solar radius out into the corona. It then becomes difficult to understand the short duration of the cm-λ burst relative to the durability of the other radiations.

2. Plage #8875 (Latitude S22)

The sunspot group in plage #8875 (CMP July 4.5) underwent rapid growth on July 1 and 2. On the 4th and 5th considerable flaring activity was observed in it, with flares all of imp $\leq$ 1. On the 9th an imp 1b flare was reported, while on July 11 one cinematographic flare patrol station (Cape) reported an imp 2n flare on the limb at 1027 UT. We have no X-ray data for that time. The spot group, reported δ on the 5th and 7th, had simplified to α by west limb passage on the 10th of July.

Ascription of the observed Type IV and soft X-rays to an infra-limb flare in this region poses less height difficulties than does ascription to plage #8871. Extrapolated flare longitudes indicate it should have taken place 11° (±2°) behind the limb; sagittal heights down to 2 x 10^4 km were being observed. That no visible flare was observed is consistent with the observations of August 18, 1967 and October 30, 1967, already discussed. Further, the relative amplitudes of cm-λ burst and soft X-ray burst are generally in accord with the relation established for visible flares, although the relative times of maxima are in violation of the established relative timing for maxima. The observation of Type IV radiation leads us to believe that a particle acceleration event took place. While our X-ray data do not rule out an impulsive phase, the 2800 MHz data kindly sent to us by Dr. Covington show that there was no impulsive phase at cm-λ. Thus, if an acceleration event did occur, it must have taken place at altitudes below 2 x 10^4 km, if we wish to assign this event to an infra-limb flare in place #8875.

Summary

Soft X-ray, radio-frequency and optical observations have been described for five inferred infra-limb flare events.

On August 18, 1967, solar atmospheric levels down to ~ 10^4 km were observed in the event. A portion of the Hα flare was seen above the limb and both the cm-λ and X-rays were strongly impulsive. The interrelations among the burst timing and amplitudes were such as to suggest that most or all of the source volumes were visible to the earth.

In the event of June 1, 1967, atmospheric levels down to ~ 10^4 km were again observed. While the 2000 MHz burst was strongly impulsive, the soft X-rays were not, and we have inferred a separation of source volumes with the cm-λ source lying at or above 10^4 km altitude, and the initial X-ray source below this. During the event, the X-ray source appears to have expanded to higher levels, a phenomenon that was probably associated with formation of a system of loop prominences.

Atmospheric levels down to ~ 10^4 km were again observed on October 30, 1967. The cm-λ and soft X-ray bursts were not strongly impulsive, although the occurrence of loop prominences may require that an acceleration event did occur. The data again suggest a separation of source volumes, with the greater part of the soft X-rays associated with the main flare phase being generated below the sagittal level while at least a part of the cm-λ source was located above that altitude. The slow development of the soft X-ray enhancement was associated with formation of loop prominences.

On October 31, 1967, atmospheric levels below 6 x 10^4 km were unobservable. The data suggest that during the inferred main flare phase both the soft X-ray and cm-λ sources lay below that altitude. As on October 30, a slow development of soft X-radiation was associated with a major loop prominence system.

The July 11, 1967 cannot be ascribed reliably to an inferred infra-limb flare in any particular active center.

It is not advisable to generalize on basis of this small sample of observed phenomena, especially since an observational selection has strongly biased the choice of events towards those inferred infra-limb flares which give rise to loop prominence systems. It has not escaped our notice, however, that among the first three events discussed, all having roughly the same sagittal height of 10^4 km, only that event having a clearly identifiable Hα counterpart above the limb displayed impulsive characteristics in both cm-λ and soft X-rays. This comment will apply if we choose to ascribe the July 11, 1967, event to a flare in plage #8875, also. The data suggest that the volume in which the "flare impulse" or explosion occurs certainly lies below 6 x 10^4 km altitude, and may in some flares lie in the vicinity of h = 10^4 km, as on October 30, 1967.

It is a pleasure to thank the following people who shared their data and/or comments concerning the events discussed: Dr. Arthur Covington, ARO, National Research Council, Canada; Dr. S. Enome, The Research Institute of Atmospherics, Nagoya University; Dr. Charles Hyder, Sacramento Peak Observatory; Dr. John Jeffries and Mrs. Marie McCabe, Institute for Astronomy, University ofHawaii; Dr. A. Kreiger, American Science and Engineering; Dr. Alan Maxwell, Harvard Radio Astronomy Station; Mr. Samuel Miller, Lockheed California Company; Drs. L. E. Peterson and H. S. Hudson, The University of California at La Jolla.

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FIGURE CAPTIONS

Figure 1. The August 18, 1967, soft X-ray burst—portrayed in the top panel—saturated our OSO-III detector for 8 min. A change in slope on the ascending branch of the X-ray flux curve occurs at the time of the second component of the radio burst. X-ray flux is given as the energy flux integrated over the wavelength interval 8 to 12 Å as measured at the earth. Radio flux density is measured in units of 10^{-22} watts $m^{-2}Hz^{-1}$.

Figure 2. H-alpha flare patrol frame taken at Haleakala at 02^h48^m UT August 18, 1967. Solar north is at the top, east to the left. The reported limb subflare may be seen on the east limb.

Figure 3. At the top of this summary of solar data for June 1, 1967, we depict the times of beginning, maximum and ending reported for flares. Radio spectrum events are shown below the flare data. On this date, only Type III bursts were reported in the Quarterly Bulletin of Solar Activity (QB). Centimetric and decimetric wavelength radio bursts are shown schematically, according to the author's interpretation of data published in the QB. At bottom is the soft X-ray flux. The loop prominence system was seen in progress at 1103 UT, ending by about 2040 UT.

Figure 4. Summary of data for October 30 and 31, 1967. Reported flares and radio spectrum events are shown at the top. Below these is shown the soft X-ray flux record and in the lower half of the figure we schematize single-frequency bursts as reported in the QB. Times of observed loop prominence activity are shown just above the X-ray record.

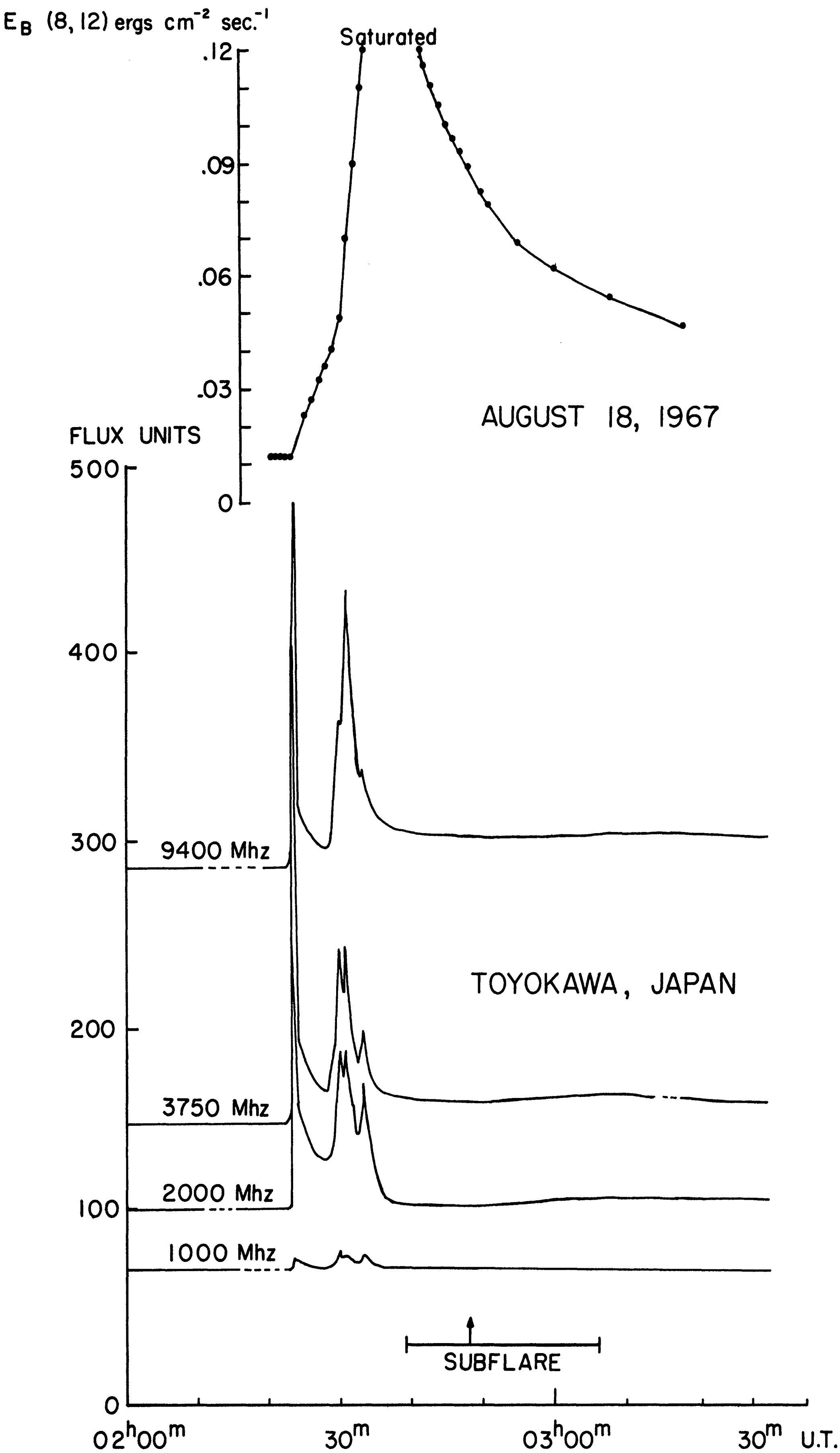
Figure 5.

a. Loops in H-alpha at $21^h42^m53^s$ UT, October 31, 1967. Sacramento Peak film.

b. Loops in H-alpha at $22^h34^m20^s$ UT, October 31, 1967. Sacramento Peak film.

c. Flare-patrol frame in H-alpha, 20^h08^m UT October 30, 1967. Lockheed Observatory film. The feature identified as a system of loop prominences is at the lower left, pointing at the clock image.

Figure 6. Data for July 11, 1967, showing reported course of dekameter Type IV burst, soft X-ray flux and 2700 MHz record. No flux scale is provided for the latter, but the scale may be judged from the reported amplitude of the 2800 MHz burst at 2043 UT: 2.6 flux units. The X-ray detector changed its energy sensitivity at 2040 UT and again at 2206 UT.



E_B (8, 12) ergs cm^-2 sec.^-1
Saturated
.12
.09
.06
.03
0
AUGUST 18, 1967
FLUX UNITS
500
400
300
200
100
0
9400 Mhz
3750 Mhz
2000 Mhz
1000 Mhz
TOYOKAWA, JAPAN
SUBFLARE
02h00m
30m
03h00m
30m U.T.

Figure 1

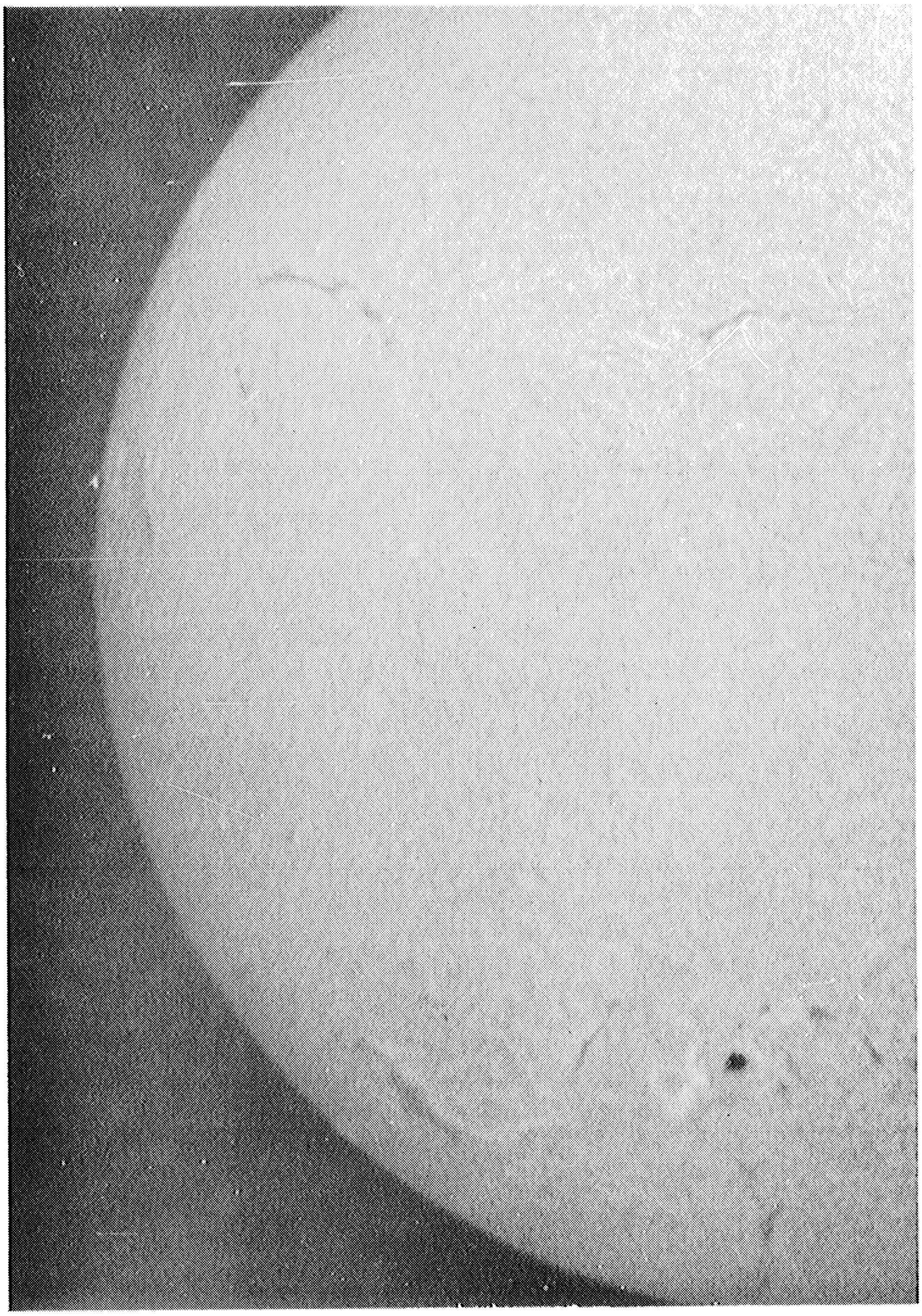
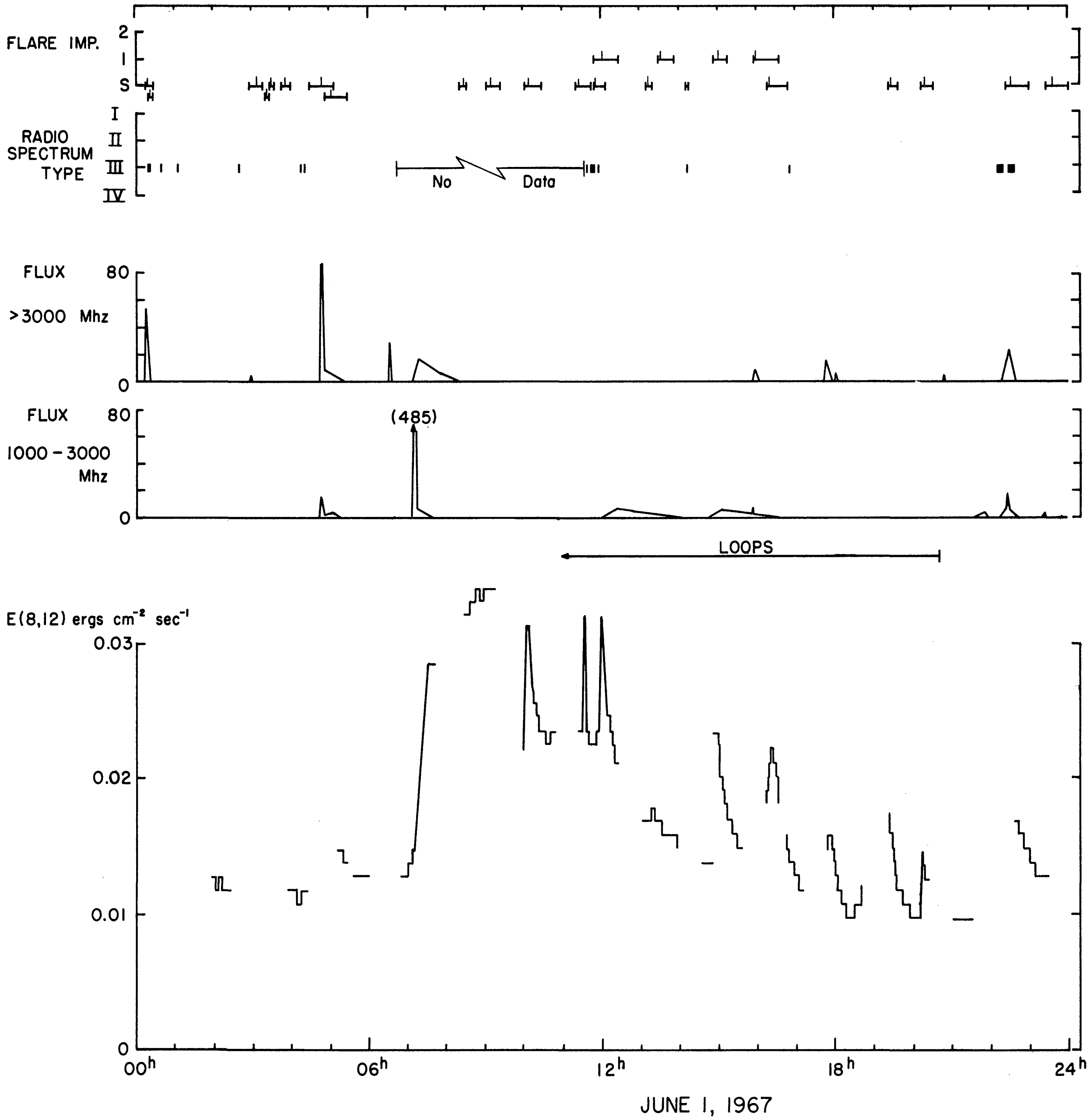


Figure 2


FLARE IMP.
2
1
S
RADIO SPECTRUM TYPE
I
II
III
IV
No Data
FLUX >3000 Mhz
80
0
FLUX 1000 - 3000 Mhz
80
(485)
0
LOOPS
E(8,12) ergs cm^{-2} sec^{-1}
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0.02
0.01
0
00^h
06^h
12^h
18^h
24^h
JUNE 1, 1967

Figure 3

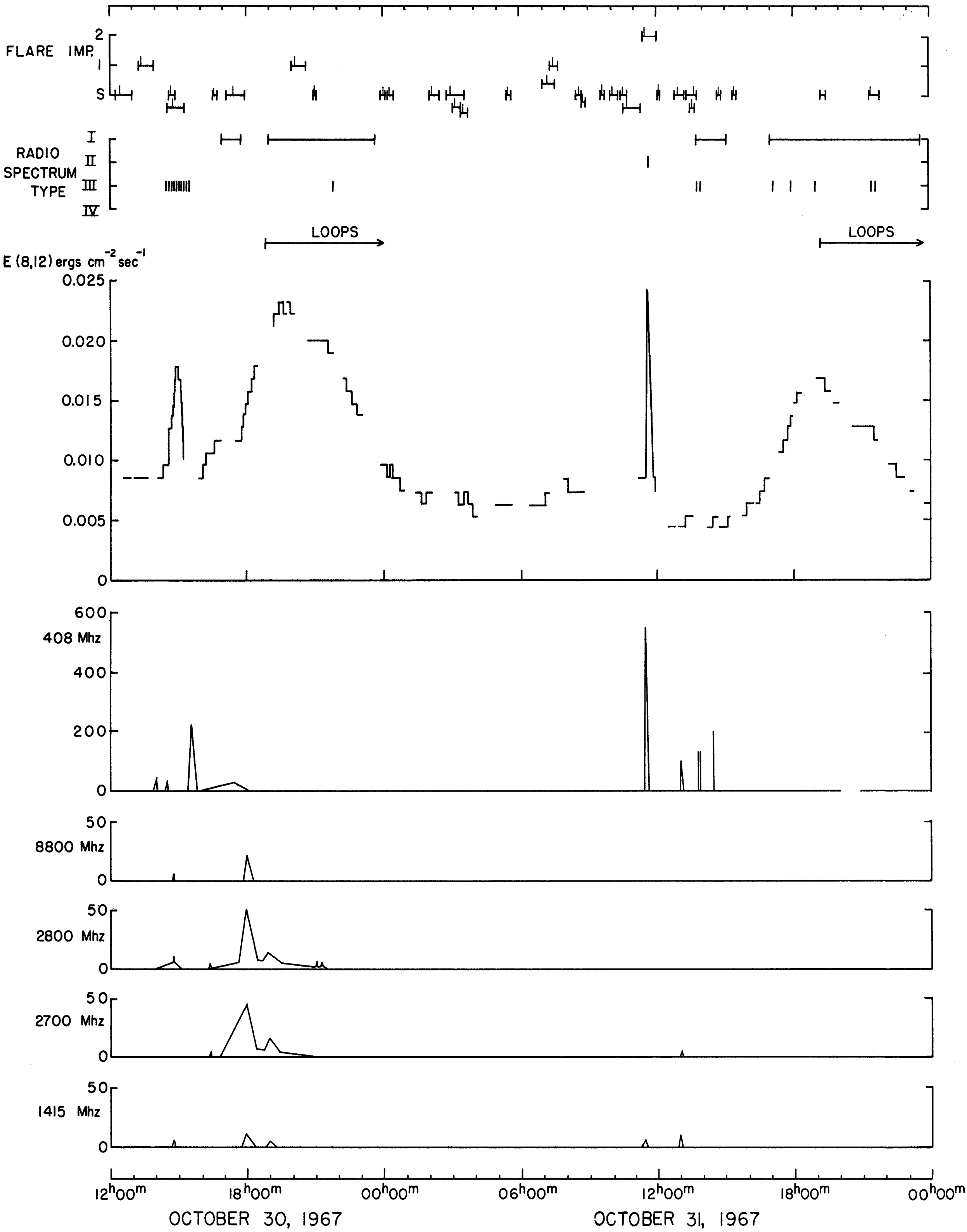
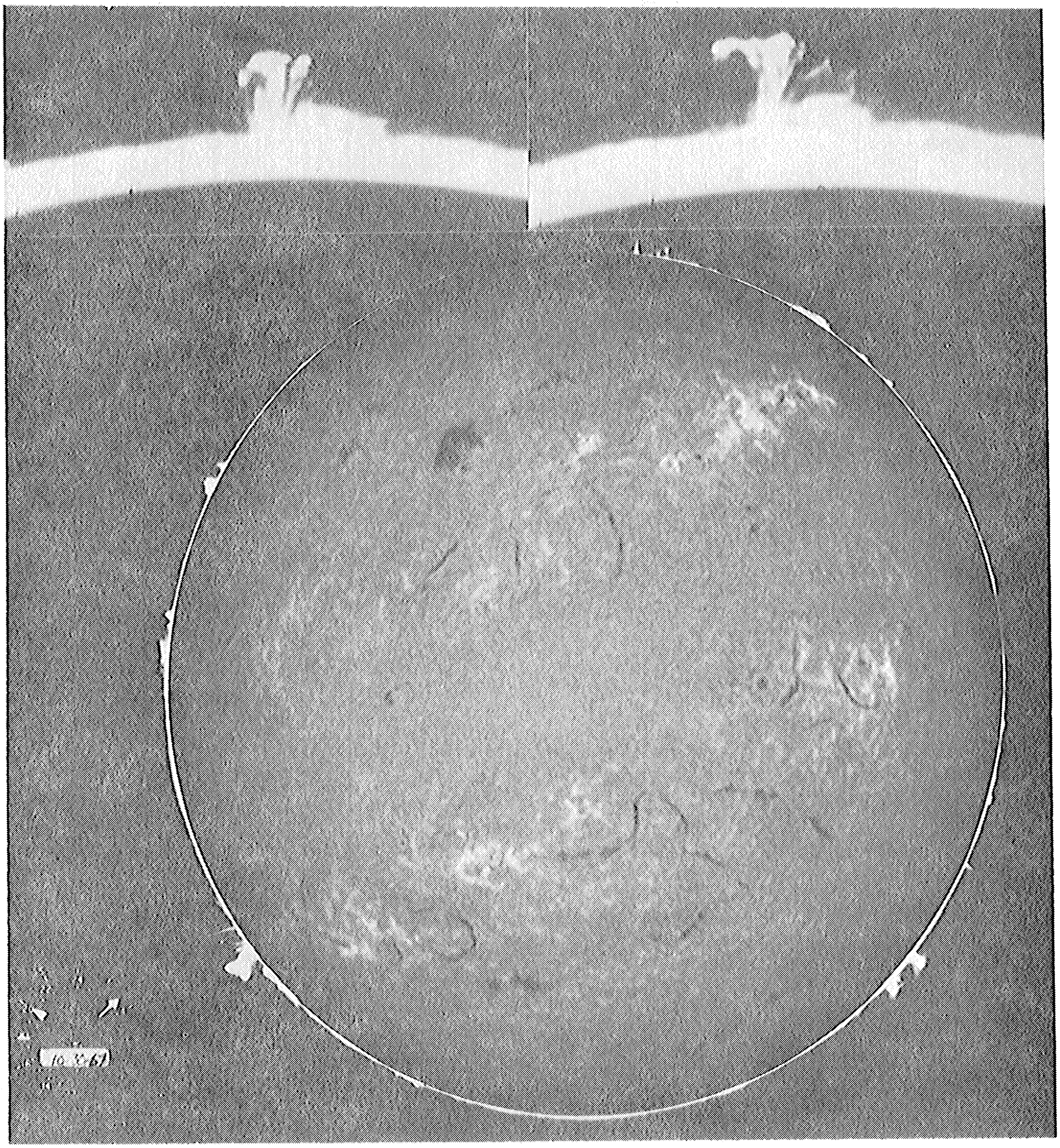

FLARE IMP.
2
1
S
RADIO
SPECTRUM
TYPE
I
II
III
IV
LOOPS
LOOPS
E (8,12) ergs cm⁻² sec⁻¹
0.025
0.020
0.015
0.010
0.005
0
600
408 Mhz
400
200
0
50
8800 Mhz
0
50
2800 Mhz
0
50
2700 Mhz
0
50
1415 Mhz
0
12h00m
18h00m
00h00m
06h00m
12h00m
18h00m
00h00m
OCTOBER 30, 1967
OCTOBER 31, 1967

Figure 4

a. b.



c.

Figure 5

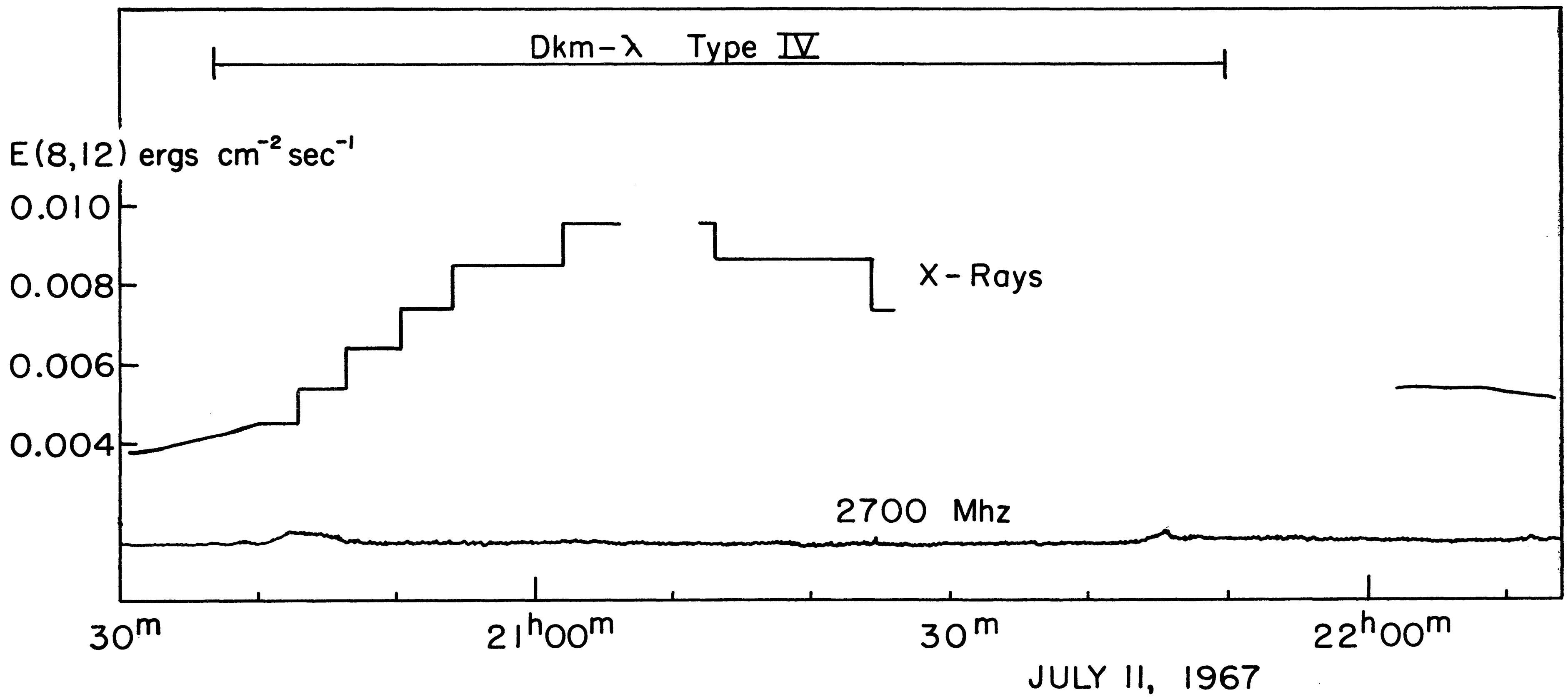

Dkm-λ Type IV
E(8,12) ergs cm⁻² sec⁻¹
0.010
0.008
0.006
0.004
X-Rays
2700 Mhz
30m
21h00m
30m
22h00m
JULY 11, 1967

Figure 6