GEOMETRICAL AND PHYSICAL PROPERTIES OF SXR LOOP-TOP FLARE KERNELS

P. PREŚ and S. KOLOMAŃSKI
Institute of Astronomy, University of Wrocław, Kopernika 11, 51-622 Wrocław, Poland
(pres, kolomans@astro.uni.wroc.pl)

Received; accepted

Abstract.
We investigate how the geometrical and physical properties of soft X-ray flare kernels change with their altitude above the photosphere. We analyze limb flares well observed by Yohkoh/SXT showing clear geometry with well separated loop-top kernels. Our analysis concerns relations between kernel size, plasma pressure, energy release and the kernel altitude. We define scaling laws describing how the sizes and its physical properties of kernels vary with the altitude above the photosphere. We interpret the observed relations in terms of the general magnetic structure of active regions.

Keywords: Sun: corona – Sun: flares – Sun: X-rays, gamma rays

1. Introduction

The loop structures making up soft X-ray (SXR) flares generally show bright regions at their tops, which we here call kernels. They form before maximum and in long-duration flares may last for hours, with new kernels forming after the flare maximum. A kernel’s surface brightness may be ten times as bright as the rest of the flare loop. High-resolution images show the thermal structure to be uniform (Feldman et al., 1995; Jakimiec et al., 1998) and about half the total flare emission measure is contained with the kernel.

The classic model describes solar flare as a hydrodynamic reaction of dense chromospheric plasma to a sudden release of energy in the corona. This energy conducted down along the magnetic lines and transferred by energetic electrons heats up the cool, dense chromosphere and forces it to fill magnetic flux-tube, where the energy release occurred (Bentley et al., 1994; Tomczak, 1997). In a case of simple magnetic structure the plasma should fill it uniformly, without local condensation. The observed kernels can be brighter due to higher density or temperature, and in a simple magnetic loop any kernel should disappear in a very short time due to expansion or conduction. Some kind of restriction efficiently preventing outflow of mass and energy even for hours must be present at the boundary of a kernel (Vorpahl, Tandberg-Hanssen and Smith, 1977).

Loop-top kernels are recognizable in the the flare images from Skylab. Although widely commented on since the Yohkoh Soft X-ray Telescope
(SXT) observations (e.g. Acton et al., 1992; Doschek, Strong and Tsuneta, 1995; Jakimiec et al., 1998), they are still not well understood. Recently proposed mechanisms are based on MHD turbulence (Jakimiec, 2002), fast-mode MHD shock (Yokoyama and Shibata, 1998) or magnetic trap at the top of the cusp structure (Karlický and Bartá, 2006).

The ratio of the kernel soft X-ray emission to the total emission of the flare is in the range 0.35 to 0.45 for different flares, and moreover remains nearly constant for the whole period of kernel existence (Doschek, Strong and Tsuneta, 1995). This property makes the kernels a useful tool to analyze the evolution of the whole flare. In this paper we focus on how the geometrical and physical properties of loop-top kernels depend on their altitude above the photosphere. To this work we utilize the observations of Yohkoh SXT instrument (Tsuneta et al., 1991), which form a large database of soft X-ray flares over the period from October 1991 to December 2001 (maximum of Cycle 22 to maximum Cycle 23). Data from the SXT allow us to determine at the same time both geometrical properties of flare kernels as well as physical properties of the plasma.

2. Sample description

To estimate a kernel altitude \((h)\) we need to know its position on the SXT image and assume above which point of the photosphere it is situated (sub-kernel point). The \(H\alpha\) database and ‘Masuda method’ (Masuda, 1994) are the most helpful in locating this point. The uncertainty of its position is the main source of error in estimating the kernel altitude. The uncertainty is least at the limb, so we chose to analyze events close to the limb. We searched the GOES database for flares with location within 10 degrees from the limb. Looking at SXT images of these flares we chose events with simple structure showing a single loop-top kernel or in the case of multi-kernel flares we chose the kernels well separated from other sources. We enlarged the sample with some flares at longitudes slightly greater than 10 degrees from the limb or located behind the limb. To obtain reliable physical properties of the emitting plasma we selected the flares observed with the use of the SXT thick aluminium (Al12) and beryllium filters (Be119) in full angular resolution \((2''45)\) during the flare maximum.

As each flare evolves greatly with time, we compared the properties of flare kernels at the time of maximum emission in the SXT Al12 filter. We found 48 suitable events (see Table I) during the entire period of Yohkoh operations (Oct 1991 to Dec 2001). The sample consists of 8 X-class flares, 24 M-class and 16 C-class events. 34 of them were located within 10 degrees from the limb, while for 6 flares the SXR footpoints seen on SXT images were located between 60 and 80 degrees of heliographical longitude. To this
Table I. The sample of selected flares. Remarks in the last column: A - flare with one kernel, B - flare with more than one kernel but only one analyzed, C - flare with two kernels, both analyzed.

| No | date       | GOES maximum [UT] | X-ray class | co-ordinates | NOAA active region | remarks |
|----|------------|--------------------|-------------|--------------|-------------------|---------|
| 1  | 17-Nov-91  | 07:16              | M1.1        | E87 N13      | 6929              | A       |
| 2  | 19-Nov-91  | 09:32              | C8.5        | W64 S13      | 6919              | A       |
| 3  | 02-Dec-91  | 05:01              | M3.6        | E87 N16      | 6952              | B       |
| 4  | 09-Dec-91  | 09:44              | M4.1        | E89 S05      | 6966              | A       |
| 5  | 09-Dec-91  | 23:49              | M1.0        | E81 S07      | 6966              | A       |
| 6  | 13-Jan-92  | 17:34              | M2.0        | W90 S16      | 6994              | A       |
| 7  | 30-Jan-92  | 17:15              | M1.6        | E83 S13      | 7042              | A       |
| 8  | 06-Feb-92  | 03:29              | M7.6        | W85 N06      | 7030              | C       |
| 9  | 17-Feb-92  | 15:46              | M1.9        | W80 N15      | 7050              | A       |
| 10 | 28-Jun-92  | 05:14              | X1.8        | W102 N13     | 7205              | B       |
| 11 | 28-Jun-92  | 14:24              | M1.6        | E90 N14      | 7216              | B       |
| 12 | 05-Jul-92  | 12:04              | C4.1        | E82 S11      | 7220              | A       |
| 13 | 12-Oct-92  | 21:53              | C2.5        | W83 S19      | 7303              | A       |
| 14 | 02-Nov-92  | 03:08              | X9.0        | W99 S24      | 7321              | A       |
| 15 | 21-Nov-92  | 07:13              | C5.0        | W81 S16      | 7341              | A       |
| 16 | 23-Nov-92  | 13:59              | C4.0        | W84 S08      | 7342              | A       |
| 17 | 29-Nov-92  | 08:58              | C9.1        | W90 S27      | 7345              | A       |
| 18 | 17-Feb-93  | 10:40              | M5.8        | W88 S07      | 7420              | A       |
| 19 | 02-Mar-93  | 15:10              | C5.0        | E82 S04      | 7440              | A       |
| 20 | 15-Mar-93  | 21:35              | M2.9        | W94 S02      | 7440              | A       |
| 21 | 12-Jun-93  | 09:06              | C3.5        | W95 S11      | 7518              | A       |
| 22 | 25-Jun-93  | 03:22              | M5.1        | E84 S09      | 7530              | A       |
| 23 | 27-Sep-93  | 12:12              | M1.8        | E86 N10      | 7590              | A       |
| 24 | 28-Jan-94  | 17:04              | M1.8        | W87 N06      | 7654              | A       |
| 25 | 27-Feb-94  | 09:20              | M2.8        | W97 N10      | 7671              | C       |
| 26 | 30-Aug-94  | 19:54              | C6.2        | E77 S09      | 7773              | A       |
| 27 | 21-Apr-95  | 13:41              | C5.1        | W75 S01      | 7863              | A       |
| 28 | 17-Sep-97  | 11:43              | M1.7        | W81 N21      | 8084              | A       |
| 29 | 26-Nov-97  | 04:47              | C4.7        | E86 N20      | 8113              | A       |
| 30 | 08-May-98  | 02:04              | M3.1        | W88 S16      | 8210              | A       |
| 31 | 18-Aug-98  | 08:24              | X2.8        | E91 N33      | 8307              | A       |
| 32 | 18-Aug-98  | 22:19              | X4.9        | E86 N33      | 8307              | A       |
| 33 | 19-Aug-98  | 14:26              | M3.0        | E79 N33      | 8307              | A       |
| 34 | 22-Nov-98  | 06:42              | X3.7        | W76 S28      | 8384              | A       |
| 35 | 22-Nov-98  | 16:23              | X2.5        | W81 S28      | 8384              | A       |
| 36 | 24-Nov-98  | 02:20              | X1.0        | W98 S29      | 8384              | A       |
| 37 | 23-Dec-98  | 06:59              | M2.3        | E90 N23      | 8421              | B       |
| 38 | 25-Jul-99  | 13:38              | M2.4        | W82 S39      | 8639              | B       |
| 39 | 21-Sep-99  | 10:47              | C6.4        | W96 S25      | 8692              | A       |
| 40 | 23-May-00  | 17:54              | C4.3        | W75 S21      | 8996              | B       |
| 41 | 01-Jun-00  | 06:17              | M2.5        | E80 N21      | 9026              | A       |
| 42 | 30-Sep-00  | 23:21              | X1.2        | W93 N08      | 9169              | A       |
| 43 | 14-Oct-00  | 08:40              | M1.1        | W81 N02      | 9182              | A       |
| 44 | 14-Oct-00  | 12:05              | C8.4        | W80 N02      | 9182              | A       |
| 45 | 28-Oct-00  | 07:10              | C9.7        | E80 N08      | 9212              | A       |
| 46 | 26-Nov-00  | 16:34              | M1.0        | E82 N13      | 9233              | A       |
| 47 | 11-Mar-01  | 08:56              | C5.0        | E89 S15      | 9376              | A       |
| 48 | 29-Oct-01  | 01:59              | M1.3        | W88 N13      | 9415              | A       |
number we added 8 flares located no more than 12 degrees behind the
limb for which the loop-top kernels were not occulted by the limb. In our
sample only two flares had two well-separated loop-top kernels, allowing us
to analyze both kernels. 6 flares had more than one kernel but only one of
them could be analyzed. The rest of our events (i.e. 40) had only one kernel.
Thus, a total of 50 flare kernels were analyzed.

3. Analysis

The geometrical parameters of interest here are the size and altitude of
each kernel, and the physical ones are plasma density, pressure and energy
release rate in the kernel. The kernel size we defined by a 50% isophote \((I_{50})\)
relative to the brightest pixel in the Al12 image. We measured the area, \(A\),
of the kernel projected on the plane of the sky. The kernel altitude, \(h\), was
calculated from the position of its centroid and coordinates of the sub-kernel
point. The kernel centroid was estimated as a center of gravity in the sense
of intensity distribution within the isophote \(I_{50}\). From the kernel area we
summed the Al12 and Be119 flux to estimate the emission measure, \(EM\),
and temperature, \(T\), of emitting plasma using the filter ratio method as
described by Hara et al. (1992).

The estimation of kernel volume is not straightforward. Usually the kernel
image has a circular or elliptical shape. If we assume that its volume is
ellipsoidal we can calculate it as \(V = (4/3) \pi abc\) where \(a\), \(b\) and \(c\) are the
three semi-axes. In general we can estimate two semi-axes from the kernel
image, but the third dimension along the line-of-sight must be reasonably
guessed. Generally the smaller of the two taken from the image is used to
estimate the volume. This assumes that the main axis of ellipsoid is located
in the plane of image. However, we do not know definitely the orientation
of the kernel relative to the plane of the sky, so the effective depth of the
kernel can be greater. To avoid this underestimation we assume that the
depth is close to the geometrical mean of the two axes seen on the image.
This assumption gives the estimation of kernel volume as

\[
V = \frac{4}{3} \frac{A^{3/2}}{\sqrt{\pi}}
\]

where \(A\) is the plane-of-sky kernel area.

Having estimates of the kernel volume we can calculate the plasma mean
density and pressure within the kernel as \(N_e = \sqrt{EM/V}\) and \(p_e = 2k_B T N_e\)
where \(k_B\) is Boltzmann constant. One should remember that such estima-
tions are sensitive to the influence of filling factor and in general should be
treated as lower estimates.
The kernel area is defined by half the intensity of its brightest pixel, so the uncertainty in this pixel’s flux directly affects the uncertainty $\Delta I_{50}$ of the isophote $I_{50}$ and the uncertainty $\Delta A$ of the kernel area. Estimation of $\Delta A$ is also affected by the data pixelation. For small kernels the pixelation makes it impossible to estimate $\Delta A$, because there may be no change of $A$ within the range $(I_{50} - \Delta I_{50}, I_{50} + \Delta I_{50})$. To overcome this limitation we closely analyzed for each kernel how the number of pixels brighter than a given level changes with an isophote $I$ in the range $(I_{50} - 5 \Delta I_{50}, I_{50} + 5 \Delta I_{50})$. The step function obtained we fitted by a low degree polynomial. Using this polynomial we interpolated the area $A$ at the $I_{50}$ level and estimated the error $\Delta A$ for $\Delta I_{50}$. In the same way we calculated the flux emitted from within the isophote $I_{50}$ in both SXT filters and an error of the flux. Our method allowed us to estimate the size of a kernel and its flux with precision greater than one pixel.

The error $\Delta A$ affects not only the estimated volume but also all physical properties of kernel plasma: the total brightness in both filters, and therefore the kernel temperature and emission measure, electron density and pressure. The error of kernel altitude comes from two uncertainties, one related to the kernel centroid position and second to the location of sub-kernel point. The second uncertainty is usually several times larger than the first. All errors mentioned affect the calculation of heating rate within the kernel.

4. Results

The flare kernel altitudes in our sample vary from $3.2 \times 10^8$ to $5.8 \times 10^9$ cm. The distribution of altitudes decreases with rising altitude. This distribution is shown in Fig. 1 and may be described as exponential, $N \propto \exp(-h/h_0)$, where $h_0 = (2.2 \pm 0.6) \times 10^9$ cm.

Figure 2 presents the relation of the kernel size and altitude during the course of a few arbitrarily selected flares. As can be seen, individual flares may evolve in this diagram in very different ways, showing both correlation and anti-correlation as well as lack of any relationship. However, when we compare all the flares in our sample the general tendency becomes clear: the higher the kernel, the larger its size. Figure 3 illustrates this effect in an example of three arbitrary selected flares. The changes of kernel size and altitude during the course of all analyzed flares are shown in Fig. 4. To correctly compare all kernels we had to choose one specific moment in their evolution, which we chose the moment of kernel brightness maximum. Figure 5 presents the result of our analysis. The projected area of a loop-top kernel distinctly rises with its altitude. The relation is a power-law, $A \propto h^n$, where the index $n = 1.13 \pm 0.04$. This relation has power index 0.56 for the kernel mean radius, and 1.69 for the volume.
Figure 1. The observed distribution of loop-top kernel altitudes.

Figure 2. The changes of the projected kernel area and its altitude above the photosphere for a set of arbitrary selected flares. Individual kernels show different correlations but the overall tendency is visible. The numbers denote the flares listed in Table I.
Figure 3. Three examples of flares with loop-top kernels at different altitudes. The extension of each kernel is marked by a 50% isophote relative to the brightest pixel in SXT Al.12 image. Each image covers the area of $140'' \times 140''$. Note the increase of the kernel size when going to higher events.

Figure 4. The changes of the projected kernel area and its altitude above the photosphere. Measured kernel areas and altitudes at all times during all the flares analyzed are plotted here. The overall tendency is clearly visible, higher kernels are usually bigger.
Our sample shows no relation between temperature or emission measure and the altitude of the kernel. Nor is there correlation with kernel area. Kernel emission measure correlates well with GOES X-ray class. Its median value rises from $3.1 \times 10^{48}$ cm$^{-3}$ for C-class flares through $1.2 \times 10^{49}$ cm$^{-3}$ for M-class flares to $1.2 \times 10^{50}$ cm$^{-3}$ in X-class events. The dependence of kernel temperature with GOES class is weaker but also evident in our sample. This relation has been often reported and discussed in the literature in similar form as the $T-EM$ relation. In our sample it can be well described by power-law relation $T \propto EM^{0.09 \pm 0.02}$ (see Fig. 6). This dependence is weaker than others mentioned in literature. The reported power-law slopes vary from 0.13 (Shibata and Yokoyama, 2002) to 0.23 (equivalent of the exponential relation in Feldman et al. (1996)). This weak dependence in our sample is because of the small sensitivity of SXT to hot plasma (Jakimiec et al., 1998). Reconstructions of differential emission measure for flares generally show the presence of two components. One component contains the relatively cool plasma with temperatures between 5 MK and 10 MK and the other
Figure 6. Observed relation between the mean kernel temperature and emission measure. The fitted line has slope $0.09 \pm 0.02$. Here and in following figures we apply different symbols for flares of different GOES class.

component contains the hotter plasma with $T$ between 15 MK and 25 MK (Kępa et al., 2005). In the presence of the cooler component, the hotter plasma only weakly contributes to the SXT signal.

Figure 7 shows the relation between kernel density and altitude. Taking the whole sample we can hardly see any relationship, but if we divide the sample into the GOES classes the relation becomes more obvious. In a given subclass the kernel density drops with rising altitude. The observed power-law index of this relationship for C, M and X-class flares is equal $-1.12 \pm 0.11$, $-0.82 \pm 0.04$ and $-0.65 \pm 0.12$ respectively. The difference between slopes for M and X-class kernels is barely significant. The kernels of C-class flares seem to follow a significantly steeper slope, but the reliability of its estimation is weak. This sub-sample is ill-spaced with height, as it includes only 3 kernels with altitude higher than $2 \times 10^9$ cm. For such a sample ‘bootstrap’ methods give more reliable estimation of slope. Using a bootstrap resampling method (Press, Teukolsky and Vatterling, 1992) we receive the same slope.
but with error 0.60, which makes differences between all 3 slopes statistically unimportant. Similar relations are observed between plasma pressure and kernel altitude. In Fig. 8 we observe very similar power-law slopes for each GOES-class sub-sample (C: $-1.07 \pm 0.12$, M: $-0.85 \pm 0.05$, X: $-0.69 \pm 0.14$).

These slopes seem to be defined by the observed geometrical properties of flare kernels. We do not observe any correlation between temperature or emission measure with kernel size or altitude. In this case plasma density calculated from $N_e = \sqrt{EM/V}$ should systematically decrease with kernel altitude because of the increasing kernel volume. The same relation should be observed for plasma pressure because the temperature in our sample is also uncorrelated with geometrical aspects of flare kernels. As mentioned above, the kernel volume rises with altitude as $V \propto h^{1.69}$, which should result in density or pressure drop with altitude as

$$N_e = (EM/V)^{1/2} \propto h^{-0.85 \pm 0.03}$$

and

$$p_e \propto N_e \propto h^{-0.85}.$$ 

This slope is consistent with the observed relation in the sub-sample of M-class flares. For C and X-class flares the agreement is worse, but this is explained by the X-class sub-sample having small number of events, and the sub-sample of C-class kernel being ill-spaced as mentioned above.

We interpret these relations as nearly identical concerning the slope, but differing in the intercept parameter. Stronger flares involve more emission measure within the same volume, i.e. larger flares need higher densities and pressures.

5. Energy release within the kernels

Loop-top kernels are the brightest parts of the soft X-ray flares and presumably are the places where the plasma heating is most effective. The next physical parameter we estimated for the flare kernels was the heating rate during the kernel maximum. Close to flare maximum, when the energy transport by plasma flow is negligible we can build a simplified model of the evolution of thermal energy ($E_{th}$) content as the sum of heating ($E_H$) and cooling processes (radiative and conductive losses: $E_R$ and $E_C$):

$$\frac{d}{dt} E_{th} = E_H - E_C - E_R.$$ 

Moreover, at the flare maximum the changes of thermal energy content are insignificant, so we can estimate the energy release rate for this moment as
Figure 7. Relation between the kernel plasma pressure and altitude above the photosphere. The lines show power-law fits to each of three GOES sub-samples.

\[ E_H \approx E_C + E_R. \]

Radiative loss can be calculated knowing the temperature and plasma density estimates, \( E_R = N_e^2 \Lambda(T) \), where \( \Lambda(T) \) is the radiative loss function taken e.g., from Rosner, Tucker and Vaiana (1978).

We estimate the kernel heating in the way already shown by Jakimiec, Falewicz and Tomczak (2002), which we briefly summarize here. We assume that the kernel is nearly spherical and it is heated by some process with the mean rate \( E_H \). The total flux of thermal energy flowing out of the kernel may be estimated as \( (4\pi/3)R^3(E_H - E_R) \), where \( R \) is the kernel radius and \( E_R \) is the mean radiative loss from the kernel. This flux has to be transported down by thermal conduction along the both legs of the loop containing the kernel. If we take the diameter of this loop to be the same as that of the kernel, then the conductive flux in the legs is \( F_C = (2/3)R(E_H - E_R) \). Knowing this value we can integrate the equation of conduction,

\[ F_C = \kappa_0 T^{2.5} dt/ds, \]
along the loop of semilength $L$, assuming constant $F_C$. The result is

$$0.286T^{3.5} = \left(\frac{F_C}{\kappa_0}\right)L,$$

where $T$ is now the temperature of the kernel. From these two equations we can estimate the mean heating within the kernel as

$$E_H = 3.9 \times 10^{-7} T^{3.5}/RL + E_R.$$  

The first term on the right hand of this formula is the conductive loss from the kernel. Its formulation differs than the radiative losses from the simple loop. We want to stress that this estimation does not implicitly involve which process is responsible for the kernel formation.

We applied the above formula to the analyzed sample, taking the geometrical mean of two semi-axes seen on SXT image as the kernel radius, and the approximation of the loop semi-length as $L = (\pi/2)h$. A typical value of heating is a few ergs per second in each cubic centimeter; however, the observed values within our sample span two orders of magnitude. Figure 9 shows a clear decrease of the heating rate with the altitude of a kernel.
C and M-class kernels show a very similar dependence of heating with kernel altitude, \( \log E_H = 15.63 - (1.70 \pm 0.05) \log h \). This is similar to the results obtained by Jakimiec, Falewicz and Tomczak (2002) who analyzed a set of 27 limb flares of mostly M-class and loop-length longer than 10\(^9\) cm. They estimated that the flare heating rate drops with loop-length as \( \log E_H = 13.91 - 1.46 \log L \). Bąk-Stęślicka and Jakimiec (2005) enlarged this sample by adding 10 slow long duration flares, which allowed them to widen the range of analyzed loop-lengths by an order of magnitude. They obtained the relation \( \log E_H = 16.3 - 1.72 \log L \). Within errors this is nearly identical to the relation obtained here for C and M-class flares. Our sample consists also of 8 X-class flares, for which the dependence between heating rate and kernel altitude is \( \log E_H = 13.0 - (1.33 \pm 0.20) \log h \), but the same slope as in C and M flares cannot be excluded. X-class flares require about four times higher heating rates, which in our calculations is caused mainly by distinct increase of emission measure. The radiative losses in these kernels are correspondingly high to balance the higher level of heating.

These slopes again seem to result mainly from the geometrical properties of the kernels. During the flare maximum radiative and conductive losses are usually comparable, \( E_C \sim E_R \) (see Fig. 10). With the lack of any dependence of temperature on kernel altitude, the conductive losses scale as \( E_C \sim (RL)^{-1} \). Taking our result, \( R \sim L^{0.56} \), we obtain \( E_H \sim E_C \sim L^{-1.56} \). This slope differs from the relations in Fig. 9 by no more than 3\( \sigma \).

Figure 10 also shows that the ratio between the radiative and conductive losses changes when going from weak to strong flares. The stronger the flare, the more important the influence of radiative losses. Conductive losses depend on the geometrical aspects and the plasma temperature. The geometrical properties of flare kernels are more or less the same for each GOES sub-sample. Taking the relation between temperature and emission measure observed in our sample we can show that \( E_C \propto T^{3.5}/RL \propto EM^{0.315}/h^{1.56} \). Radiative losses are proportional to emission measure, \( E_R = EM \times \Lambda(T)/V \propto EM^{0.94}/h^{1.69} \), where we assumed that \( \Lambda(T) \propto T^{-2/3} \). Both losses have similar dependence on the kernel altitude, but different on the emission measure, which makes radiative cooling more important in strong flares, \( E_R/E_C \propto EM^{0.63}/h^{0.13} \). This result is, however, sensitive to the assumed dependence between temperature and emission measure. The SXT instrument has limited sensitivity to the hot plasma which is the cause of the quite flat relation between these two parameters in our sample. It is enough to assume relation \( T \propto EM^{0.24} \), which is power-law equivalent of the relation presented by Feldman et al. (1996), to get the ratio \( E_R/E_C \) independent of the kernel emission measure.

The limited temperature sensitivity of the SXT affects both radiative and conductive cooling. Underestimation of kernel temperature results in overestimation of radiative and underestimation of conductive losses. The
second effect is stronger, because it depends on temperature to a much higher power. Thus the heating rate calculated in this paper seems also to be underestimated and should be treated as a lower limit. This bias should be more important for stronger flares. A typical value of kernel temperatures for X-class flares in our sample is $T \approx 12$ MK, which seems to be a factor 2 less than temperatures reported by other similar instruments. This would result in underestimating of conductive losses by about one order of magnitude and overestimating the radiative losses by a factor 1.6. Good estimation of cooling and heating rates for strong flares requires an imaging X-ray telescope with better temperature sensitivity than SXT.

6. Discussion and conclusions

The observed relation between kernel size and its altitude is not an obvious result. If we assume that kernel is part of the loop that appears to contain it, than the loop cross-section area must show the same relation. This means
that the higher flare loops are not linearly scaled version of the smaller loops, i.e. the loop diameter, $\Phi \approx (4A/\pi)^{1/2}$ is not proportional to the loop length, but rather to its square root, $\Phi \sim h^{1.13/2} \sim L^{0.56}$. The higher loops must be systematically more narrow than the smaller ones.

The relation between plasma pressure and the kernel altitude allows us to put some constrains on the magnetic field structure in active regions. The kernel plasma of a given pressure must be trapped within a field with magnetic pressure greater than plasma pressure, $B^2/8\pi > p_e$. This allows us to determine the minimum magnetic strength necessary to contain the kernel plasma as $\log B_{\text{min}} = 5.86 - 0.43 \log h$ for M-class kernels. This constraint slightly depends on the GOES class. If we assume that for all flares $\log p_g$ decreases with altitude with the same slope as for M-class kernels, the intercept parameter of $\log B_{\text{min}}$ in C-class flares is 5.71 while in X-class flares it is 6.11. This estimation does not take into account the influence of possible field helicity, which allows a weaker field effectively to trap a kernel.
plasma. The field helicity is unfortunately difficult to determine with present X-ray observations of flares.

The observed relation $B_{\text{min}}(h)$ is also in quite good agreement with estimates of magnetic field in active regions shown by Aschwanden et al. (1999). They approximated the field with a magnetic dipole, $B(h) \approx B_0(1 + h/h_D)^{-3}$, where $h_D$ is the dipole depth estimated by them as $7.5 \times 10^9$ cm, and $B_0$ is the mean magnetic field at the photospheric level. Fig. 11 shows that our sample is consistent with the dipole field with $B_0$ in the range of 70 to 400 G.

The relation obtained between kernel heating and its altitude may also shed light on the magnetic field structure in active regions. If we hypothetically assume, as in Jakimiec, Falewicz and Tomczak (2002), that the energy release rate is somehow proportional to the density of magnetic energy $E_H \sim B^2/8\pi$, then we should observe decrease of the magnetic field with height as $B \sim h^{-0.85}$. Jakimiec, Falewicz and Tomczak (2002) suggested in the same way that magnetic field responsible for flare heating decreases with height as $B \sim h^{-0.73}$. This relation has a different slope from the decrease
of magnetic field necessary to trap the kernel plasma, but both relations may describe different parts of the field supporting the kernel. The field necessary to contain the kernel plasma may be more related to the kernel surroundings, while the field responsible for heating is obviously related to the location of energy release. These two places are not by definition the same location as it is discussed e.g. in Karlický and Bartá (2006).

The reported here relation between the kernel size and its altitude should be considered regarding the flare scaling laws. It is generally accepted that during the flare maximum radiative and conductive losses are of the same order, $E_R \sim E_C$. Conductive losses for a simple flaring loop without a kernel, $E_C \propto T^{3.5}/L^2$, changes into $E_C \propto T^{3.5}/RL$ when we describe a loop-top kernel. In this case the scaling takes the form $N_e^2 \Lambda(T) \sim T^{3.5}/RL$. If we substitute $\Lambda(T) \sim T^{-\beta}$, then we can rewrite this scaling as

$$N_e^2 RL \sim T^{3.5+\beta}.$$  

The relation between kernel size and its altitude is $R \sim h^{0.56}$, which makes the product $RL \sim h^{1.56}$ close to kernel volume $R^3 \sim h^{1.68}$. Thus, the left side of the above equation roughly scales as kernel emission measure. The scaling $E_R \sim E_C$ turns into a relation between flare temperature and emission measure, $EM \sim T^{3.5+\beta}$. Taking $\beta = 2/3$ we achieve $T \sim EM^{0.24}$ which is very close to the relation shown by Feldman et al. (1996).

The existence of flare kernels should be taken into account also when analyzing stellar flares. It is hard to imagine that in stellar flares loop-top kernels are not present when in solar ones they are common. We should be careful when transferring the scaling laws of solar kernels onto flares on other stars. Recognizing how the overall magnetic structure affects formation and evolution of a flare kernel is necessary. The Sun represents stars with very low magnetic activity. We cannot exclude the possibility that the kernel scaling laws may have different formulation on highly active stars, which seems to be fully covered by active regions. However, we remark that the similarity of a $T – EM$ relation for stellar flares with a solar one (see e.g. Fig. 1 in Shibata and Yokoyama, 2002) suggests that kernel scaling laws on other stars may not differ substantially.

Flare loop-top kernels are obvious characteristics of SXR solar flares. The kernel emission is usually constant part of the total flare emission, what allows to describe overall evolution of a flare by the evolution of its kernel(s). A correct model of either solar or stellar flares cannot be built without understanding their properties and nature.

This study shows that the set of basic observables describing the flare loop-top kernels, which we obtain from SXT images, separates into two independent pairs. One pair describes the geometrical properties of a kernel (size and altitude), the other pair is plasma temperature and emission measure. As we report here, kernel size and altitude are not independent parameters.
Although in individual flares one can see different types of relation between them, when comparing many flares, a clear dependence emerges: the higher the kernel, the bigger the size. The second pair, temperature and emission measure, is also internally related, but these parameters are not correlated with the kernel altitude and size. To describe many flares, it is sufficient to take only two observables, viz. emission measure and kernel height. Other physical parameters of emitting plasma like density, pressure or heating rate are related to these two quantities.

To determine more precisely the kernel scaling laws, we need a larger sample of limb flares. We expect that the forthcoming imaging instrument in soft X-rays, \textit{XRT} onboard \textit{Solar-B}, will open new possibilities in analyzing the physics of flare loop-top kernels. The expected improved angular resolution will allow better determination of kernel geometrical properties. Improved thermal sensitivity of \textit{XRT} should allow us to achieve more precise determination of physical properties of the emitting plasma. We may expect better determination of conductive losses and heating rates, which strongly depend on the estimated kernel temperature. The next few years of soft X-ray observation of the Sun will allow us to substantially enlarge the sample of suitable, near-limb flares and take a closer look on the kernel properties. Difficult to model, flare kernels still await our attention.

**Acknowledgments**

The \textit{Yohkoh} satellite was a project of the Institute of Space and Astronautical Science of Japan. This work has been supported by the Polish Ministry of Science and High Education grant N203 001 32/0036.

**References**

Acton L. W., Feldman U., Bruner M. E., et al.: 1992, \textit{PASJ} 44, L71.
Aschwanden M. J., Newmark J. S., Delaboudinière J.-P., et al.: 1999, \textit{Astrophys. J.} 515, 842.
Bąk-Stęślicka U., Jakimiec. J.: 2005, \textit{Solar Phys.} 231, 95.
Bentley R. D., Doschek G. A., Simnett G. M. et al.: 1994, \textit{Astrophys. J.} 421, L55.
Doschek G. A., Strong K. T., Tsuneta S.: 1995, \textit{Astrophys. J.} 440, 370.
Feldman U., Seely J. F., Doschek G. A., et al.: 1995, \textit{Astrophys. J.} 446, 1034.
Hara H., Tsuneta S., Lemen J. R., Acton L. W., McTiernan J. M.: 1992, \textit{PASJ} 44, L135.
Jakimiec J.: 2002, \textit{Adv. Space Res.} 30, 577.
Jakimiec J., Tomczak M., Falewicz R., Phillips K. J. H., Fludra A.: 1998, \textit{Astron. Astrophys.} 334, 1112.
Jakimiec J., Falewicz R., Tomczak M.: 2002, \textit{Adv. Space Res.} 30, 659.
Karlický M., Bartá M.: 2006, *Astrophys. J.* **647**, 1472.
Kępa A., Sylwester J., Sylwester B., Siarkowski, M., Kuznetsov, V.: 2005, in Proceedings of the 11th European Solar Physics Meeting *ESA SP-600*, ed. D. Danesy, S. Poedts, A. De Groof & J. Andries, 87.1.
Masuda S.: 1994, Ph.D. Thesis, University of Tokyo.
Press W. H., Teukolsky S. A., Vetterling W. T.: 1992, in *Numerical Recepies in Fortran*, 2nd ed., Cambridge and New York, Cambridge University Press.
Rosner R., Tucker W. H., Vaiana G. S.: 1978, *Astrophys. J.* **220**, 643.
Shibata K., Yokoyama T.: 2002, *Astrophys. J.* **577**, 422.
Tomczak M.: 1997, *Astron. Astrophys.* **317**, 223.
Tsuneta S., Acton L., Bruner M. et al.: 1991, *Solar Phys.* **136**, 37.
Vorpahl J. A., Tandberg-Hanssen E., Smith J. B.: 1977, *Astrophys. J.* **212**, 550.
Yokoyama T., Shibata K.: 1998, *Astrophys. J.* **494**, L113.
