Properties of Thermal Flares (4–30 MK) Derived from Observations: Does a Reconnection Mechanism Have a Role in the Flare Process?

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Abstract. One of the most violent and best observed phenomena occurring in the solar upper atmosphere is flare emission in the 4–30 MK temperature range. This emission can vary in intensity by more than five orders of magnitude, yet exhibits regular and predictable properties. A wealth of observational data regarding 4–30 MK solar flares has been collected and some of it will be described during the course of my talk. It is my belief that any credible flare model must account for the observations I am about to describe.

1. Introduction

Skylab spectroheliograph images in Fe XV, which are believed to trace coronal magnetic fields show that as new magnetic regions emerge through the photosphere the magnetic field lines of all nearby active regions rearrange themselves into new configurations. These observations convincingly demonstrate the occurrence of magnetic reconnection in the solar atmosphere. The issue behind my talk is not if magnetic reconnection occurs in the solar atmosphere, but if the sun is utilizing magnetic reconnection to energize the 4–30 MK flare plasmas. For convenience I will call the 4–30 MK flare the thermal flare.

In an earlier talk Dr. H. Hudson showed that Yohkoh observations fail to detect certain thermal flare signatures predicted by magnetic reconnection models. In reply, Professor E. R. Priest suggested that the difficulties brought up by Dr. Hudson are due to the inherent faintness of the sought after signatures. To avoid such difficulties, I have decided to follow a different approach. Instead of searching for signatures predicted by the magnetic reconnection process that indeed may be too faint to be detected, I will describe unmistakable observations related to thermal flare plasmas. It will fall upon those who believe that magnetic reconnection provides the energy to fuel thermal flares to explain the observations in terms of their model.

My talk will concentrate on five well established properties typical of the majority of thermal flares. I will describe light curves, flare morphologies, electron temperatures, electron densities, and mass motions in thermal flares. A more complete account of such observations is given in a recently written review (Feldman 1996).
2. The Nature of Thermal Flare Light Curves

2.1. The Shape of the Light Curve

Soft X-ray flares span more than five orders of magnitude in flux at peak emission. They last from tens of seconds to tens of hours. Most thermal solar flares rise and decay monotonically, independent of their peak flux or duration. This is in contrast to hard X-ray emission ($E \geq 30$ keV), also emitted during the rise phase of flares, which fluctuates on sub-second time scales.

The general properties of soft X-ray flare light curves are best seen in 1–8 Å GOES records (Fig. 1).

The M1 flare on 1991 December 26 at 10:50 is an example of an event having a uniform rise and a uniform decay that lasts for less than ten minutes while the one at 21:40 is a typical example of an event that lasts several tens of minutes. The M5 flare on 1992 February 6 is an example of an event with a uniform rise and decay which lasts over five hours, while the X9 flare on 1992 November 2 at about 03:00 is an example of a very bright, long duration event, lasting for more than 24 hours.

Flare light curves do not seem to end abruptly, but rather exhibit a gradual decrease in intensity. Once light curves start their exponential decay, their exponential slope does not become steeper, but either stays constant or becomes shallower. The 1991 December 26 flares occurring at 6:50 and at 14:40 are typical examples of events composed of a number of almost simultaneously occurring eruptions. Complex light curves, like the one corresponding to the 1991 December 26 event, or the 1992 November 2 event, can usually be deconvoluted into several simple exponential rise and decay curves.
Properties of Thermal Flares

Figure 2. Sequences of four Fe filter images of the 1992 February 17 near limb flare. Each frame consists of $32 \times 32$ pixels. Each pixel is $2.45 \times 2.45$ arcsec$^2$.

Soft X-ray fluxes during the rise and decay phases of simple flares can be approximated by two exponentials. The e-folding times of the exponentials can vary between ten and hundreds of seconds.

2.2. Do We See Preflare Activity?

During periods of high solar activity the Sun produces a large number of flares of various sizes. When monitoring the Sun with GOES type detectors it appears as if each flare is preceded by a smaller event. The idea of preflare activity may have been a result of such observations.

When an increase in X-ray activity is observed by a full Sun detector prior to the onset of a flare the question arises as to whether or not this activity increase is related to the onset of the flare. During periods of high activity the frequency of flares of magnitude C1 and brighter is 1.4 per hour, and the frequency of flares brighter than B1 is 10 per hour (Feldman and Doschek 1996). Thus, a conclusion that a faint flare appearing within 30 minutes of a bright flare constitutes preflare activity is questionable, especially during periods of high activity. At times when the GOES 1–8 Å background is at an A4 level or lower it is expected that the random occurrence of flares with magnitudes brighter than A4 will be 0.22 per hour and those brighter than B1 are expected to occur at a rate of only 0.03 per hour. Many flares erupting at such times do not have precursor events.

A typical active region consists of a number of very distinct loop like structures. In general, the active region loops appear to be isothermal with 0.01–2.5 MK temperatures. Examples of loops with temperatures in the 0.5–3 MK range are found in the Atlas of Skylab Images (Feldman et al. 1987). Coronal loops of 2 MK and higher are observed by Yohkoh. To the best of my knowledge, no pre-existing loop has been identified that later become the site of a thermal flare. It appears that flares are formed in regions that, prior to flare onset, were devoid of loop like structures.

3. The Morphology of Thermal Flare Plasmas

The image of the limb flares shown in Figures 2 and 3 represents the morphology of most thermal flares occurring on the Sun. Such flares are composed of one or more loop like structures having a bright region at their top. By contrast, the
candle flame like 1992 February 21 event that was shown several times during
the meeting is an example of an atypical event. Only a very small number of
Yohkoh flares display such morphology. I will limit my discussions to flares
resembling the morphology of the 1992 November 2 event.

3.1. Limb and Disk Flares

The morphology of flares is best observed from events occurring near the so-
lar limb. In such events, the shape of the thermal flare, the location of the
emitting regions and the rate of the rise above the solar surface can be mea-
sured. Thermal flares are generally composed of one, two and occasionally three
or more loops (Feldman et al. 1994). In some cases, at flare onset, the loop
footpoints are comparable in brightness to the loop top. Shortly after flare on-
set, the top becomes the dominant region. It persists as such throughout the
maximum and part of the decay phase. Late in the decay phase the loop top
brightness expands into the legs. The height of flaring loops and the separation
of their footpoints continuously increases. Properties of the bright loop tops are
described quantitatively in (Feldman et al. 1994).

An example of a single loop flare near the solar limb was produced by an
M1.9 flare that occurred on 1992 February 17 at 1537 UT and peaked some five
minutes later. Fig. 2 is a mosaic of the four images recorded through a 119
μm Be filter. Intensities in each frame were normalized to the brightest pixel
in each frame. This mode of depiction produces visually appealing images but
gives the false impression that the intensity of the flaring loop does not change
with time. In reality the brightness of the footpoints does not seem to increase
with time while the loop top brightness increases appreciably. The intensity
ratio at flare peak between the loop top and the footpoints can exceed an order
of magnitude. In flares consisting of a number of loops, individual loops may
emerge, reach maximum and decay on different schedules.
Figure 4. Four 64 × 64 pixel SXT images of the 1992 February 27 disk flare. Superimposed are the sunspot contours seen in white light images also recorded by the SXT.

While non-impulsive events may last for an hour or less, long duration flares may last for more than a day. As seen from the GOES light curve (Fig. 1), the 1992 November 2 X9 event is an example of a flare lasting well over 24 hours (Feldman et al. 1995). The X-ray emission as recorded by GOES shows that the onset time of the 1992 November 2 flare was 02:30 UT, with a peak 40 minutes later, and a decay lasting until November 3 at 09:00 UT. The flare occurred in an active region that was already behind the west limb. Eight SXT images recorded at various times during the 1992 November 2 flare are shown in Fig. 3. The first, well exposed SXT image that was recorded near flare maximum was not centered in the field of view. The SXT image consists of a small number of loops which changed very slowly. By 05:04:44 UT, the bright emitting region consisted of perhaps three distinct loops and after 08:00 UT, only two of the loops were bright enough to be visible. It appears that whenever one flaring loop fades away the slope of the GOES intensity versus time changes. A notable feature seen after 19:30 UT on November 2 is the extension of the bright region down the southern, but not the northern, leg. It is quite common that late in flare decay phases one leg becomes brighter while the other remains faint.

On 1992 February 27 a major flare of class X3 occurred near Sun center at N06W02 (Feldman et al. 1995). The GOES records show that the main flaring event started at 09:43 UT, peaked at 09:54 UT, and had decayed by a factor of 200 by 20:00 UT. A single, soft X-ray loop dominates the image with one footpoint near a sunspot (see Fig. 4). Contours of the stationary sunspot seen in white light images also recorded by SXT are superimposed on the soft X-ray images. The flaring loop increases in size by as much as a factor of 5 during its lifetime.

3.2. Rate of Increase in Size of Thermal Flare Loops

Upward motion of the hot thermal region of several large non-impulsive (M type) solar flares observed by Solflex were measured by a Doppler shift technique (Seely and Feldman 1984). The measurements show that centroids of the 10 MK emission regions during rise phases of non-impulsive flares move to higher altitudes with speeds that range between 20–80 km s⁻¹. As flares approach maximum brightness the upward speed of the centroid of the 10 MK plasma decreases significantly. A Solflex long duration limb flare that occurred on 1980 November 14 also showed that the 10 MK emitting region initially increased in
Figure 5. Flux and temperature as a function of time in a medium size flare.

height at a rate of 30 km s$^{-1}$ and later slowed down to 1.7 km s$^{-1}$ (Kreplin et al. 1985). The height of the loop top of the November 2 limb flare increased during most of the flare decay period at an average rate of 1 km s$^{-1}$.

Disk observations show that flare footpoints do not always move at equal rates relative to the solar surface. One of the many examples of such behavior is provided by the 1992 February 27 long duration event shown in Fig. 4. Most, if not all, of the separation between the footpoints of the 1992 February 27 disk flare was due to motions of only one of the footpoints. The second footpoint that was anchored near the sunspot appeared to remain stationary.

4. Electron Temperature Measurements of Thermal Flare Plasmas

4.1. Variations in Plasma Temperatures During a Flare’s Lifetime

Fig. 5 shows fluxes and temperatures as a function of time for a non-impulsive flare. As seen from the figure, the plasma temperature at the flare onset is fairly low. During the flare rise phase the plasma temperature increases monotonically, until it reaches a maximum at approximately the time that the flare attains maximum brightness. After maximum the temperature begins a monotonic decline.

4.2. The Distribution of Temperature Within the Flaring Loop

The temperature of the plasma within the confines of the loop was first determined from Skylab spectroheliograph observations of the 1973 June 15 flare. Images emitted by plasmas having temperatures larger than 10 MK were dis-
distinctly different from those produced by temperatures lower than 10 MK. The loop top bright region was seen in radiation produced by Fe XXIV (18 MK) resonance lines during the rise, the peak, and the beginning of the decay phase of the event (Widing 1975). The Ca XVII image (7 MK) did not show the loop top, however, it showed the loop legs (Fig. 6).

Occasionally, only the loop tops of flares located far behind the limb are visible to a space instrument. Using the uncollimated BCS Yohkoh observations the temperatures of the loop tops were compared with those produced by disk flares (Mariska et al. 1996; Khan et al. 1995). The comparison showed that loop top temperatures were at least as high as temperatures in which both loop tops and loop legs are visible. Observations show that loop tops have the highest temperature within the confines of the flaring loop.

4.3. Electron Temperature Versus Emission Measure and Versus X-ray Flux

A display of the electron temperature versus X-ray class (flux) is shown in Fig. 7 (Feldman et al. 1996). The most striking characteristic of the figure is the almost linear relationship between X-ray classes, or more precisely the log(flux) measured by the 1–8 Å GOES detector, and the electron temperature. The flux versus temperature curve spans five orders of magnitude between the X-ray classes X20 and A2. Among the entire sample of flares in the study no event of X-ray class M1 or larger was found with a temperature lower than 15 MK during peak emission. Similarly, no flare of X-ray class A9 or fainter was found with a temperature higher than 10 MK at peak emission.

The slope of the line representing the functional dependencies of the log(emission measure) versus electron temperature distribution is somewhat smaller than the slope representing the log(flux) versus temperature distribu-
Figure 7. A display of the X-ray class from the GOES 1–8 Å detector versus peak electron temperature.

5. Electron Densities in Thermal Flare Plasmas

Electron density measurements of flaring plasmas with temperatures in excess of 10 MK are quite difficult. Thus far only a few such measurements in solar flares are available.

The intensity ratio of the He-like forbidden line to the intercombination line is density sensitive. The He-like ions that are of interest in measuring electron densities in solar flare plasmas are O VII, Ne IX and Mg XI. He-like ions from heavier elements are not expected to be sensitive at flare densities. O VII line ratios showed that electron densities increase during the flare rise phase to reach values of $1-2 \times 10^{12}$ cm$^{-3}$ at the time of peak flare intensity. During the decay phase the electron densities decreased to their preflare values (McKenzie et al. 1980, and Doschek et al. 1981). Mg XI line ratios indicate electron densities of $5 \times 10^{12}$ cm$^{-3}$ for a compact flare (Linford and Wolfson 1988). Neither O VII nor Mg XI lines provide information on high temperature plasmas since they are sensitive to 2 MK and 6 MK respectively.

Fe XXI and Fe XXII line ratios (Phillips et al. 1995) implied that the electron densities reached values of $1 \times 10^{13}$ cm$^{-3}$ one minute after the flare peak and decreased to $2-3 \times 10^{12}$ cm$^{-3}$ about five minutes later. It appears that the density of flaring plasmas can increase by several orders of magnitude over coronal plasmas.
6. Mass Motions in Thermal Flare Plasmas

During flare rise phases, line shapes exhibit blue shifted emissions in addition to symmetric line broadenings. For most flares observed by Solflex the average shift of the blue-shifted component represented as a single Gaussian was about 150–300 km s\(^{-1}\). In extreme cases blue shifts during a flare rise phase can reach values as high as 800 km s\(^{-1}\).

Properties of the blue shifted components were studied using Yohkoh BCS spectra from a large number of fairly intense flares, (Mariska et al. 1993 and Mariska 1994). The study consisted of a comparison between spectral line profiles during the rise phase and those late in the decay phase to determine the magnitude of the shifted component. The study showed that the average centroid of the 10 MK blue shifted components were shifted to the blue by 65 km s\(^{-1}\). The centroid shifts show only very small center to limb variations.

Early in their rise phase, about 10% of the flares exhibit unusually large blue shifts (Mariska et al. 1993). Although the locations of the blue shifted emission were identified, no obvious rising fronts of plasma along the legs of the flaring loops were observed. Some of the blue shifted sources were not obviously physically related to the main source of the soft X-ray emission.

7. Summary

I believe that a credible flare model must be able to explain the observations discussed in the talk which are summarized below:

(1) Light curves of simple flares rise and fall exponentially with a constant e-folding time for the rise phase and another for the decay phase. Light curves of complex flares most likely can be deconvolved into a number of simple rise and fall exponential curves. Flare light curves do not seem to end abruptly, i.e., once a flare starts its exponential decay, the light curve e-folding time does not decrease.

(2) Thermal flare plasmas are confined within one, two and less frequently several loops. Some loops may last for the duration of the event, while others last only for a fraction of the time.

(3) The brightest part of the flaring loop during the rise, peak and part of the decay phases is located in a small volume at the loop top. The loop’s height and the distance between their footpoints continuously increases.

(4) For at least some flares, no soft X-ray preflare activity is detected. The thermal flare loop is not visible prior to the flare onset. Therefore, at least for some flares, flare energy seems to be confined in a leak free environment prior to eruption.

(5) The highest temperature within a flaring loop is at the loop top region. The electron temperature of flaring plasmas increases during the flare rise phase and decreases during the decay phase. Flare temperature and flux peak at about the same time. The maximum temperature of the largest solar flares (~X10) can be in excess of 30 MK while the maximum temperature of very small flares (A1) can be as low as 5 MK.
(6) The electron densities of flaring plasmas seem to peak at about the time that the flux peaks. The electron density during peak emission of intense flares may reach values of $1 \times 10^{13}$ cm$^{-3}$.

(7) During the flare rise phase, blue shifted emission of 200–300 km s$^{-1}$ is present. Only seldom does such emission reach values that exceed 800 km s$^{-1}$. The blue shifts disappear during the decay phase.

I would like to suggest that the thermal flare is not governed by phenomena that depend on the arbitrary distribution of the magnetic field or on the rate by which different parts of the magnetic field are pushed toward each other. I believe that a more valid description of a thermal flare would be given by a process analogous to the electric discharge of an RLC circuit where the distinguishing qualities of the eruption are determined by the relationships between say, the stored energy, the resistivity, inductance and capacitance of the system.

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References


