REMOTE FLARE BRIGHTENINGS AND TYPE III REVERSE SLOPE BURSTS

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Abstract. We present two large flares which were exceptional in that each produced an extensive chain of Hα emission patches in remote quiet regions more than 10^5 km away from the main flare site. They were also unusual in that a large group of the rare type III reverse slope bursts accompanied each flare. The observations suggest that this is no coincidence, but that the two phenomena are directly connected.

The onset of about half of the remote Hα emission patches were found to be nearly simultaneous with RS bursts. One of the flares (August 26, 1979) was also observed in hard X-rays; the RS bursts occurred during hard X-ray spikes. For the other flare (June 16, 1973), soft X-ray filtergrams show coronal loops connecting from the main flare site to the remote Hα brightenings. There were no other flares in progress during either flare; this, along with the X-ray observations, indicates that the RS burst electrons were generated in these flares and not elsewhere on the Sun. The remote Hα brightenings were apparently not produced by a blast wave from the main flare; no Moreton waves were observed, and the spatially disordered development of the remote Hα chains is further evidence against a blast wave. From geometry, time and energy considerations we propose: (1) That the remote Hα brightenings were initiated by direct heating of the chromosphere by RS burst electrons traveling in closed magnetic loops connecting the flare site to the remote patches; and (2) that after onset, the brightenings were heated by thermal conduction by slower thermal electrons ($kT \sim 1$ keV) which immediately follow the RS burst electrons along the same loops.

1. Introduction

The negative-slope fast drift bursts on dynamic spectra are one of the variants of type III bursts, the type III-RS (reverse slope) bursts. They are the second branches of U bursts (Tarnstrom and Hehntner, 1975), where the electron beams are channeled along closed magnetic arches, first moving upward from the acceleration site and then downward in the returning leg of the arch. The RS bursts are not frequently observed. Only 11 days with more than two type III-RS bursts were reported in the five years 1970–1974 (LaBonte, 1976).

We present observations of two large (Hα class 2) flares which produced large groups of RS bursts. Each flare was also unusual in that an extensive chain of discrete Hα brightenings spanning 370 000–470 000 km in length was produced in a remote quite region $1\text{–}2 \times 10^5$ km away from the flare. A typical remote Hα patch first appears as a faint bright area a few arc seconds in diameter, gradually attains maximum brightness and doubles or triples in size in 1–2 min, and then fades away in the next 15–45 min. Onset is the time of the first detectable brightening when the remote flare brightening is traced backward in time. The onsets of many of these remote Hα emission patches were found to be simultaneous with the type III-RS bursts. From the coincidence and from energy estimates, we propose that the RS-burst electrons reached the chromsphere in sufficient numbers to initiate the remote Hα brightenings. Thereafter the emission patch was powered by another mode of energy transport along the loop, probably thermal conduction. Thus, the remote brightenings marked the footpoints of those select magnetic loops which connected back to the site of the flare and into which flare-accelerated particles were injected.

Moreton waves from explosive flares are known to cause distant brightenings of weak plages and elements of the chromospheric network as the expanding blast wave passes over them (Švestka, 1976a; Reigler *et al.*, 1980). The remote brightenings in our flares were clearly not produced in this way. Our Hα filtergrams showed no evidence of Moreton waves. The disjointed sequence in which the births of the bright elements took place further rules out the possibility of a radially expanding shock wave as the cause of the brightenings.

2. Observations

2.1. The flare of August 26, 1979

McMath region 16239 was a mere 6° N of the equator, a rather rare occurrance in a solar maximum year. Magnetically it was a side-by-side double reversed polarity region. The leading spot was a mixed-polarity spot. The magnetic makeup was so right for flare generation that one hundred flares, including six class 1 and two class 2 flares, were reported in *Solar Geophysical Data.*

On August 26, the region was just west of central meridian. To the west of it was a weak old unipolar field (white) as shown in the magnetogram in Figure 1a. Further to the west lay a coronal hole – the light region where the absorption was conspicuously absent in the He λ 10830 spectroheliogram in Figure 1b. The Hα filtergram in Figure 1c shows the 2-ribbon flare in the active region and the remote bright chain in the shape of a Figure 7 to the west. The drawing in Figure 1d shows the proximity of the chain to the eastern edge of the coronal hole; all of the bright patches are outside the hole. Since the magnetic field lines outside of coronal holes return to the surface, we know that the remote brightenings are the footpoints of closed loops.

An impulsive flare began next to the neutral line in the mixed-polarity preceeding spot at 16:39 UT and reached maximum at 16:46 UT. A large group of type III reverse-slope bursts were recorded on film at Weissenau in the next 5 min beginning 16:46:27 UT in addition to two other bursts at 16:42 and 16:43 UT that were also recorded at Bleien, Switzerland. There were at least 11 discernable reverse slope bursts in the large group with 5 each in the 160–290 MHz and 290–540 MHz range and 1 in the 540–1000 MHz range. The durations of individual bursts were 1–2 s. The lowest frequency cutoff of the bursts was around 200 MHz. Examination of dark prints (where a 10% increase in brightness can be detected) of every frame (19 s interval) of the Hα filtergram movie during the 5 min revealed a good

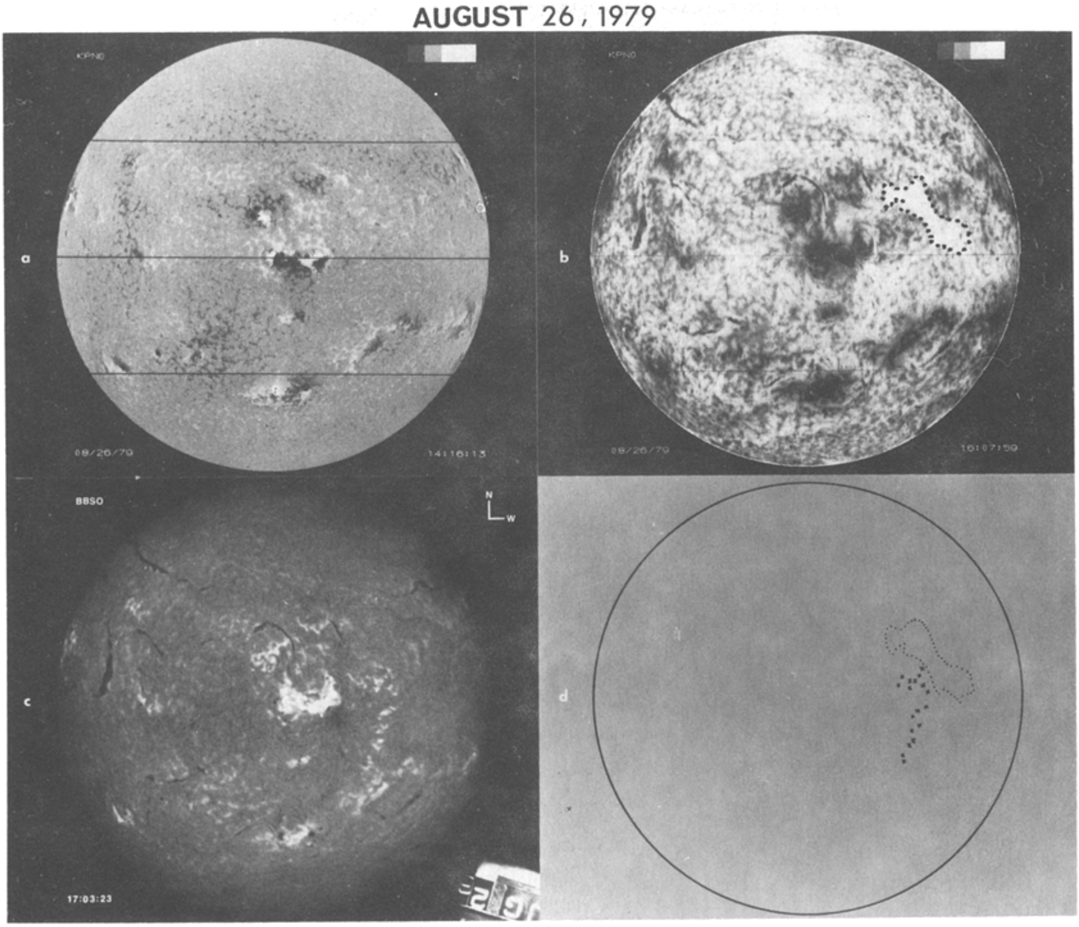

Fig. 1. (a) Magnetogram from Kitt Peak National Observatory taken about 2 hr before the flare, north is on top, west is to the right. (b) Spectroheliogram in 10830 Å from Kitt Peak National Observatory taken about 30 min before the flare. The region outlined by black dots is a coronal hole. (c) Hα filtergram at 17:03 UT when the remote bright chain (in the shape of a figure 7) was completed. (d) Drawing showing location of individual brightenings of the remote chain, indicated here by crosses, with respect to the coronal hole. Some fall very close to the edge of the coronal hole, but none are within the hole.

correlation between the onsets of remote Hα brightenings and the times of the RS bursts. To within the time resolution of the Hα movie, 7 of the 11 bursts were simultaneous with the first appearance of 6 separate remote brightenings. No Hα brightenings were observed to occur with the four other bursts. Table I lists the times of these onsets and their corresponding RS bursts.

Figure 2 shows the onset times of the remote Hα brightenings and the RS bursts on the ISEEE-3 X-ray plot. The X-ray plot shows that vigorous generation of energetic (>10 keV) electrons continued in the flare throughout the interval of all the RS bursts and remote brightening onsets. Most of the bursts and brightening onsets are grouped closely together in the plateau maximum in the 12–20 keV flux

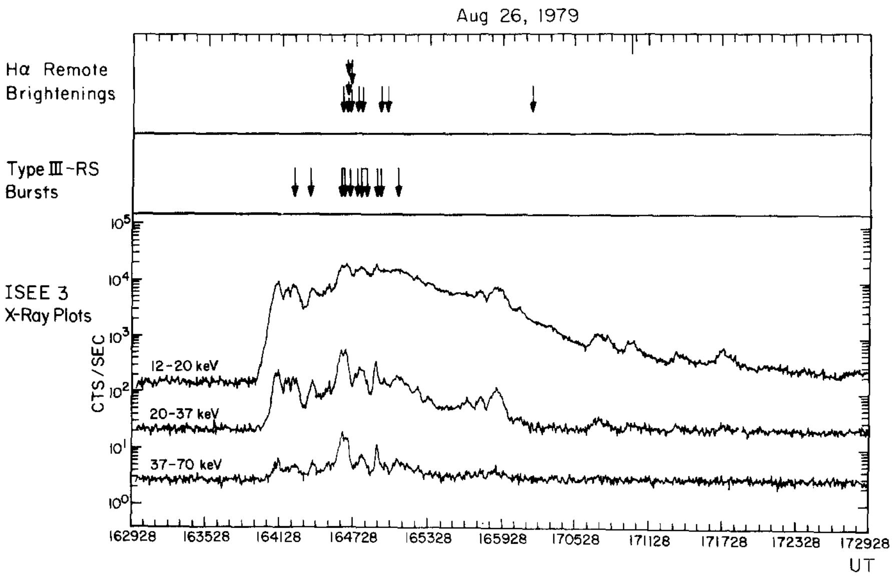

Fig. 2. Onset times of Hα remote brightenings and times of type III-RS bursts from dynamic spectra, Weissenau Observatory, are indicated by arrows above ISEE-3 X-ray plot. Linked pairs of type III-RS bursts indicate groups of 3 bursts.

from 16:46 UT to 16:51 UT. The occurrence of hard X-ray spikes during this period (most pronounced in the 20–37 keV flux) is good evidence that the RS bursts electrons were accelerated in this flare rather than elsewhere on the disk.

Since it is difficult to show the onset of the brightening on second generation photographs, in Figure 3 we illustrate the remote brightenings near their maximum brightness. The average time between onset and maximum brightness was 76 s. The shortest time was 57 s and the largest element took 131 s to reach maximum.

Notice in Figure 3 that the remote brightenings did not begin until after the flash phase of the flare was over at 16:46:20 UT. This might suggest that the remote brightenings were triggered by the passage of a blast wave generated in the flash phase. However, it is seen in Figure 3 that the remote bright chain first brightened on the end nearest the flare, then on the far end, then again in the near end, and finally in the middle. Thus, it is clear that the brightenings did not result from one large blast wave expanding away from the flare.

The ray path of the RS burst electron streams can be roughly estimated as follows: Non-thermal electrons with an average velocity of 10^5 km s^{-1} would cover a distance of $1–2 \times 10^5$ km during the RS burst of 1–2 s. Since a RS burst is the second branch of a U burst, the total length of the path would be a few times 10^5 km. The observed lowest frequency cutoff of the RS bursts is 200 MHz. This gives a plasma frequency of 200 MHz if the observed frequency is the fundamental plasma frequency or 100 MHz if the second harmonic is observed. The frequency range of 200–100 MHz corresponds to a source height of $1–3 \times 10^5$ km above the

TABLE I

Onset times of remote brightening patches and type III RS bursts August 26, 1979

Remote brightening patches	1	2	3	4	5	6	7	8	9	10
Onset	16:46:39	16:46:58	16:46:58	16:47:17	16:47:17	16:47:55	16:48:14	16:50:26	16:49:30	17:00:02
Type III RS bursts	16:46:27 16:46:31 16:46:35	–	–	16:47:12	16:47:12	16:47:47	16:48:07	–	16:49:25	–

TABLE II

Onset times of remote brightening patches and type III RS bursts June 16, 1973

Remote brightening patches	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
Onset	14:26:40	14:23:50	14:25:06	–	14:26:20	14:26:20	14:29:22	14:29:22
Type III RS bursts	14:26:30– 14:26:40	14:23:42– 14:23:47	–	–	14:26:15	14:26:15	–	–

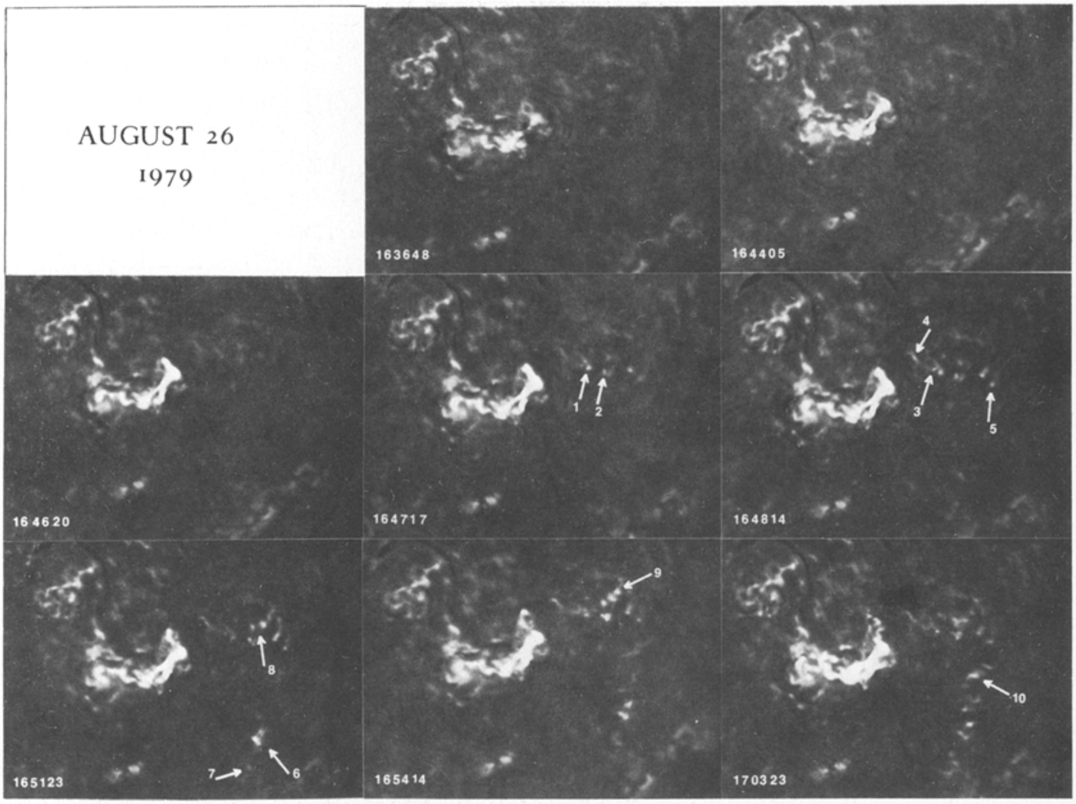

Fig. 3. Time sequence of Hα filtergrams from before the flare to 17:03 UT. Arrows indicate individual new brightenings as they reached maximum brightness. Numerals correspond to the remote brightening patches listed in Table I.

photosphere (Švestka, 1976b). The height of the top of our loop thus has a lower bound of $1\text{–}3 \times 10^5$ km. The ground distance between the flare site and the remote chain in Figure 3 is $1\text{–}2 \times 10^5$ km – a likely dimension for the estimated length and height of the closed magnetic arches.

Investigators in the past have found some good, and some not so good correlation between type III bursts (Vorpahl, 1973) or type III-RS bursts (LaBonte, 1976) and Hα activity in the vicinity of the flare where the acceleration process takes place. In this flare we do not see a good correlation. The flare was a complex one. During the interval of the RS bursts, continuing Hα development is seen on our high resolution filtergrams with 5 s frame rate; but we do not see a clear cut development every time a burst goes off.

The flare reached maximum area around 16:59 UT. The last of the remote brightenings occurred around 17:02 UT. The remote chain lasted until 17:48 UT while the complex flare at the main site developed two new ribbons (this time oriented east–west) as the old ribbons slowly decayed and the flare ended around 21:00 UT.

2.2. The flare of June 16, 1973

The greatly enhanced arcade of loops from the flare site to the quiet region outside of the active region observed by Skylab in soft X-rays after the flare in MM 12387 on June 16, 1973 (Figure 6c) have been the subject of much investigation (Rust and Webb, 1977; Švestka and Howard, 1979; Rust and Švestka, 1979). Additional optical data from BBSO and Tel Aviv and radio data from Harvard Radio Observatory (Fort Davis), presented here for the first time, shed new light on the flare and give evidence for a different interpretation. We think the remote brightenings in this flare are the same phenomenon as those of the August 26, 1979 flare.

The flare began along a filament before 14:20 UT and reached maximum around 14:24 UT. The first of the remote brightenings began around 14:23:50 UT and the last around 14:29 UT. Figure 4 shows the preflare filament and the remote bright elements on filtergrams taken at Tel Aviv. The Tel Aviv film would have been the perfect data to use for this analysis had there not been a 30 min gap during film changing. The present study is based on our full disk filtergrams with a 5-s frame rate. These were taken with a Fabry–Perot filter with 0.7 Å FWHM bandpass,

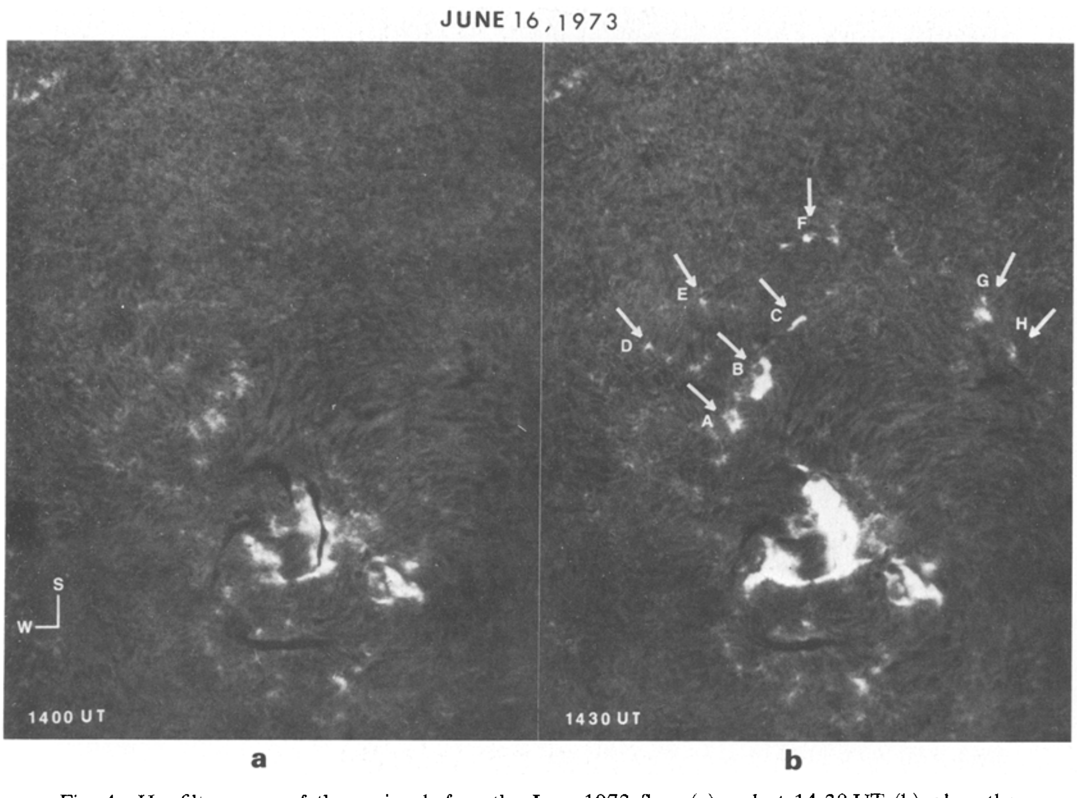

Fig. 4 Hα filtergrams of the region before the June 1973 flare (a) and at 14:30 UT (b) when the remote brightenings, indicated by arrows, reached maximum brightness. Letters correspond to the remote brightening patches listed in Table II.

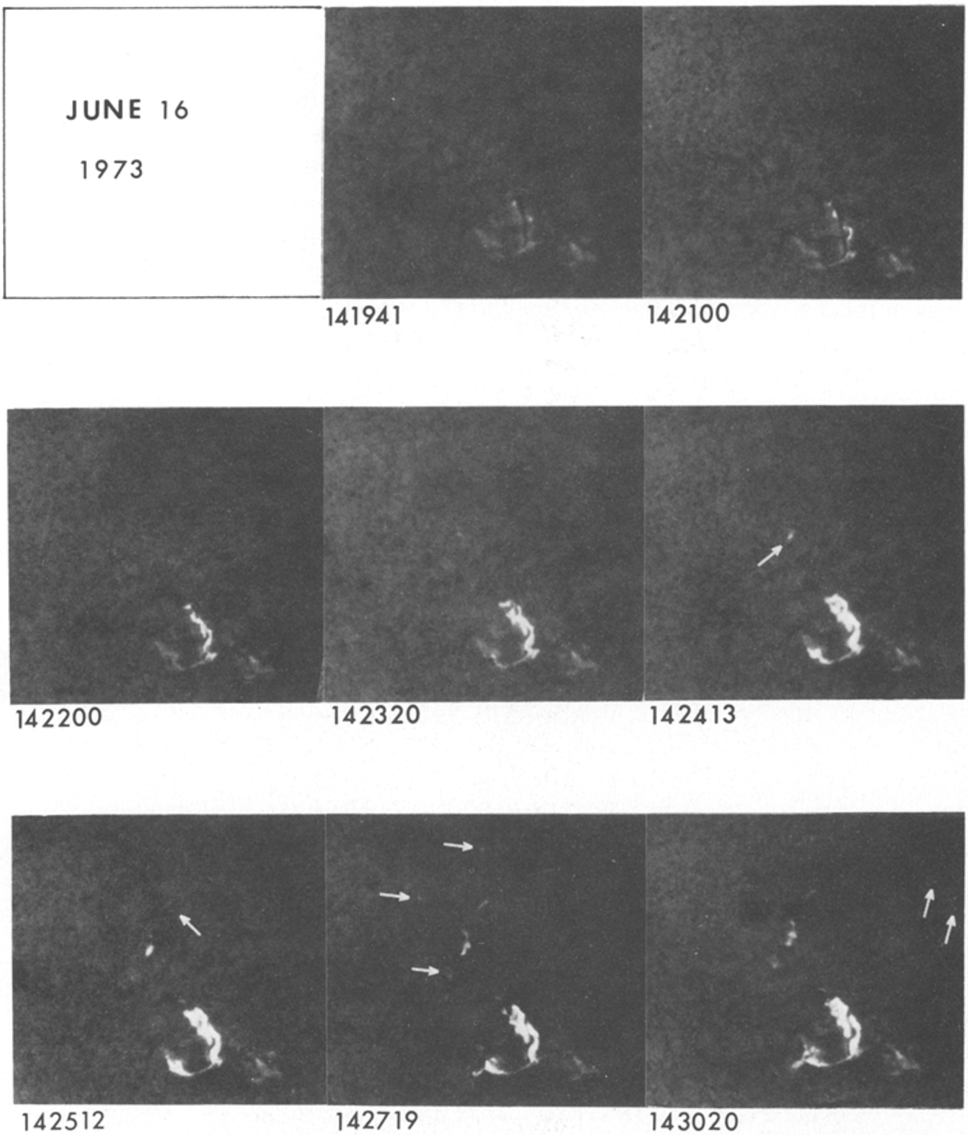

Fig. 5. Time sequence of the June 1973 flare. Arrows show the remote brightenings as they became visible. South is up, west is to the left.

which gives lower contrast than the 0.5 Å FWHM filtergrams from Tel Aviv. Figure 5 shows the development of the flare from its onset to 14:30 UT when the remote brightening was completed. Arrows indicate the remote elements sometime between onset and maximum brightness. Notice the resemblance between this flare and that of August 1979: the remote brightening took place when the flash phase of the main flare was over, the remote brightenings were discrete small patches at places often devoid of plages and the brightenings occurred in a disjointed time-distance sequence, i.e., for some successive Hα onsets, the patch closer to the flare appeared after the more remote patch.

Two large and many small groups of RS bursts as well as discrete RS bursts were observed at Harvard Observatory (Fort Davis) in the 160–2000 MHz range from 14:22–14:29 UT (also observed from 14:22–14:25 UT at Weissenau in 160 to 1000 Mhz range). The bursts before 14:25 UT were more intense; discrete bursts averaged 2–3 s in duration while the large groups spanned 30 s. After 14:25 UT the bursts consisted of small groups of finely resolved individual bursts lasting 1–2 s. They were less intense and confined mostly in the 600–1000 MHz range.

The onset of the first remote Hα brightening, *B*, (also the largest and brightest) occurred 3 s after a burst that lasted more than 5 s with a frequency cutoff around 200 MHz. The time it took to reach maximum brightness for this brightening was more than a minute, similar to the brightenings in the August 1979 flare. Onsets of three more brightenings appeared to be within seconds of a burst or group of bursts. The uncertainty was primarily due to poor contrast of the film, not from the lack of bursts to match. Table II lists the onset times of the remote flare brightenings and the corresponding RS bursts. Missing times and uncertainty are caused by poor contrast of filtergrams.

Soft X-ray coverage by the AS&E X-ray experiment aboard Skylab was limited to before and after the flare. Figure 6a shows the flare in Hα with letters indicating the remote brightenings nearby. The crosses in Figure 6b show the locations of these brightenings in the X-ray picture taken 4 hr before the flare. Brightenings at *A*, *B*, and *C* were located at the foot points of the system of arches that had a slight twist to it in the X-ray picture. Brightenings *F*, *G*, and *H* were also at the end of faint loops that originated from where the main flare site was to be. At this time, only *D* and *E* were not at the end points of any visible loops from the future flare site. Figure 6c was taken at 17:58 UT, three and a half hours after the flare. It shows the greatly enhanced arcade of loops from the main flare site to that of the remote brightening at *B*, and new easterly loops to the south that were not present at 10:27 UT.

The length of the prominently enhanced loop with remote foot at *B* was estimated at 3.6×10^5 km and the height at 10^5 km by Rust and Webb (1977). The ground distance from the main flare site to brightening at *B* was 1.3×10^5 km. Using the average duration of the burst of 2–3 s we can estimate the downward branch of the ray path of the non-thermal electrons to be $2\text{–}3 \times 10^5$ km. This indicates that the closed loops had a short upward branch and a longer downward branch if the total length was 3.6×10^5 km. The enhanced loop in Figure 6c does in fact suggest such a non-circular shape.

3. Discussion

In more than half (6/10) of the remote brightenings in the August 1979 flare and in half (4/8) of those of the June 1973 flare, the onset of brightening coincided

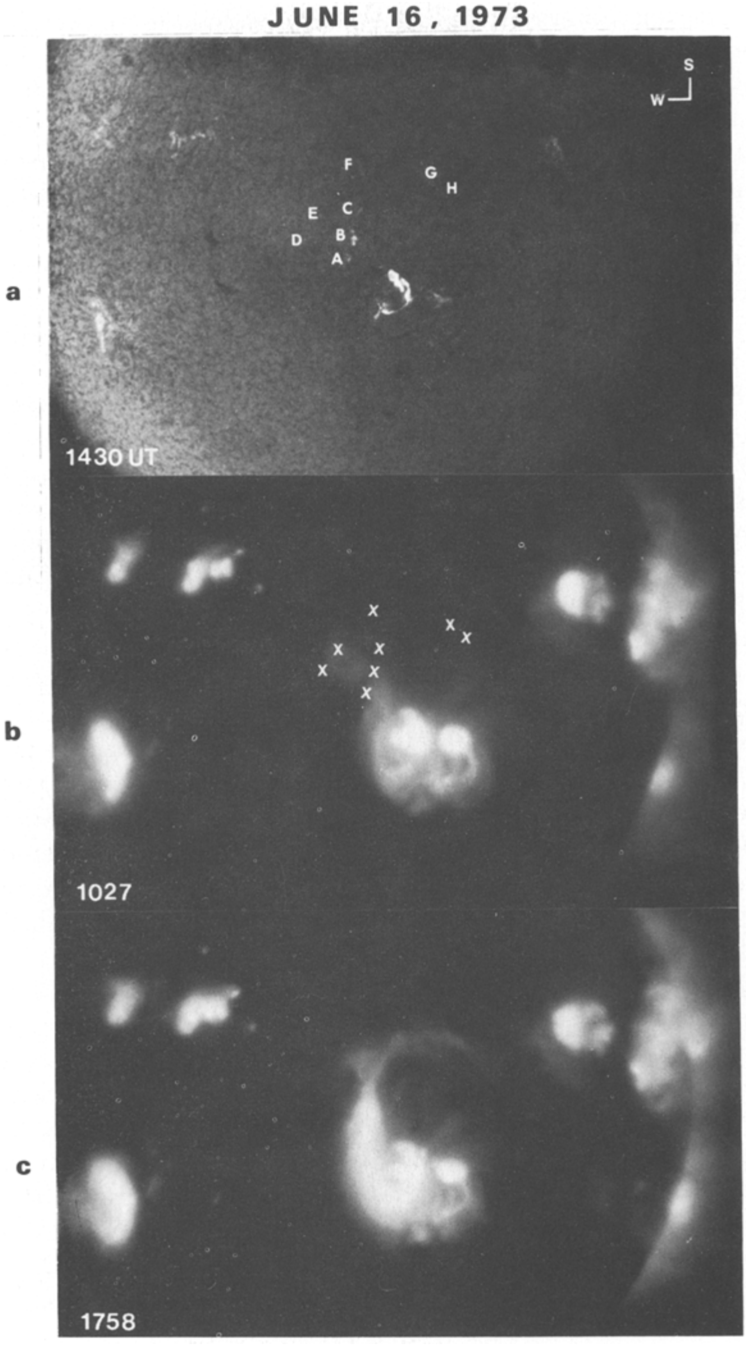

Fig. 6 (a) Hα filtergram of the June 1973 flare. Letters indicate the remote brightenings nearby. (b) Soft X-ray picture from AS&E taken aboard Skylab four hours before the flare. Crosses indicate the locations of the remote brightenings. Notice that loops leading to many of the crosses can be seen. (c) Soft X-ray picture three and a half hours after the flare. Greatly enhanced arcade of loops from the flare site to the remote sites of A, B, and (c) is evident.

within 12 s or less of a type III-RS burst in the August 1979 flare and within 5 s or less in the June 1973 flare. The actual time lag could be less since our film rate was 19 s and 5 s, respectively. In all 10 of these cases of near coincidence, the Hα onset was first discernable in the first frame *after* the RS burst.

We know from the X-ray pictures that the remote brightenings in the June 1973 flare were at the remote footpoints of closed magnetic loops from the flare site. In the August 1979 flare, since the remote brightenings were in a quiet region outside a coronal hole, they also were at the feet of large closed magnetic loops; from the similarity of the two flares and from the hard X-ray and RS burst data, we infer that those closed loops also connected to the flare site. Estimates from the burst data give the path of the electron streams a total length of a few times 10^5 km and a height of order 10^5 km. These dimensions are compatible with the surface distance of $1–2 \times 10^5$ km between the remote brightening and the main flare site, which is probably where the burst electrons were accelerated. They are also in agreement with the dimensions estimated by Rust and Webb (1977) for the X-ray loops connecting from the flare to the remote brightenings in the June 1973 event.

From the results summarized in the above two paragraphs, it seems likely that the remote Hα brightenings were initiated by heating of the chromosphere by the RS burst electrons. We have demonstrated the plausibility of the remote brightenings being at the ends of the closed loops traveled by the RS burst electrons. In addition, since (in the August 26, 1979 flare) the RS bursts occurred during hard X-ray spikes which represent new releases of energy in the flare, we infer that flare energy was first injected into any one of the large closed loops at the time of the associated RS burst. In this case, the time in which energy was transported from the flare end to the far end of the loop for the onset of the remote brightening was $\lesssim 5$ s, which requires a propagation speed $\gtrsim 6 \times 10^9$ cm s^{-1}. This is an order of magnitude faster than a flare blast wave and even exceeds the rms velocity of electrons in the 10^7 K ($kT \sim 1$ keV) coronal flare plasma. However, type III burst electrons have energies $\gtrsim 10$ keV (Ramaty *et al.*, 1980), which corresponds to electron velocities $\gtrsim 6 \times 10^9$ cm s^{-1}. Hence, if the RS burst marks the entrance of flare energy into the closed loop, the burst electrons themselves are the only plausible channeled flare product fast enough to carry energy 3×10^5 km in no more than a few seconds. Thus, from the observed geometry and from the observed near simultaneity of the remote Hα onsets with the RS bursts, we believe that the RS burst electrons supply the energy for the onsets of the remote Hα brightenings.

The energy content of an RS burst electron stream fits reasonably with that needed to initiate a remote chromospheric brightening. The observed initial brightenings on our Hα films result from an increase in emission in the central part of the Hα line (H$\alpha \pm 0.35$ Å) of about 10%, and a patch covers an area $\lesssim 10^{17}$ cm^2 at onset. The thermal energy content of the upper and middle chromosphere (where the core of Hα is formed) is of order 10^8 erg cm^{-2}, and the total radiative loss rate is of order 10^6 erg cm^{-2} s^{-1} (Athay, 1976). So, if all chromospheric heating were turned off, the cooling time would be of order 10^2 s. Conversely, a substantial brightening in Hα would occur if the thermal energy of the chromosphere were increased by of order 10^8 erg cm^{-2} in much less than 100 s. There are 10^{31}–10^{32} electrons at energies $\gtrsim 10$ keV in a single type III burst (Ramaty *et al.*, 1980), which gives 10^{23}–10^{24} erg/burst. Thus, in a few seconds time, the electrons in each RS burst could supply of order 10^8 erg to the chromosphere over an area 10^{15}–10^{16} cm^2 or 10^7 erg over 10^{16}–10^{17} cm^2. Since the area of an individual remote bright patch at onset is $\lesssim 10^{17}$ cm^2, we see that if a substantial fraction of the electrons in an RS burst reaches the chromosphere, we can expect a faint but detectable Hα brightening.

After their first appearance, the remote emission patches were observed to continue to brighten gradually for many tens of seconds. The average time between onset and maximum brightness was 76 s. After reaching maximum brightness, the remote patches slowly faded, remaining visible for at least 15–20 min. Since the RS burst electrons last for only a few seconds, and since the cooling time of the chromosphere is only of order 10^2 s, it is clear that the rise to maximum and the duration of the brightness results from some additional mode of energy transport.

Rust and Webb (1977) proposed that the remote brightenings in the June 1973 flare resulted from shock waves launched in the flash phase of the main flare and channeled along the large loops to their remote footpoints. We have presented evidence that the *onsets* of the remote brightenings did not result from shock waves but from high-energy electrons accelerated *after* the main flash phase of the flare. However, there is still the question of whether after the onset of a remote brightening any of the required additional chromospheric heating is by such a shock wave. A shock wave launched into the flare end of a 10^5 km long ducting loop at the time of the RS burst would reach the remote footpoint in of order 100 s (i.e., near the time of maximum Hα brightness in the remote footpoint) if the shock speed were of order 10^3 km s^{-1} (the speed of an ordinary flare blast wave). However, we would expect such a shock wave to pass downward through the chromosphere in no more than of order 10 s. Hence, if much of the heating the remote brightening were due to such a shock wave, there would be an impulsive increase in Hα brightness some 100 s after the onset produced by the RS burst electrons. Since no such sudden jump in brightness was observed, we feel that shock waves are of little importance in the remote chromospheric heating.

Heat conduction from the flare-generated thermal X-ray plasma in the large loops probably supplies the long-term heating for the remote brightenings. First, electrons from the $T \simeq 10^7$ K flare plasma could reach the far end of a 10^5 km long loop in no more than a few tens of seconds (i.e., a few Hα frames after the RS burst). Second, the conduction cooling time τ_c for thermal plasma of temperature T and electron density n_e in a loop of length $2L$ is given by

$$\tau_c = 4 \times 10^{-10} \frac{L^2 n_e}{T^{5/2}} \text{ s} \qquad (1)$$

(Moore *et al.*, 1980). Taking $L = 10^{10}$ cm, $n_e = 10^{10}$ cm^{-3}, and $T = 10^7$ K, which values are appropriate for large coronal loops in flares (Moore *et al.*, 1980), we have

$$\tau_c \simeq 10^3 \text{ s},$$

in reasonable agreement with the observed duration of individual remote bright patches. Therefore, it appears that the heating of the remote chromospheric bright patches is mainly by heat conduction, and that the rise and decay times of the Hα brightness of a patch are basically the rise and decay times of the thermal X-ray plasma in the large connecting loops.

The time correspondence between the type III-RS bursts and the onsets of the remote Hα brightening was not perfect. In both flares there were Hα brightenings with no reverse slope bursts recorded and vise verse.

The fact that the remote brightenings were not merged together but occurred at discrete locales shows that only certain select magnetic loops connect back to the flare and receive enough energy to appreciably heat the chromosphere at their remote ends. Convergence of the arches is likely to aid chromospheric heating at the remote footpoint. Note the largest and brightest remote brightening in the June 1973 event (see Figure 6a) and the converging configuration of the arcade of loops leading to that point in the post-flare soft X-ray picture in Figure 6c. But if convergence were the only requirement then we would expect to see the remote brightenings take place only in plages of stronger field rather than regions of little or no plage. The inclination of the field lines might be another factor. Probably a combination of suitable conditions of the magnetic arches have to be met before the RS burst electron streams can descend low enough in sufficient numbers to cause chromospheric brightening. So, it is reasonable that not all RS bursts produce detectable remote Hα onsets.

In the opposite case of a remote Hα onset with no observed RS burst, it is possible that the RS burst did occur but was not observed due to either (1) conditions at the receiving end or (2) conditions in the corona.

(1) It is not unusual for different observatories to report bursts not reported by others and to report different types of bursts during the same period of time interval. Aside from local terrestrial interference, there are instrumental characteristics that effect what are and are not observed (Benz and Asper, 1976).

(2) Conditions in the corona, not yet known, made the upward branches of the RS bursts unobservable; similar conditions may account for the missing RS bursts. Variants of type III bursts, of which reverse slope is but one of the several, account for only 11% of the total number of type III bursts during late March of 1976 at Weissenau when the burst activity increased considerably (Urbarz, 1977). LaBonte (1976) found only 11 days with 2 or more reverse slope bursts during the 5 yr between 1970 and 1974. Considering the abundance of closed magnetic field lines and the rarity of the RS bursts (and U bursts) observed we suspect that there are actually more than are observed, or at least more such electron streams in closed loops. We conclude that most of the remote Hα brightenings reported in this paper were probably initiated by heating of the chromosphere by streams of nonthermal

electrons similar to those which produce RS bursts even in those cases in which no RS burst was observed.

More cases are needed to confirm our proposed link between Type III RS bursts and remote flare brightenings. To that end good quality and high time, resolution full-disk or large partial disk Hα filtergrams are essential.

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