SOFT SOLAR X-RAYS AND SOLAR ACTIVITY

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

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

1. Introduction

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

The 8 to 12 Å solar flux was monitored by an ion chamber photometer on the OSO-III satellite (a description and some results have appeared in earlier volumes of this journal). These data demonstrated that the background fluctuations are almost always present in the solar soft X-ray flux. When solar activity is high the amplitude, duration and frequency of occurrence of background variations is high, while at low levels of solar activity the X-ray variations are infrequent and of generally lower amplitude and shorter duration. The morphology of the fluctuations is highly varied. Lasting from a few minutes to more than half an hour, they are most often characterized by rise-times which are shorter than the subsequent time to decay and have amplitudes at 1–1.5 keV photon energy ranging from a few percent to more than 20% of the 'quiet X-ray background'.

The X-ray fluctuations represent a transient energy input to the corona whose magnitude and nature it is of interest to explore. We show below that the total energy expenditure associated with them is significantly large when judged in terms of energies dissipated in flares. They thus may represent an important energy leak from active

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regions (since X-rays below 20 Å come almost exclusively from active centers). The nature of the physical mechanism which sporadically supplies the energy can only remain speculative until the location on the Sun of the source volume has been identified and the physical response of the solar atmosphere has been investigated. One place we can start to investigate the problem is to ask whether at least some of the X-ray background fluctuations are associated with optically-identifiable activity on the Sun, and, if so, to undertake to describe that activity.

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

2. Observations

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

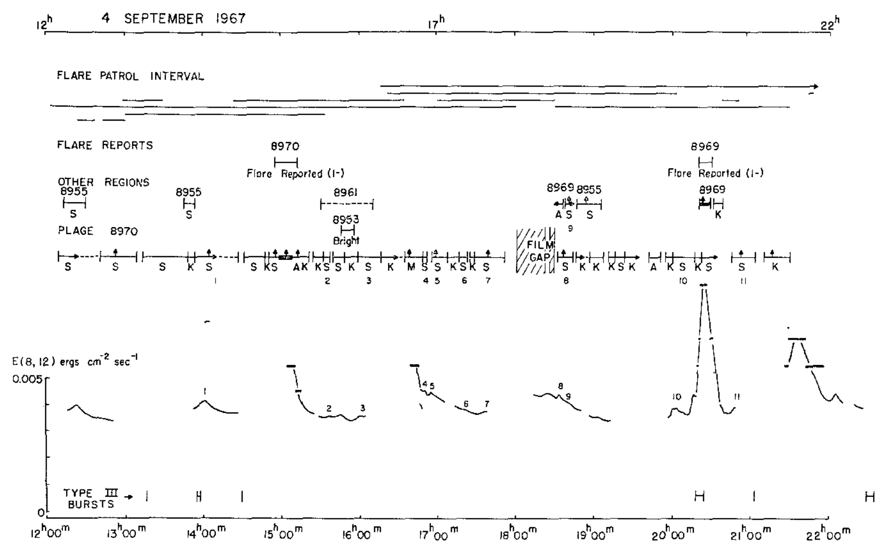

Fig. 1. A schematic representation of optical events observed on 4 September 1967, is given in connection with the soft X-ray flux curves. Gaps in the X-ray data are caused by satellite night and by tape-recorder playback. Symbols on the line above the flux curves refer to activity in plage 8970; symbols above those refer to activity in other regions on the disk. The symbols are defined in the text. A thick bar represents an event of flare magnitude. Numbers placed on the flux curves and just below the symbols representing optical activity are intended to portray some of the associations noted. Reported Type III bursts are indicated at the bottom of the diagram.

On 4 September 1967, the Sun was very quiet. No major centers of activity were on the disk nor within several days behind either limb. McMath plage 8970 was at that time on the south-east limb and plage 8969 was just behind the equatorial east limb. By the following day, both regions had moved on to the visible disk. A series of modest small brightenings and spike-like ejections took place in 8970 throughout the interval available on our flare-patrol films (the last half of the U.T. day). In addition, plage 8969 and other regions on the disk produced some visible Hα activity.

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

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

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

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

(a) Knobs ('K' in Figure 1): small brightenings of uncertain dimensions (at or below the image resolution) seen on or just above the limb;

(b) Mound ('M' in Figure 1): a feature extended along the limb and rising detectably above it, sometimes having a jagged upper profile;

(c) Arch ('A' in Figure 1): a small temporary prominence arch;

(d) Spikes ('S' in Figure 1): elongated, temporary surge-like features rising above the limb, often two or more at once.

These are illustrated by several photographs in Figure 2. The spike-like structures were often highly inclined to the local radial direction, with lengths ranging from ≈12000 km to ≈44000 km.

Most of the dynamic structures seen in 8970 were of modest surface brightness in Hα, seldom brighter than plages on the disk and often fainter than that. The activity that was seen to take place is familiar to solar observers and commonly occurs over active regions during their limb passage. As is frequently the case, the activity in

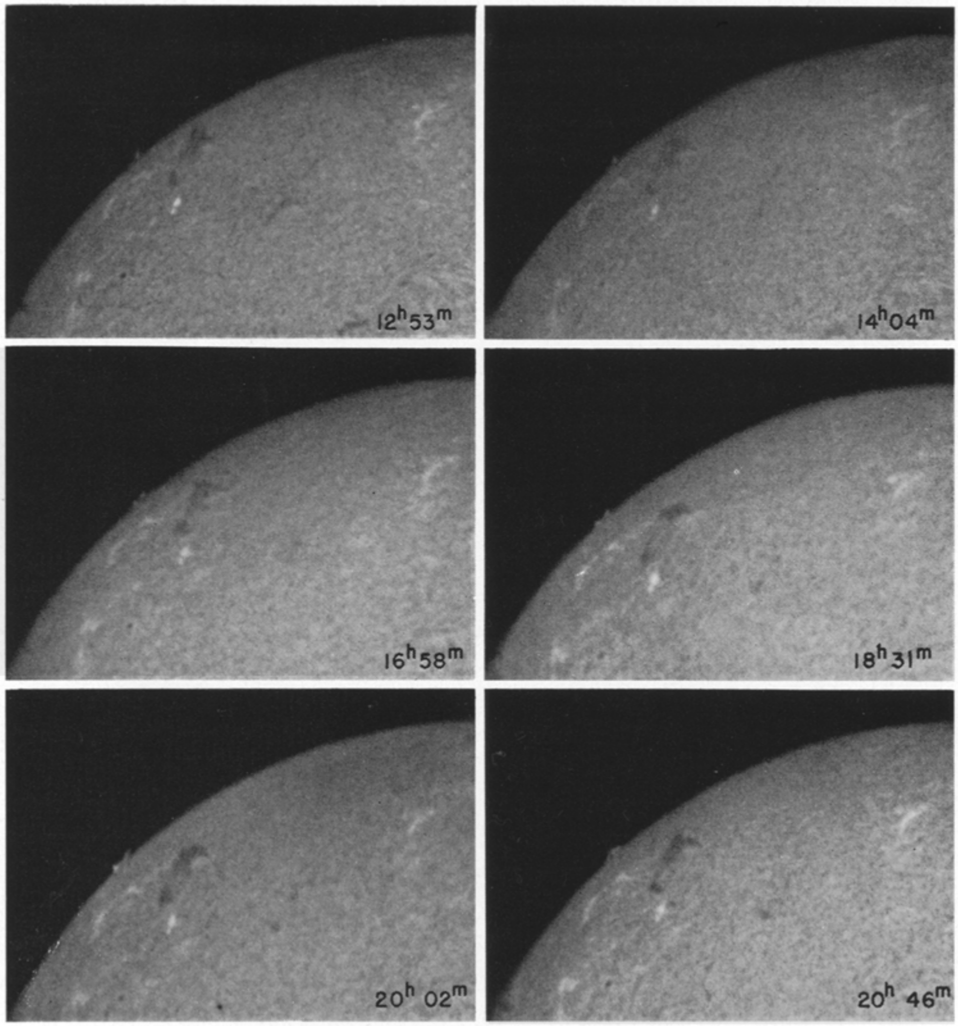

Fig. 2. Some of the spike activity seen to occur in plage 8970 on 4 September 1967, is here pictorialized (see Figure 1).

8970 was almost continuous, the structures we have called 'knobs' appearing and evolving (sometimes after a period of hesitation) into 'spikes' which then again subsided into 'knobs', the cycle then repeating. Nevertheless the activity was resolvable into a series of essentially distinctive events (Figure 1). The analysis of the films and a division of the activity into the various events was carried out without reference to the X-ray data. The films were then examined again to detect activity in other regions on the disk and limbs before comparison with the X-ray flux curves.

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

TABLE I

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

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

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

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

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

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

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

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

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

3. Discussion

There is a strong tendency for the X-ray background fluctuations to be best associated with spike-like features which occurred above plage 8970. These dynamic phenomena had the appearance of small surges but, unlike classical surges as described by Giovanelli and McCabe (1958), they were small (of length less than 44000 km), not associated with Hα flares (as defined) and were fainter, usually, than plage brightness. Thus we have called them spike-like, or surge-like, to distinguish them from the classical surges. They may, however, have a close similarity to classical surges for the following reasons: (i) The association of the spike-like events on 4 September 1967, with X-ray emission indicates their connection with coronal heating. Tandberg-Hanssen (1959) observed coronal emission lines above two surges and deduced temperatures near 3×10^6 K from the line profiles. (ii) The time-association of three spike-like events with Type III bursts indicates a possible physical connection. Loughhead *et al.* (1957) noted the flat visibility distribution of Type III bursts with solar longitude from 90° E to 30° W, a longitude interval which includes the observations being discussed here. Giovanelli (1958) and Swarup *et al.* (1960) found that Type III bursts have a higher probability of association with a flare if a surge accompanies it, while it has been generally recognized (e.g. Malville, 1962) that some Type III's do not necessarily associate with flares. Our data suggest that non-flare Type III's may at times associate with non-flare surge-like events. (iii) The small Hα 'knobs' at the base of the spike-like events may possibly be considered to be minute sub-flares. If we choose to make this assertion, the spike-like events may be thought of as the small surge counterpart in a miniature flare/surge event. The lifetimes of the spikes are similar to surge lifetimes (Bruzek, 1969).

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

Because of the significant number of time-coincidences between X-ray enhancements and small spikes which were found on 4 September 1967, we have assumed that on that day the two were indeed physically related. The evidence in our data is, however, that the relative magnitudes of the X-ray and Hα aspects of a single event are quite variable. There may be at least three accidental reasons for this: (i) moving material emitting Doppler-shifted Hα would not have been easily detectable, depending upon the line-of-sight velocity; (ii) the Hα structure of some of the events may have been partly hidden behind the chromosphere at the limb. Both would have affected an estimate of the magnitude of the Hα event. The latter effect certainly played a role in the arch structure seen in plage 8969 at about $18^h 30^m$. (iii) Faint Hα material may not have registered on the film above the scattered Hα sky-light.

A. Estimates of Energies Associated with the Phenomena

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

1. *Soft X-ray energy*

The course of the X-ray background underlying a fluctuation was estimated: this was

TABLE II

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

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

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

2. *Energy emitted in Hα*

Because of the likely possibility that some Hα emission was not observed, any estimate of total Hα energy must be treated as a lower limit. The method that was used neglects scattering of chromospheric Hα by spike material. Lengths and breadths of spike-like features were measured on the films and an emitting area of $2\pi\, rL$ assigned, assuming cylindrical symmetry and ignoring the ends of the column. The time-integral (column 5 of Table II) was obtained by multiplying half the total emission rate at maximum, given in column 4 of the Table, by the time-duration. Two methods of estimating the Hα emission rate gave nearly the same results: using $T_{ex}=4000°$ (for spicules; Michard, 1959) and $\Delta\lambda_D=0.8$ Å (for spicules; Athay, 1958) we obtained $I_{H\alpha}=2.0\times10^6$ erg cm^{-2} s^{-1}, assuming an optically-thick source. With line profiles of plages and the undisturbed disk (de Jager, 1959), which yield an equivalent width for the Hα excess from plages of ≈ 0.12 Å, we obtained $I_{H\alpha}=1.8\times10^6$ erg cm^{-2} s^{-1}. Both estimates refer to features of roughly plage brightness. An estimate of spike brightness relative to plage brightness was then used to get the results of Table I, columns 4 and 5. These are lower limits, and errors may be as large as a factor of three.

3. *Potential Energy*

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

$$\frac{\Delta V}{\varrho} = \pi r^2 L g_{\odot} \cdot \tfrac{1}{2} L \cos\varphi \quad \text{erg}\,(\text{g/cm}^3)^{-1}.$$

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

4. *Work done against the magnetic field*

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

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

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

5. *Work done against coronal gases* was also ignored.

B. PEAK EMISSION RATES IN Hα AND IN SOFT X-RAYS

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

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

The relationship implied by Figure 3 does not, by itself, necessarily indicate that there is a common initiatory process underlying flare and spike-like phenomena. It does suggest that there might be a common physical means of sharing an initial energy fund among source volumes at high temperature (X-rays) and at low temperature (Hα).

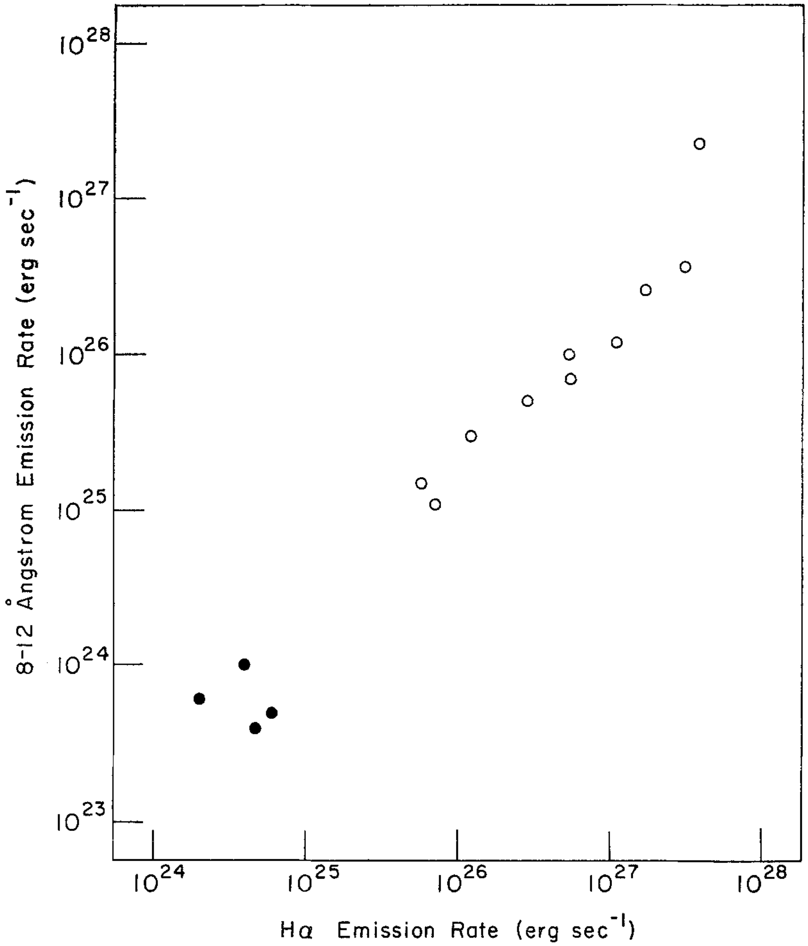

Fig. 3. Relationship of mean peak emission rates in Hα and in soft X-rays for flares (open circles) and for spike events (filled circles). Flare data have been taken from Thomas and Teske (1971).

C. TOTAL ENERGY IN Hα, X-RAYS AND POTENTIAL ENERGY

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

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

On the other hand, the rate of energy loss represented by the phenomena discussed here is quite small when judged in terms of the overall energy budget of an active region. For example, Osterbrock (1961) estimated that the rate of flow of mechanical energy across the photosphere in active regions is $\approx 3 \times 10^8$ erg cm^{-2} s^{-1}. The inferred energy loss in the events discussed here, in excess of 4×10^{29} erg in a 24-h period, may be time-averaged for comparison. While the area of plage 8970 (as seen in Ca II K) could not be measured on 4 September 1967, we guess its area to have been 1500 millionths of the hemisphere on that date (4.5×10^{19} cm^2), a guess based upon its measured area at CMP and its apparent growth while on the disk. Thus the total energy invested in these events, averaged in time and over the whole calcium plage, was $\approx 10^5$ erg cm^{-2} s^{-1}, a small value when compared to Osterbrock's estimate. Further, the energy loss by plage 8970 via excess Hα emissions alone, at an assumed rate of $\approx 1.8 \times 10^6$ erg cm^{-2} s^{-1} (and assuming a similar Hα area) amounted to some 8×10^{30} erg in a 24-hr period, roughly like one major flare of imp. 3 per day (Bruzek, 1967; see also Warwick, 1962).

4. Summary

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

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

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

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

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