

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

*D.R.A.*

## Observations of the Structure and Evolution of Solar Flares with a Soft X-Ray Telescope

(NASA-CR-145894) OBSERVATIONS OF THE  
STRUCTURE AND EVOLUTION OF SOLAR FLARES WITH  
A SOFT X-RAY TELESCOPE (Aerospace Corp., El  
Segundo, Calif.) 40 p HC \$4.00 CSCI 03E

N76-14009

Unclas

G3/92 15050

Prepared by J. A. VORPAHL, E. G. GIBSON, P. B. LANDECKER,  
D. L. MCKENZIE and J. H. UNDERWOOD  
Space Physics Laboratory

30 June 1975

Prepared for VICE PRESIDENT AND GENERAL MANAGER  
LABORATORY OPERATIONS



Laboratory Operations  
THE AEROSPACE CORPORATION

OBSERVATIONS OF THE STRUCTURE  
AND EVOLUTION OF SOLAR FLARES  
WITH A SOFT X-RAY TELESCOPE

Prepared by  
J. A. Vorpahl, E. G. Gibson, P. B. Landecker,  
D. L. McKenzie, and J. M. Underwood  
Space Physics Laboratory

30 June 1975

Laboratory Operations  
THE AEROSPACE CORPORATION  
El Segundo, Calif. 90245

Prepared for  
VICE PRESIDENT AND GENERAL MANAGER  
LABORATORY OPERATIONS

OBSERVATIONS OF THE STRUCTURE  
AND EVOLUTION OF SOLAR FLARES  
WITH A SOFT X-RAY TELESCOPE

Prepared

  
J. A. Forpahl

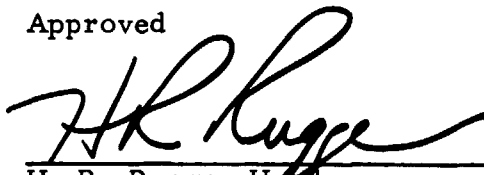
  
E. G. Gibson

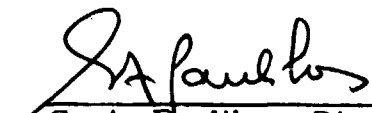
  
P. B. Landecker

  
D. L. McKenzie

  
J. M. Underwood

Approved

  
H. R. Rugge, Head  
Upper Atmospheric Physics  
Department

  
G. A. Paulikas, Director  
Space Physics Laboratory

## ACKNOWLEDGEMENTS

We express our appreciation to all the NASA personnel who made this work possible, in particular to the Skylab Astronauts and to Mr. J. E. Milligan, the S-056 Principal Investigator for most of the duration of this project. We thank W. C. Medawar, J. B. Paul, G. E. Schacht and R. J. Maulfair for the patient darkroom work needed to produce the photographs. Magnetograms were kindly supplied by Kitt Peak Observatory. This work was performed under NASA Contract NAS8-29602.

## CONTENTS

ACKNOWLEDGEMENTS . . . . .	iv
ABSTRACT . . . . .	vii
1. INTRODUCTION . . . . .	1
2. SOFT X-RAY FLARE OBSERVATIONS . . . . .	3
3. X-RAY STRUCTURES NEAR FLARE MAXIMUM . . . . .	4
4. EVOLUTION OF FLARE STRUCTURES . . . . .	13
5. LIMB FLARES . . . . .	23
6. CORRELATION OF X-RAY PHOTOGRAPHS WITH OTHER FLARE PHENOMENA . . . . .	25
7. SUMMARY AND CONCLUSIONS . . . . .	28
REFERENCES . . . . .	33

## TABLES

1. Characteristics of X-Ray Filters . . . . .	2
2. Frequency of Occurrence of Categories of Flare Cores Observed Near Flare Maximum . . . . .	12
3. The Length of X-ray Core Features vs the Presence of Nonthermal Radio Bursts . . . . .	26

## FIGURES

1.	Sketch showing how "loops" or "linear features" may be resolved into arcades . . . . .	6
2.	Distributions of length and width of 186 individual features observed in 132 flare cores . . . . .	8
3.	Flare of 1 September 1973 . . . . .	11
4.	X-REA plot for flare in Figure 3 . . . . .	15
5.	McMath region 12512 on 1 and 2 September 1973 . . . . .	17
6.	Flare of 6 September 1973 . . . . .	20
7.	X-REA plot for the flare of Figure 6 . . . . .	21
8.	McMath region 12507 on 6 September 1973 . . . . .	22
9.	Limb flare of 6 September 1973 . . . . .	24

## ABSTRACT

132 soft x-ray flare events have been observed with The Aerospace Corporation/Marshall Space Flight Center S-056 x-ray telescope that was part of the ATM complement of instruments aboard SKYLAB. Analyses of these data are reported in this paper. The observations are summarized and a detailed discussion of the x-ray flare structures is presented. The data indicated that soft x-rays emitted by a flare come primarily from an intense well-defined core surrounded by a region of fainter, more diffuse emission. Loop structures are found to constitute a fundamental characteristic of flare cores and arcades of loops are found to play a more important role in the flare phenomena than previously thought. Size distributions of these core features are presented and a classification scheme describing the brightest flare x-ray features is proposed.

The data show no correlations between the size of core features and: 1) the peak x-ray intensity, as indicated by detectors on the SOLRAD satellite; 2) the rise time of the x-ray flare event; or 3) the presence of a non-thermal x-ray component.

An analysis of flare evolution indicates evidence for preliminary heating and energy release prior to the main phase of the flare. Core features are found to be remarkably stable and retain their shape throughout a flare. Most changes in the overall configuration seem to be the result of the appearance, disappearance or change in brightness of individual features, rather than the restructuring or reorientation of these features.

Brief comparisons with several theories are presented.



## 1. Introduction

The S-056 x-ray telescope was one of a cluster of solar instruments carried on the Apollo Telescope Mount (ATM) section of the Skylab space station. This vehicle was in operation from May 1973 to February 1974. A detailed description of the telescope has been given elsewhere (Underwood et al., 1975) but the principal features of the instrument are summarized here.

The x-ray telescope used optics of polished fused silica arranged in a Wolter type I configuration. The effective focal length was 190.3 cm and the collecting area  $14.8 \text{ cm}^2$ . The solar images were recorded on film which was carried in a cassette in roll form. Five filters of thin metal foil could be inserted into the optical path just in front of the film and provided some spectral discrimination. Their characteristics are summarized in Table 1.

The instrument could be operated in any one of a number of modes, chosen by the crew member on the basis of the current solar activity. The range of exposures possible with any particular filter was 1.25 seconds to 40 minutes or more. If the crewman was aware that a flare was in progress (by observing on-board instruments or from information supplied by the control center) he would normally initiate an automatic sequence employing the shorter exposures.

In addition to the x-ray telescope, the S-056 instrument package contained an "X-Ray Event Analyzer" (X-REA) consisting of two uncollimated proportional counters and associated electronics to monitor the total solar flux in the wavelength ranges  $2-8\text{\AA}$  and  $8-20\text{\AA}$ . The two counters had windows of thickness

TABLE 1

## Characteristics of X-Ray Filters

Filter No.	Material	Thickness (mg/cm <sup>2</sup> )	Bandpass* (Å)
1	aluminum	3.45	8-16
2	aluminum	1.56	8-22
3	titanium	0.99	6-14 and 27-47
4	beryllium	4.60	6-18
5	beryllium	13.1	6-13

\* Wavelength region where the product of filter transmission and telescope reflectivity exceeds  $10^{-4}$ .

46.9 mg/cm<sup>2</sup> beryllium and 1.71 mg/cm<sup>2</sup> aluminum, respectively. The time resolution of these counters was 2.5 sec. Pulse height analysis was performed on board to obtain spectral data.

## 2. Soft X-Ray Flare Observations

During the three manned Skylab missions, the S-056 x-ray telescope obtained more than 27,000 frames of solar x-ray data. A survey of this data revealed that several hundred flare-like transient brightenings had been photographed at some stage of development. Here we chose to analyze those which showed enhancements equivalent to a C0 flare or greater in the 2-8Å X-REA detector or the SOLRAD records and for which there were good observations near flare maximum. 132 events met these requirements. The crew members were requested to start the S-056 experiment if there were the slightest reason to believe that a flare or transient event might occur. Because of this policy, we obtained observations during the rise of 121 of the 132 x-ray flares. In 40 cases the camera was operating when x-ray flux first began to increase, and the actual start of the flare was observed.

Two-thirds of the 132 events were associated with an H $\alpha$  flare or subflare listed in Solar Geophysical Data bulletins. We found that, while almost all confirmed H $\alpha$  flares and subflares were associated with x-ray brightenings, the converse was not true. Transients showing on the film, but having neither a sufficient X-REA nor a SOLRAD signature, were classified as "minor brightenings" and excluded. For some events, the X-REA or SOLRAD records showed a multiple-peaked time structure. If the x-ray intensity fell to its

pre-flare value before rising to the next peak, the event was counted as two flares. Events which showed a second or third peak while the first was still near maximum were counted as a single flare unless the two peaks could be attributed to flares in different regions, in which case they were counted as separate but possibly sympathetic flares.

### 3. X-Ray Structures Near Flare Maximum

As the photographic images provide spatial resolution unobtainable with previous instruments, it was natural to examine first the 132 events classified as soft x-ray flares for evidence of a characteristic or prevalent flare structure. We found that in almost all flares the bulk of the radiation comes from a compact and well defined "core" which is surrounded by a larger, fainter and less well defined area of emission originating from the active region in which the flare is embedded. In some cases, when the flare core was very bright, the wings of the telescope point spread function contributed to this diffuse component, but the active region contribution could almost always be distinguished due to its characteristic structure, usually taking the form of diffuse loops or arcades of loops.

Since the core is responsible for most of the x-ray emission, its shape provides important clues to the physical mechanisms by which flare energy is released. It will be shown later in the section on evolution that an individual core feature normally varies only in brightness, maintaining its shape throughout the duration of an event. Consequently, in categorizing the flare cores, we used the time period near flare maximum when all the flare features are usually

present and they are best defined. We chose the particular frames which showed the flare core structure best, regardless of filter or exposure time, although usually the shorter exposure times (less than 15 sec) were most suitable. The spectral effects introduced by the filters are subtle, and the flare cores did not in general show marked differences from filter to filter. Viewed near flare maximum, the cores exhibited a wide variation in structure, from a simple type consisting of one predominant bright feature to more complex shapes containing several features of flare brightness, often connected by fainter x-ray filaments or wispy structures.

The feature seen most often as a simple flare core, or as a component of a complex core, was a linear one with a width of 5 - 10 arc seconds and a length ranging from 5 arc seconds to one or two arc minutes. These features were often curved, suggesting loops seen in projection. When seen at or near the limb, they frequently appeared arch-like. For this reason we refer to all straight or curved structures as "loops." It should be noted however that, upon close examination, some apparently "linear" structures turned out to be an entire arcade of closely spaced loops or the superposition of several overlapping, partially aligned smaller loops. Some examples of observed structures are demonstrated in Figure 1; we shall discuss this further in a later section.

Practically all core features with one dimension greater than 10 arc seconds had a loop-like or filamentary appearance, and many of those smaller than 10 arc seconds could be clearly resolved as tiny loops. This suggested that the loop structure is a basic characteristic of flare cores and that loop lengths might be continuously distributed. We measured the dimensions of 186 loops and linear

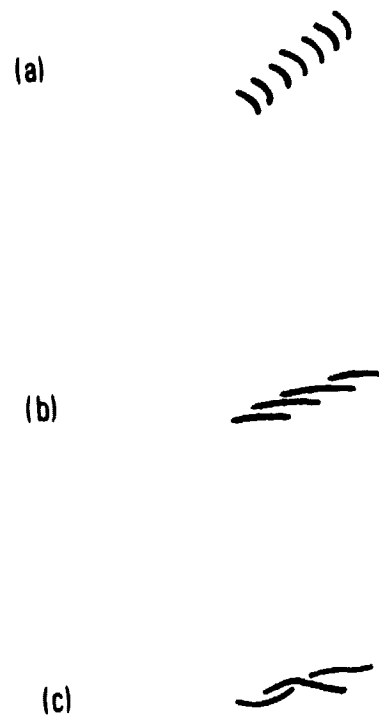


Figure 1 Sketch showing how "loops" or "linear features" may be resolved into arcades.

features (more than one such feature per flare could occur) found in the cores near maximum and obtained frequency distributions of their lengths and widths (Figure 2). We found a continuum of lengths, peaking in the 4,000 - 20,000 km (~5-25 arc seconds) range. Most of the features (93%), were less than 50,000 km long, but a few (<2%) with lengths greater than 100,000 km were seen. On the other hand, the measured widths appear to be almost exclusively below 15,000 km, with a mean of 5,000 km. Thus, the loop-like features appear to be very similar, both in geometry and in size distribution, to the green line loop features discussed by Kleczek (1963) and Dunn (1971).

From these observations we infer that the few very small features near the limit of resolution under the viewing conditions used, which could not be resolved as loops, would have appeared as small loops in observations of higher resolution. Therefore, they deserve to be classified separately only by virtue of their unresolvable structure. Following Beigman et al. (1969) we call these features "knots". The knots reported by these workers were probably larger than those reported here because their experiment had relatively poor resolution. We define a knot as a feature smaller than 10 arc seconds with a length/width ratio of less than 2, while a feature of similar size but with a length/width ratio of 2 or greater is called a small loop.

In a study of 12 flares observed with another ATM experiment (S-054) in early September 1973, Kanler et al. (1975) also noted the presence of looplike structures in the flare during the maximum phase. They found, in addition, that a different class of structure, small pointlike features which they termed "x-ray kernels," appeared during the flare rise and that these features "gave

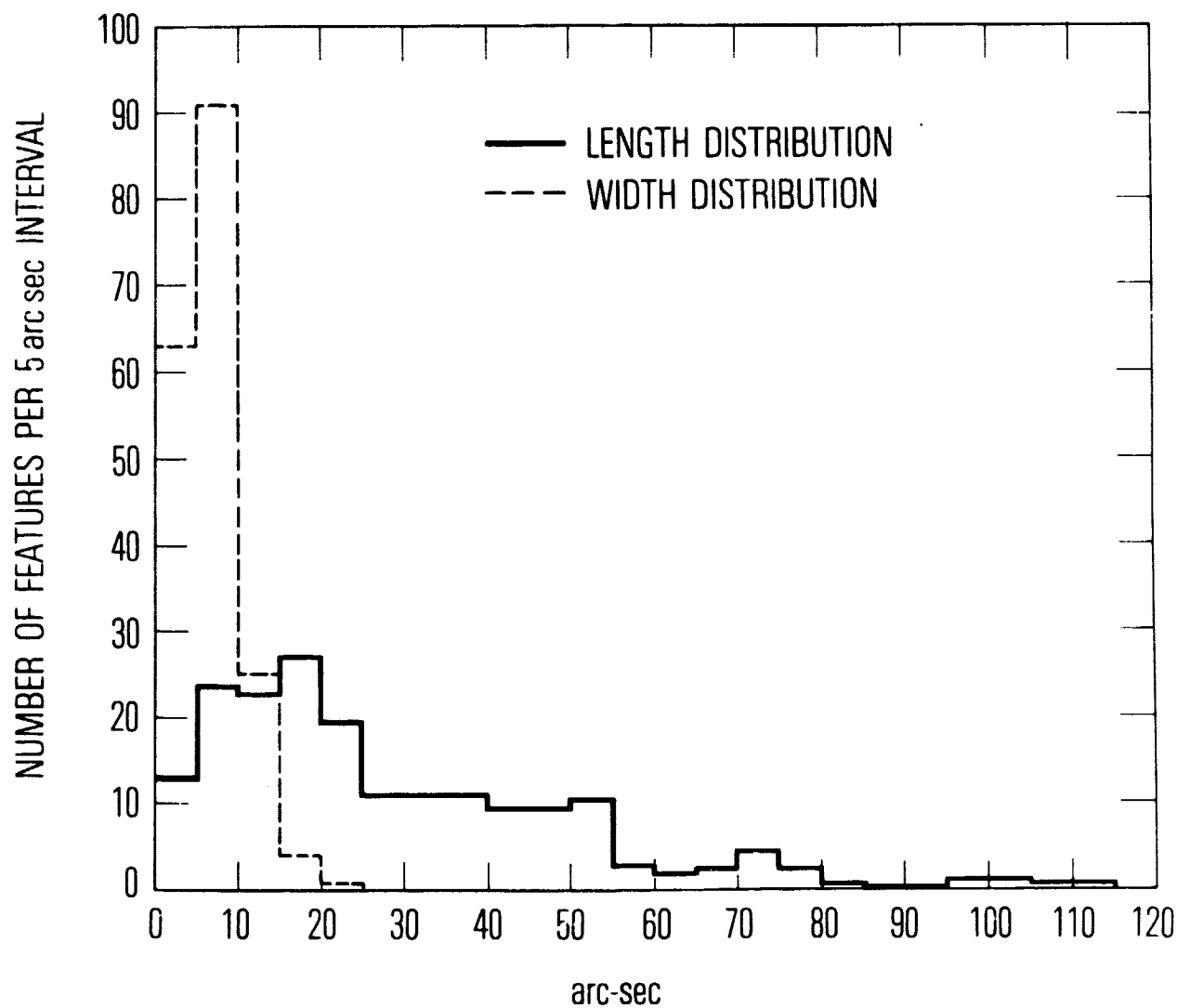


Figure 2 Distributions of length and width of 186 individual features observed in 132 flare cores.



way" to loops as the flare progressed. In an earlier work, Glencross et al. (1974) used the term kernels to describe small features which they assumed developed during the course of a flare and which were responsible for secondary peaks in the time structure.

It is of interest to ask how these kernels relate to the knots and small loops that we observed in the flare core near maximum. Since several of the flares listed in Table 1 of Kahler et al. were also recorded by the S-056 telescope, a direct comparison is possible in these cases. We found that each listed kernel could be seen in the S-056 exposures. However, since we were able to resolve several of them as small loops we could apply neither the term knots nor the term kernels to all of them. One example of this is a flare on 1 September 1973 to be discussed later. There are other important differences between the "kernels" described by Kahler et al. and our "knots" and "small loops" which justify the use of separate terms. These differences are discussed in later sections.

Using the definitions of loops and knots given above, we have devised a simple notation to classify flare cores. In this scheme, a core is classified by the number of loops or linear features (L) or knots (K) that it contains. Thus, a core consisting of a single loop or linear feature is designated L and one consisting of a single knot is designated K. Both K and L cores are called "simple" cores. Complex cores, in which several intersecting components appear, are designated mKnL where m is the number of knots and n the number of loops that appear to intersect, i. e. 2K2L denotes two intersecting loops with two knots superimposed. If the features are non-intersecting or are disjoint, a + sign is used to denote this, e. g. K + L, 2K + KL. Infrequently we have

observed complex cores which cannot be described in simple terms of loops and knots. These are designated as I (irregular). Examples of a knot and loop observed during the precursor of a flare on 1 September 1973 are shown in Figure 3 and will be discussed later. Figure 6 shows a flare, classified as Irregular, observed on 6 September 1973. In applying this classification we are concerned only with the flare core — the region of the flare responsible for most of the emission near flare maximum and which could be seen on the shorter exposures taken during the flare. We make no attempt to include the fainter features and the more diffuse structures in the envelope surrounding the core.

All 132 soft x-ray events were classified according to this scheme, and the results are presented in Table 2.

It can be seen that the typical core consists of 2 resolved loops, with the single loop being next most frequent. We want to emphasize, however, that at least 6 of the 36 events classified as simple L were suspected of being an entire arcade with individual loops that were beyond the limit of resolution. Consequently, some simple events probably consist of multiple features as well. We feel, however, that at least some flares evolve by the simple brightening of one loop. Such events can best be seen, and interpreted unambiguously, near the limb. Of the 7 events with a knot superposed on a loop, KL, the knot was usually at one end rather than somewhere along the length of the loop. Here also the data suggest that we are actually seeing one small feature, near the footpoint of a large one, or one bright loop in a linear feature consisting of several unresolved loops in an arcade.

ORIGINAL PAGE IS  
OF POOR QUALITY

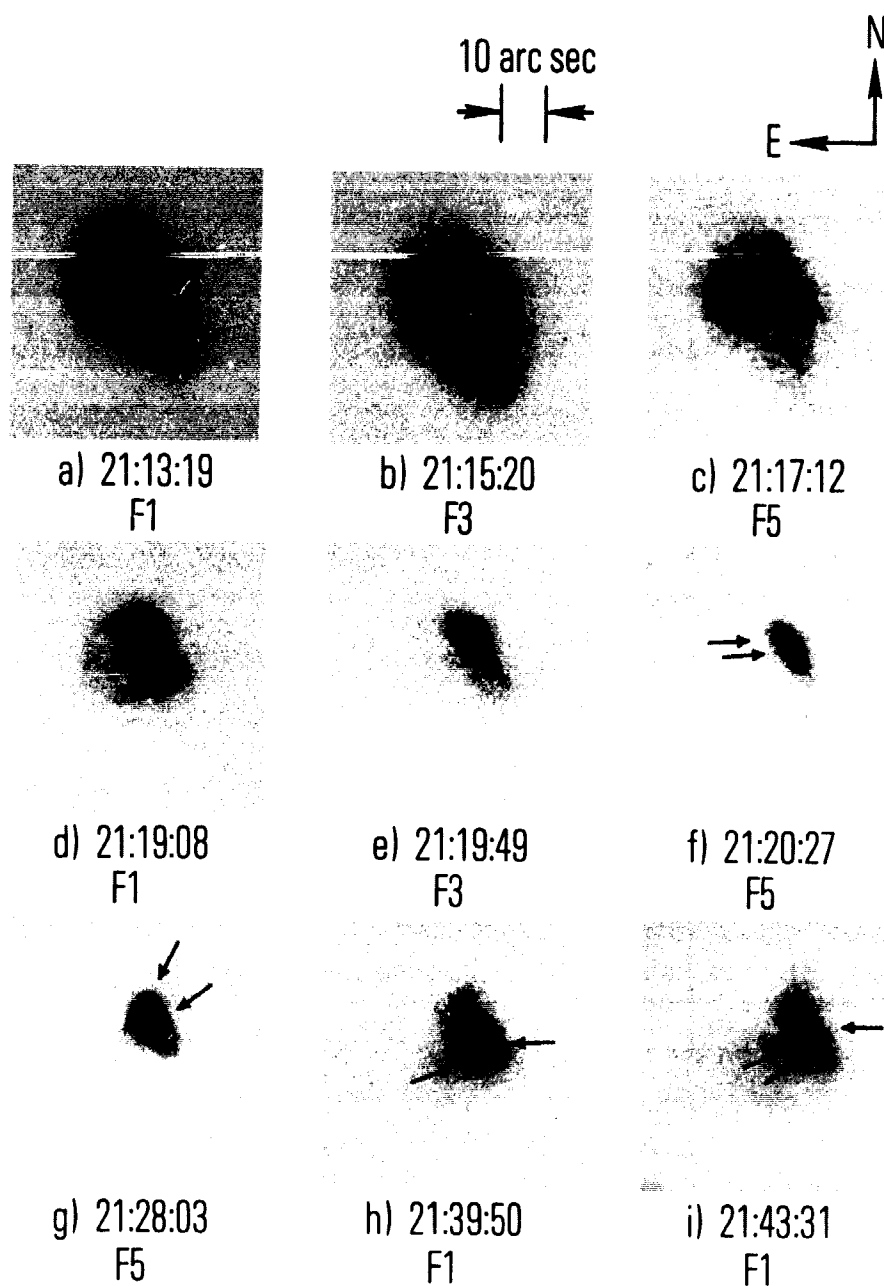


Figure 3. Flare of 1 September 1973. The filter and the universal time of exposure start are given under each frame. The exposure times are: (a) 86s, (b) 49s, (c) 53s, (d) 26s, (e) 15s, (f) 16s, (g) 14s, (h) 14s, (i) 14s. The arrows give the approximate direction of crosswise striations in the x-ray core.

TABLE 2

Frequency of Occurrence of Categories of Flare Cores Observed Near  
Flare Maximum

Category of Flare Core	Number Observed	Percent
Simple		
L	36	27.3
K	14	10.6
Complex		
2L	40	30.3
3L	9	6.8
4L	4	3.0
2K	3	2.3
3K	1	0.8
KL	7	5.3
K + L	4	3.0
K + 2L	3	2.3
I	11	8.3
TOTAL	132	100.0

#### 4. Evolution of Flare Structures

In addition to the high resolution spatial information, the x-ray telescope provided time sequences of exposures which enable us to study the evolution of the core as the flare passed through the rise, maximum and decay phases. Due to the policy of starting the camera on any indication of a flare, we obtained observations during the rise of 121 of the 132 x-ray flares, with the starts observed in 40 cases. Our observations show that many times the flare core can be seen in longer exposures taken before the x-ray flux begins to rise in the X-REA or SOLRAD detectors. We interpret this to mean that some gradual heating or energy release occurs before the more catastrophic event takes place. In addition, the shape that an individual core feature has near the beginning of an event is usually maintained throughout its lifetime, regardless of whether the event was simple or complex. Cores which exhibited simple K or L structure evolved by the simple brightening and fading of this feature. We found that no simple generalization could be made regarding the sequence in which the separate components of a complex core evolve. At times all of the features brightened simultaneously; however, in most cases, a loop brightening was followed by another, or a knot by a loop, etc. Our data do not support the suggestion of Kahler et al. that "kernels" appear most prominently during the flare rise and are a morphological characteristic common to all or nearly all x-ray flare events. Conversely, we found that if knots or small loops are present, they may appear during any phase of a flare, not merely during the rise and that small features do not necessarily "give way" to loops as the flare evolves.

In 61 of the 132 events, we were able to follow the flare throughout the decay phase and determine what happened to the core. In 51 cases the core features merely became fainter and more diffuse while in the remaining 10, significant changes in structure occurred.

An attempt was made to find a correlation between the physical size of a flare core, or of a single core feature showing a separate and distinct peak, and the rise time of the corresponding x-ray event. Kahler et al. infer such a correlation. Rise times between the 10% and 90% of peak points were studied, using data from the 8-20 $\text{\AA}$  X-REA detector. Rise times range from less than one minute up to 15 minutes, with one or two exceptional events of the gradual rise and fall (GRF) type taking much longer to reach maximum. The length of the largest feature involved in producing the x-ray peak was taken as a measure of size. No correlation between the core size and the rise time of the event was found from our data however.

In a few cases, in particular some of those which were also observed and described by the S-054 group, knots and small loops appeared early in the event and later seemed to be accompanied, or sometimes connected, by larger x-ray filaments. An example of such evolution is given in Figure 3, a sequence of exposures for a class C4 flare that occurred between 2118 and 2145 UT on 1 September 1973 in McMath 12512 (Boulder 215). Figure 4 shows the total number of counts between 2-8 $\text{\AA}$  in the X-REA detector during this event. McMath 12512 was a very young region and began flaring within hours after initially becoming visible around 0100 UT on 1 September. Its detailed magnetic structure could not be discerned accurately on 1 September because of close proximity to the limb (S15, E65) but on the following day the region manifested

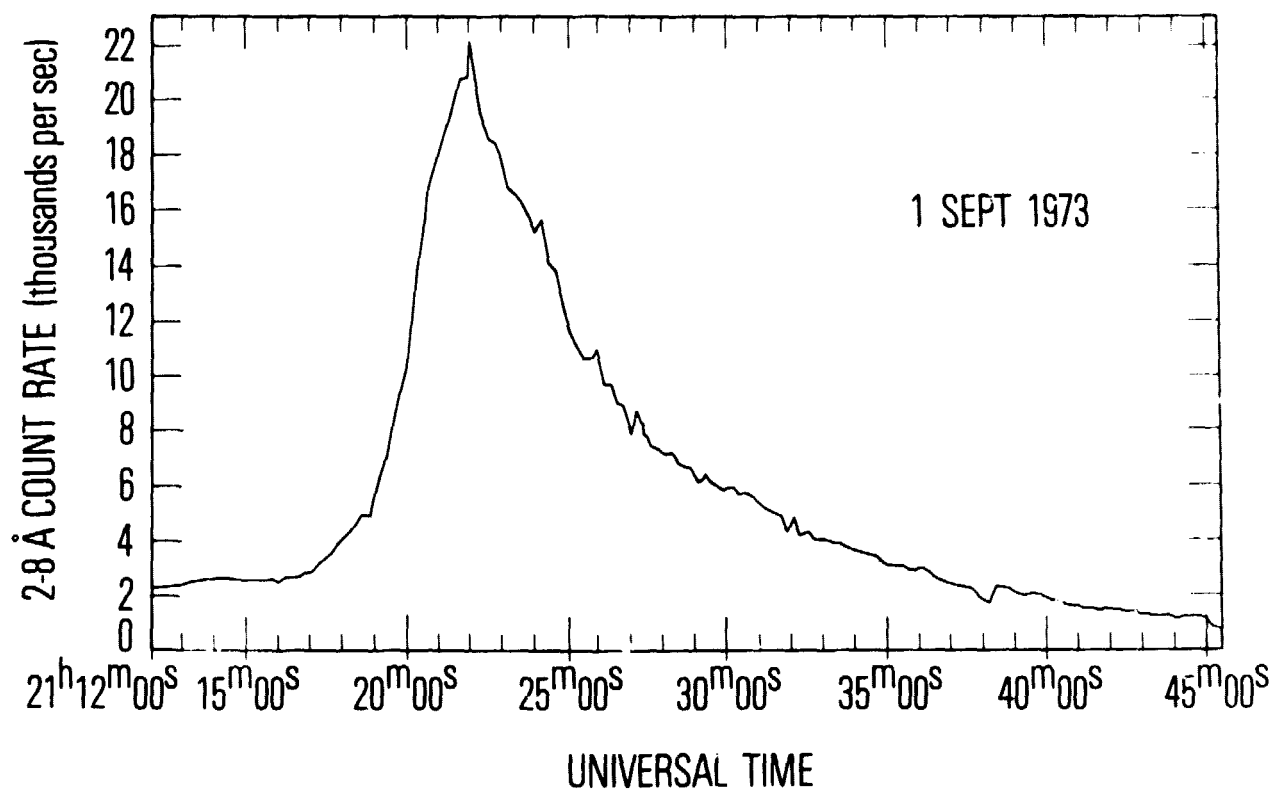


Figure 4 X-REA plot for flare of Figure 3. The ordinate represents the total counts recorded by the Be window (2-8Å) proportional counter.

itself as bipolar with several smaller pockets of leader polarity positioned in the large follower fields. These inclusions of opposite polarity proved to be intimately related to various components in the x-ray flare core. In Figure 5 we show Kitt Peak magnetograms for both September 1 and 2, as well as a sketch made to a similar scale, to assist in identifying the flare features. The x-ray sketch has been positioned to best agree with the September 2 magnetogram.

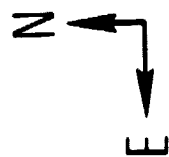
Two sets of overlapping x-ray arcades (a) and (b), positioned at an angle to each other, are visible in preflare exposures taken with filter 1 (8-16Å) and filter 3 (6-14Å, 27-47Å) in the first row of Figure 3. These arcades are not visible in a similar exposure of filter 5 (6-13Å), although two features (c) and (d) are very bright and well defined. This suggests that the arcades existed prior to the flare as cooler structures, while features (c) and (d) which appeared during the early rise were much hotter.

In the second row of Figure 3, shorter exposures (about one-third as long as those in the first row) show only the flare core itself. Here feature (c), the brightest part of the flare, continues to intensify; however, the most rapid rise in the X-REA time profile did not occur until the entire space between (c) and (d) had brightened. Photos in the third row show the core in the decay phase of the flare.

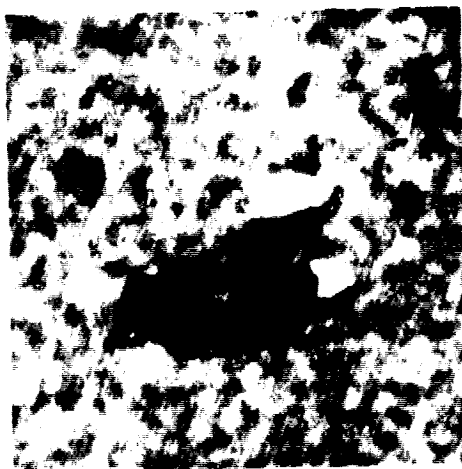
Comparison of the x-ray photos with the KPNO magnetograms in Figure 5 show that the arcades (a) and (b) connect regions of opposite fields, especially concentrating on the small inclusions located in the following polarity. In fact, the footpoints of some loops in the arcades lie on, or near, the flare's most intense features, (c) and (d). The x-ray loop (f) lies near another small bit of leader polarity in the south, while the diffuse x-radiation outlines the eastern part of the magnetic field.



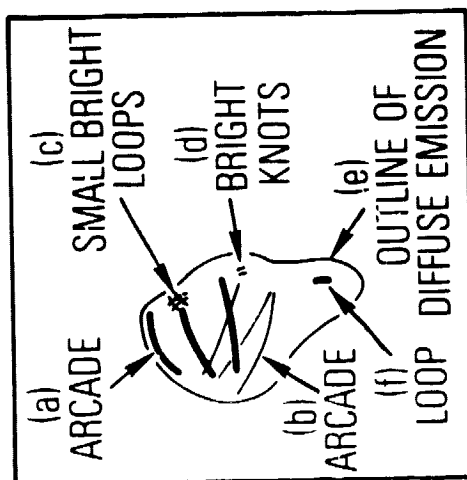
ORIGINAL PAGE IS  
OF POOR QUALITY



10 arc sec  
→ | ←



1 SEPT 1973  
14:48 UT



2 SEPT 1973  
07:01 UT



Figure 5 McMath region 12512 on 1 and 2 September 1973. The center sketch is a key to the x-ray structures seen in the core of the flare of Figure 3; the labeled features are discussed in the text. The right and left frames are magnetograms taken at Kitt Peak National Observatory

At first, this flare might seem to be a case in which two features brighten and are eventually joined by a line, or loop, of emission. This is the type of flare, however, in which closely spaced loops can very easily be interpreted as one linear feature. Examination of the last four photos in Figure 3 shows that the 1 September flare was really the brightening of an entire arcade, with features (c) and (d) forming part of that configuration. The arcade was not simple, but instead exhibited signs of crossed loops and other similar types of complicated structures. In fact, feature (c) consists of two sets of closely spaced, overlapping lines of x-ray emission.

Although the 1 September flare had complicated x-ray structures, with the most intense features occurring near inclusions of opposite polarity, it was not an energetic event in terms of producing nonthermal electrons. No microwave or type III radio noise was reported at the time of the flare.

Sometimes the X-REA or SOLRAD records showed a multiple-peaked or structured time profile. We examined 22 of these events occurring during the first ten days of September, and found that the irregular time variation in x-radiation was due to: a) secondary enhancements in the same flare kernel(s) - 14 times; b) the appearance of new kernels within the same active region - 4 times; and c) flare brightenings in close time coincidence from different active regions - 4 times.

We interpret the fact that the x-radiation from a single flare core feature can change in time, sometimes quite abruptly, as evidence for a variation in the energy release itself rather than for the storage of electrons. Furthermore, the fact that the same feature normally undergoes additional brightenings,

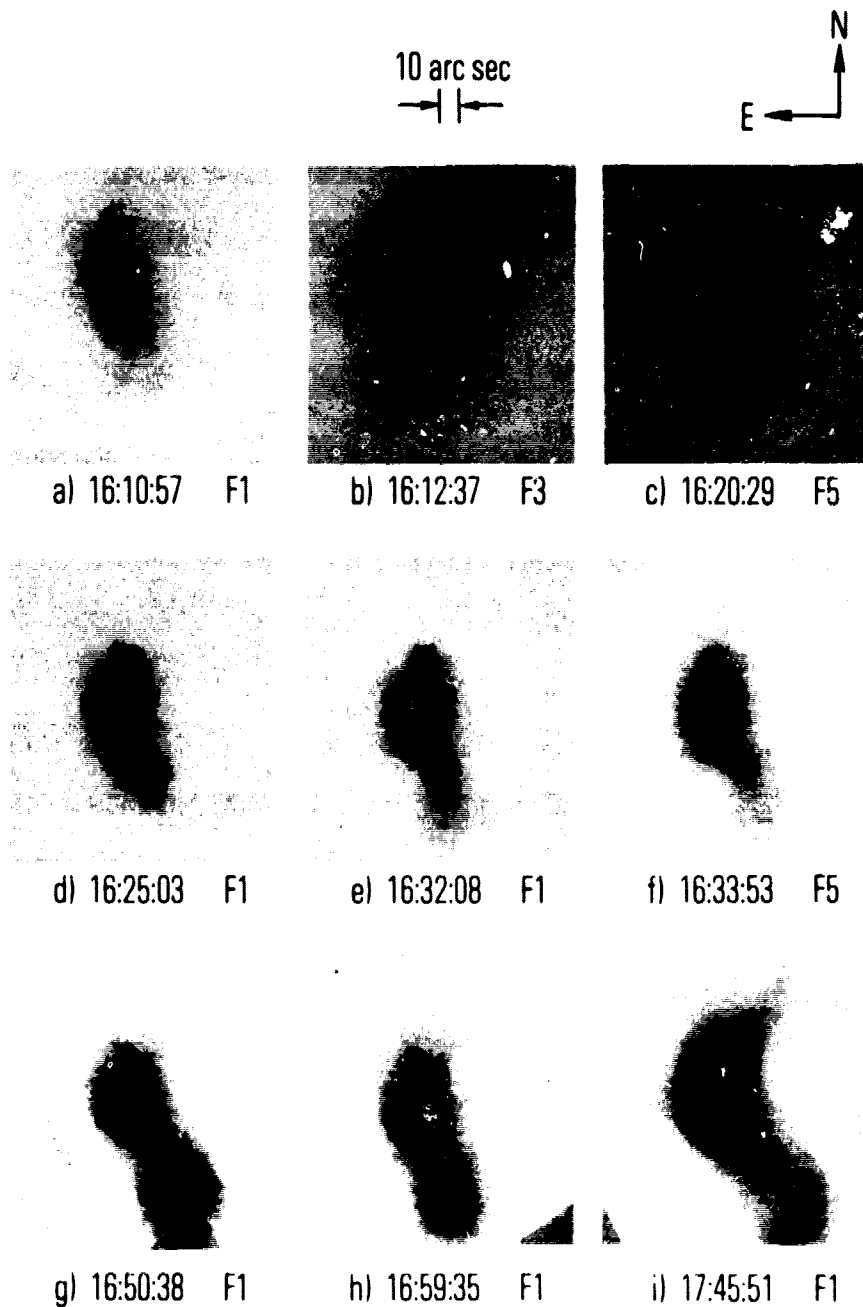
instead of having different kernels appear within the same active region, implies that new energy releases most often occur in the same place.

Four of the multiple-peaked or structured flares coincided with simultaneous x-ray brightenings in more than one spot group. In three cases, however, both regions were already bright on films taken after a data gap, and the exact time coincidence cannot be determined. In the fourth event, the regions did intensity within 6 minutes of each other, thereby suggesting sympathetic activity.

An example of an event showing a complex time history, as well as a complex core structure, is given in Figure 6. This is one of the events we classified as I (Irregular). The flare occurred on 6 September 1973 between 1610 and 1650 UT in McMath 12507 (Boulder 209). Figure 7 shows the total number of counts between  $2-8\text{\AA}$  in the X-REA detector during this event, rated C3 on the SOLRAD scale. The X-REA plot shows that a very small precursor was observed at 1612 UT, with the major part of the flare beginning to rise slowly after 1617 UT. The maximum intensity occurred at about 1625, with small peaks at 1620, 1621, 1631 and 1634 UT. We again include a KPNO magnetogram for the 6th, with a sketch made to the same scale of some major x-ray features for identification purposes (Fig. 8).

Most of the flare's x-ray emission came from a series of features which lay along the neutral line between the leader and follower polarity. Each of the three most intense features (a), (b) and (c) in the flare actually consisted of several short lines 20-25 arc secs or less in length joining opposite fields.

ORIGINAL PHOTOGRAPH  
OF POOR QUALITY



**Figure 6** Flare of 6 September 1973. The filter and the time of exposure start are given for each frame. The exposure times are: (a) 26s, (b) 14s, (c) 16s, (d) 26s, (e) 26s, (f) 16s, (g) 26s, (h) 26s, (i) 26s.

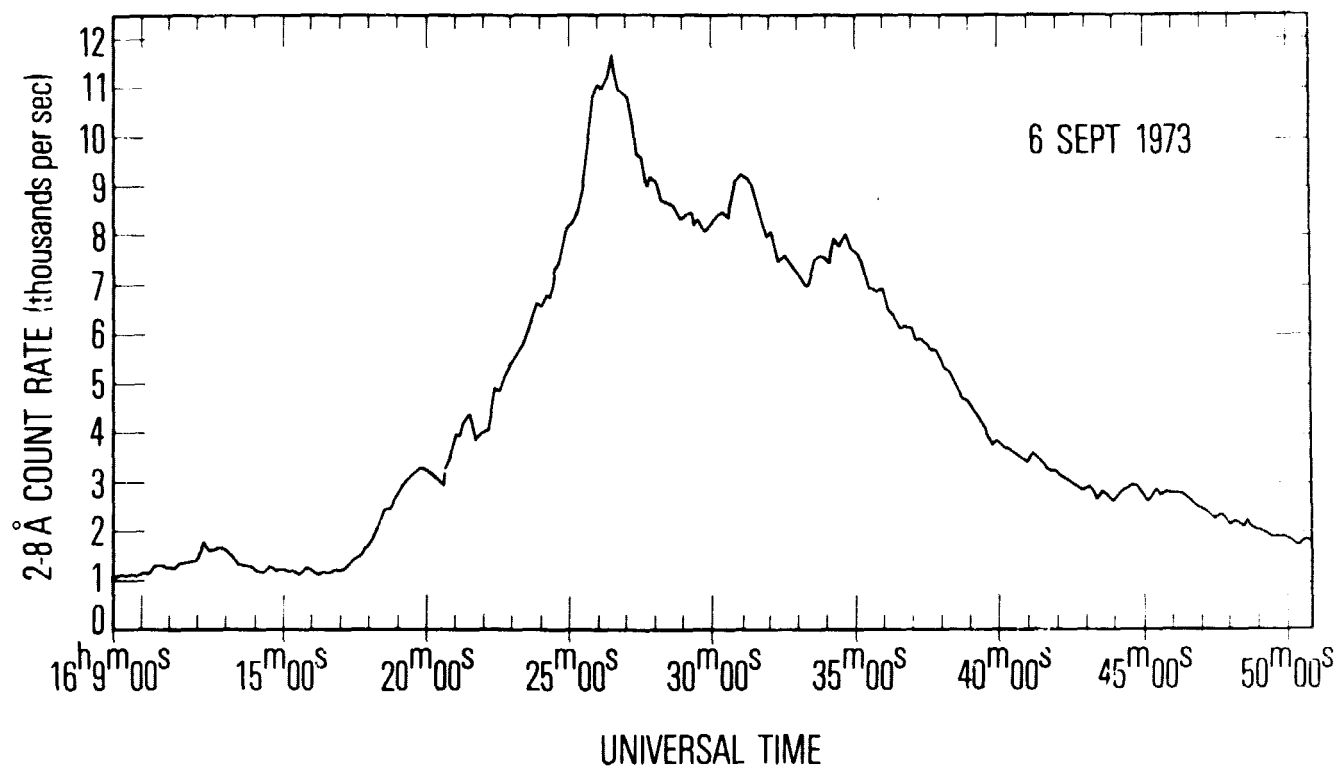


Figure 7 X-REA plot for the flare of Figure 6.

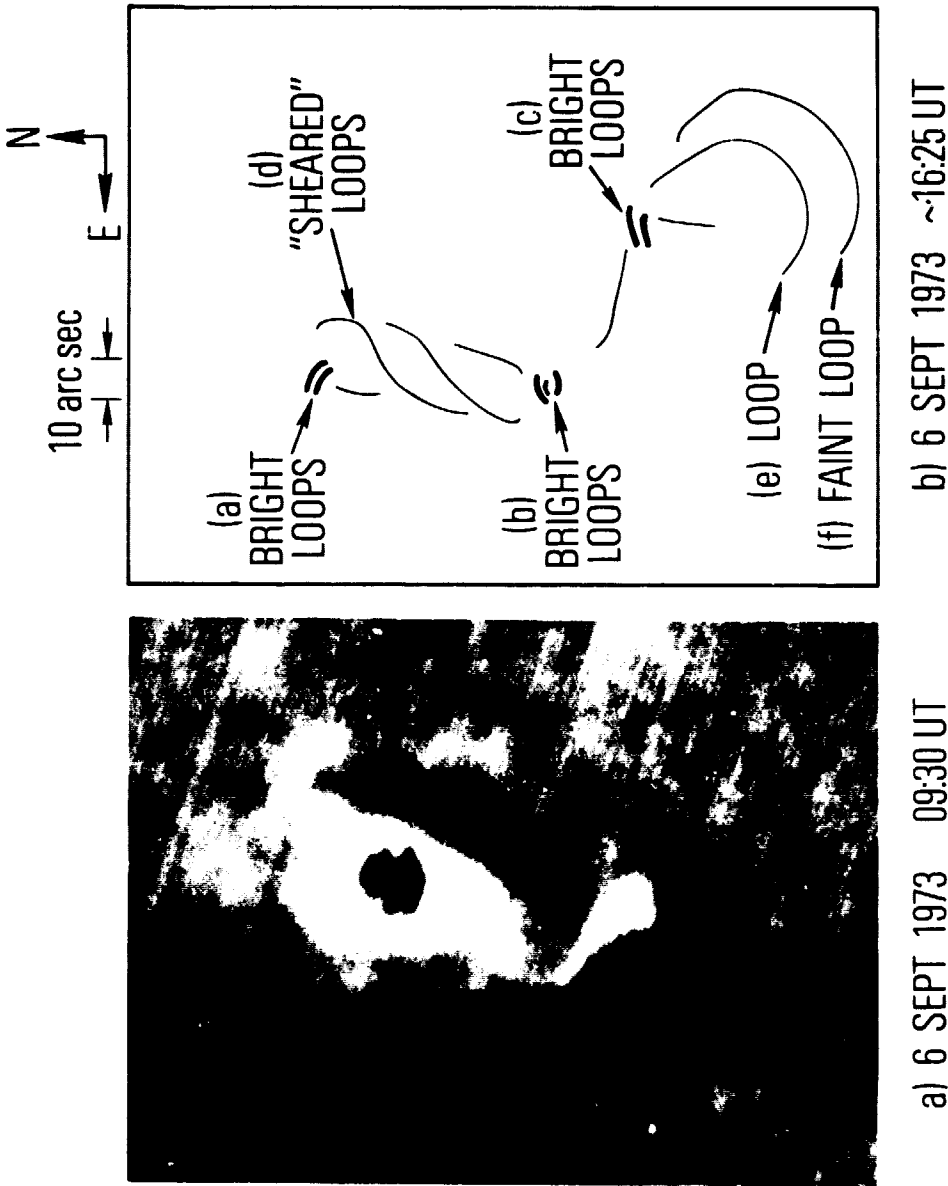


Figure 8 McMath region 12507 on 6 September 1973. The Kitt Peak Observatory magnetogram is on the left. The right hand sketch is a key to the structures seen in the flare of Figure 7; the labeled features are discussed in the text.

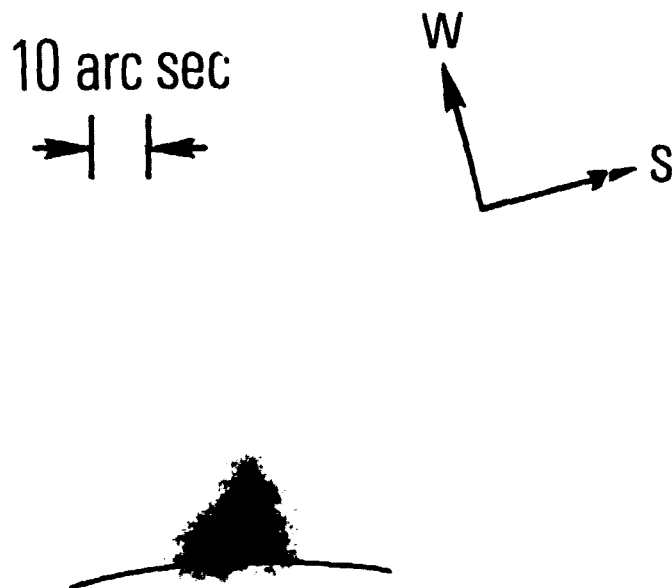
ORIGINAL PAGE IS  
OF QUALITY

Features (a) and (b) were already evident in the preflare picture at 1610 UT, with (a) brightening in the 1612 UT picture to correspond to the small precursor in the X-REA plot. Several different parts of the flare had intensified by flare maximum near 1625 UT, with individual loops (d) located in a sheared position across the neutral line. Secondary peaks in the X-REA plot at 1631 and 1634 UT corresponded to brightenings and rebrightenings in different parts of the active region, resulting in a change in appearance of the overall x-ray configuration. By the late decay phase of the flare at 1650, another loop (e) had intensified. The larger loop (f), which appeared as a faint postflare feature, was a member of a nest of loops in the southern part of McMath 12507 and appear to have been brightened by the flare. Also, by 1745 UT, the appearance of the active region had changed so that the most intense part was composed of several overlapping loops.

There was no evidence of non-thermal electrons in terms of type III or impulsive microwave emission in the 6 September flare.

### 5. Limb Flares

Twenty-five flares were observed at the limb or within  $20^\circ$  of the limb. In these cases it was possible to observe the vertical structure of the flare core. On several occasions we observed a single, well defined loop core to change in shape, first developing a bright spot at the top of the loop and then evolving into a spike-like structure reminiscent of a helmet streamer. One example of this type of structure is depicted in Figure 9, which shows the core of a flare occurring at 1216 UT on 6 September 1973.



6 SEPT 1973  
12:16:20 UT

Figure 9 Limb flare of 6 September 1973. This is an 85s exposure which started at 12:16:20 UT. Filter 1 was used.



## 6. Correlation of X-Ray Photographs with Other Flare Phenomena

Vorpahl (1972) observed that hard x-rays are emitted at times when intense H $\alpha$  kernels rapidly appear within the flaring structure. It is natural to ask whether these kernels may be seen in x-rays, in particular, whether any of the knots or small loops we found could be identified as the source of x-ray bursts. Since neither extensive hard x-ray measurements nor high spatial resolution H $\alpha$  observations were made during the Skylab mission, a direct correlation with either of these phenomena is not possible. Instead, we examined the flare records for impulsive radio events that provided evidence for the production of energetic non-thermal electrons within the flare plasma. An event was considered to have a non-thermal component if either a type III burst or an impulsive radio event with flux above 2000 MHz was observed during the rise phase of the soft x-ray flare. In order to test the association of these events with small features (knots or small loops) we divided the events into those which showed features smaller than 10 arc seconds in the core and those which did not. We also divided the events into those having non-thermal components and those which did not, giving the four-celled Table 3. It is clear from an inspection of cells 1 and 2 of this table that the majority of events showing non-thermal manifestations have neither knots nor small loops in the core, and from cells 1 and 3 we see that most knots and small loops do not, in most cases, give rise to non-thermal radio bursts. Simple  $\chi^2$  tests were used to show that these data do not support other hypotheses. We looked for a relationship between the presence of non-thermal emission

Table 3. The Length of X-ray Core Features vs the Presence of Nonthermal Radio Bursts

	Flare Cores With Features < 10" in Length	Flare Cores With Features > 10" in Length
With Non-thermal Radio Bursts	11 Events $\frac{1}{-}$	35 Events $\frac{2}{-}$
Without Non-thermal Radio Bursts	24 Events $\frac{3}{-}$	53 Events $\frac{4}{-}$

during a flare and the area of a soft x-ray core feature, but the two parameters proved to be essentially independent. Although we recognize that there are selection effects in these data (either x-ray features or radio bursts may have been below the limit of sensitivity of the particular instrument used) and while specific small features may be associated with specific impulsive radio events, we feel that the general association of small x-ray features which appear during the early phases of a flare with non-thermal events remains to be proven.

We also attempted to find a correlation between the size of the core (measured as the total length of core features) and the flare intensity according to the SOLRAD records. The correlation, if any, was weak: small cores often gave rise to flares with large peak fluxes and some of the larger cores produced flares that were quite weak. This is to be expected if there is a considerable range of density and temperature from one flare core to another, or even within the separate components of a single flare. A more detailed study of this problem, in which the emission measure is related to the density through the observed size and geometry of the core, is in progress.

## 7. Summary and Conclusions

We analyzed 132 events equivalent to a C0 flare or greater in the 2-8Å X-REA or SOLRAD detectors and for which good observations were made near maximum. Data were taken during the rise of 121 of the events, with the starts observed in 40 cases. Our data show that compact, well defined loop structures are a fundamental characteristic of flare cores and, further, that arcades play a more important role in flares than was previously thought. Individual components in an arcade would sometimes brighten initially, with most x-ray flux occurring when the entire arcade intensified. In some instances, a complete set of loops became uniformly bright, while in others, a large intensity gradient developed across select components. The arcades were not simple, but exhibited complicated structures, with the most intense flare parts consisting of closely spaced, crossed x-ray filaments.

Linear features in a flare's core exhibited a continuum of lengths varying from 3600 km to as much as 100,000 km and peaking in the 4,000-20,000 km range. Measured widths were exclusively below 15,000 km with a mean of 5000 km. Some features classified as linear were suspected of being an arcade of loops crosswise to the long dimension. This means that the length of individual loops taking part in the flare may be comparable to the width of a "linear" feature, i.e., 5,000-15,000 km. In fact, the most intense part of a flare core seemed to consist of short loops, while larger loops in a core were fainter.

The range in lengths discussed above give some indication of the height at which soft x-radiation is produced. Since x-ray loops are normally about half as high as they are long when observed at the limb, typical source heights of 2000-10,000 km are suggested for the soft x-ray component of flares.

Our observations show that many times the flare core could be seen in longer exposures taken before the flare actually started. We interpret this to mean that some gradual heating or energy release occurs before the more catastrophic event takes place. In addition, the shape that an individual core feature has near the beginning of an event is usually maintained throughout its lifetime. We find that no simple generalization can be made regarding the sequence in which the separate components of a complex core, consisting of knots and linear features evolve. Our data do not support the suggestion of Kahler et al. that "kernels" appear most prominently during the flare rise and are a morphological characteristic common to all or nearly all x-ray flare events. In fact, we found that if knots or small loops are present, they may appear during any phase of a flare, not merely during the rise, and that small features do not necessarily "give way" to larger loops as the flare evolves. We followed the flare throughout the decay phase of 61 events and found that in 51 cases the core features merely became fainter and more diffuse, while in the remaining 10, significant changes in structure occurred.

The size (length) of core features was compared to: 1) the possible presence of a non-thermal component as indicated by either type III or impulsive radio burst above 2000 MHz, 2) the peak x-ray intensity as indicated by the SOLRAD records, and 3) the rise time of the corresponding x-ray event. Core feature size was found to be essentially independent of the other three parameters, however. In fact, the majority of events showing non-thermal manifestations had neither small loops nor knots and, furthermore, cores with small features were usually not associated with non-thermal radio bursts. It is not too

surprising that core size is unrelated to these parameters. For example, we would not expect core size and peak intensity to be correlated since there is a considerable density and temperature range from one flare to another, as well as within the separate components of a single flare. A better study would be the comparison of emission measure with density. This study is presently in progress.

The observations given here lend some support to theories such as that of Cheng and Spicer (1974) which demand that the flare process take place in a loop of coronal plasma. Observations of limb flares, however, in which a spike develops at the top of a loop cannot be explained within this framework. Conversely, limb observations bear some resemblance to the configuration proposed by Sturrock (1968) in which field reconnection takes place at the top of a loop. Interestingly enough, the core features are remarkably stable and almost always retain their structure well throughout the course of a flare. Most changes in the overall flare seem to be due to variations in brightness of individual features, or to the appearance of new ones, rather than to a reorientation of individual features that might be caused by gross magnetic field restructuring. It should be noted, however, that the closely spaced, crossed x-ray structures constituting the most intense part of a flare would be a natural place for field line reconnection to occur over a small area. Detailed comparisons with theory await a determination of more quantitative conditions in the flare core.

Finally, the observation that the soft x-ray emitting plasma is not always confined to a single loop does not render invalid theories of flare cooling such as that of Culhane et al. (1970); but rather, simple modifications should be made to these theories to express the fact that the plasma is contained in multiple loops and sometimes entire arcades.

## REFERENCES

- Beigman, I. L., Grimeva, U. I., Mandelstam, S. L., Vainstein, L. A.,  
and Zhitnik, I. A.: 1969, *Solar Phys.*, 9, 160.
- Cheng, D. and Spicer, D. : 1974, To be published in Proceedings of IAU/Cospar  
Symposium No. 68, held in Buenos Aires, Argentina, June 11-14, 1974.
- Culhane, J. L., Vesecky, J. F. and Phillips, K. H.: 1970, *Solar Phys.*,  
15, 394.
- Dunn, R. B.: 1971, *PHYSICS OF THE SOLAR CORONA*, (ed. C. J. Macris),  
Reidel Publishing, Dordrecht-Holland, 114.
- Glencross, W. M., Dorling, E. B., and Herring, J. R. : 1974, *Solar Phys.*,  
38, 183.
- Kahler, S. W., Krieger, A. S. and Vaiana, G. S.: 1975, *American Science*  
and Engineering preprint ASE-3668.
- Kleczek, J.: 1963, *Publ. Astron. Soc. Pacific*, 75, 9.
- Sturrock, P. : 1968, *Proc. IAU Symp. No. 35. Structure & Development*  
*of Active Regions*, 471.
- Underwood, J. H., Milligan, J. E., deLoach, A. C. and Hoover, R. B.: 1975,  
*Space Sci. Inst.*, in press.
- Vorpahl, J. A.: 1972, *Solar Phys.*, 26, 397.

NO COPY MADE BECAUSE NOT FILMED