ABSTRACT

The discovery of hard X-rays from tops of flaring loops by the HXT of YOHKOH represents a significant progress in the understanding of solar flares. This report describes the properties of 20 limb flares observed by YOHKOH from October 1991 to August 1998, 15 of which show detectable impulsive looptop emission. Considering the finite dynamic range (about a decade) of the detection it can be concluded that looptop emission is a common feature of all flares. The light curves and images of a representative flare are presented and the statistical properties of the footpoint and looptop fluxes and spectral indexes are summarized. The importance of these observations, and those expected from HESSI with its superior angular, spectral and temporal resolution, in constraining the acceleration models and parameters is discussed briefly.

INTRODUCTION

The most significant discovery of the HXT instrument on board the YOHKOH satellite has been the detection of hard X-ray emission from the top of solar flare loops as well as their footpoints. The first so-called “Masuda” flare is that of January 13, 1992 (Masuda et al. 1994; see also Alexander & Metcalf 1997), which is clearly delineated by a soft X-ray (thermal) loop, and shows three compact hard X-ray sources, two located at the footpoints (FPs) and a third near the loop top (LT). Several other such sources are described in Masuda’s thesis (1994). As pointed out by Masuda et al. (1994), these observations lend support to theories that place the location of flare energy release high up in the corona. The power law hard X-ray spectra of the LT sources indicate that electron acceleration is indeed occurring at or near these locations. The exact mechanism of the acceleration is a matter of considerable debate. In previous works (see Petrosian 1994 and 1996) we have argued that among the three proposed particle acceleration mechanisms (electric fields, shocks, and plasma turbulence or waves) the stochastic acceleration of ambient plasma particles by plasma waves provides the most natural mechanism and can explain the observed spectral features of flares (Park, Petrosian & Schwartz 1997; hereafter PPS). In two recent works (Petrosian & Donaghy, 1999 and 2000; PD) we demonstrated that the observed characteristics of the Masuda flares can be used to constrain the model parameters. In order to gain a clearer picture of the frequency of occurrence of LT sources and the relative values of the fluxes and spectral indexes of the FP and LT sources, we (Petrosian, Donaghy & McTiernan 2002; PDM) have expanded and extended Masuda’s analysis. In the next two sections I first
summarize the results of this work and then comment on their consequence for the acceleration mechanism.

DATA ANALYSIS AND RESULTS

We have used The YOHKOH HXT Image Catalogue (Sato et al. 1988) to search for flare candidates for detection of LT emission. We have used Masuda’s (1994) selection criteria (heliocentric longitude $> 80$ degrees, peak count rate $> 10$ counts per sec per subcollimator in the $\sim 33 - 53$ keV range, i.e. the M2 channel). We found 20 such events from 10/91 through 8/98, of which 11 were selected by Masuda for the period of 10/91 to 9/93. Observations of two events are interrupted by spacecraft night. Of the remaining 18 events, 15 show detectable impulsive looptop emission. As described below, considering that the finite dynamic range (about a decade) of the detection introduces a strong bias against observing comparatively weak looptop sources, one can conclude that LT emission is a common feature of all flares. An interesting aside, is that of the 9 new events, 3 appear to be examples of interacting loop structures with multiple LT and FP sources, of the type analyzed by Aschwanden et al. (1999). It is surprising that none of the 11 Masuda events are in this category.

![Diagram](image)

Fig. 1. Images (right panel) and light curves (left panel) for the December 18, 1991 flare. The contours and the gray scale show the HXT (channel M2; $\sim 33 - 53$ keV) and SXT images of the loop, respectively, for the specified time. The diagonal line shows the location of the solar limb. The brightest contour and the contour separations are $B_{\text{max}} = 8.1$ and $\Delta B = 0.73$ counts/pixel with 2.5 sq. arc second size pixels. The light curves of the the LT and FP sources refer to the counts integrated over regions shown on right panel. The dashed histogram shows the average of the ratio of counts $\mathcal{R} = FP_s/LT$ (multiplied by 10) for three time intervals.

We have constructed HXT images and investigated their evolution throughout all these flares using the YOHKOH spectral and spatial analyses software packages. In a few cases we have also used the Alexander & Metcalf (1997) “pixon” method of image reconstruction. From the investigations of these images we have determined the locations of LT and FP sources and produced separate light curves for the well defined sources. Figure 1 shows an example of a simple loop with an intermediate strength LT source and Figure 2 shows a flare with a more complex morphology consisting of two loops with different but related temporal evolution.
Fig. 2. Same as Figure 1 for the August 18, 1998 flare. The upper left and right panel light curves represent the southern (AEB) and the northern (BDE) loops, respectively. Note that for the LT source D we plot counts divided by 3. In the HXT image (lower left panel) $B_{\text{max}} = 14.8$, $\Delta B = 0.82$ counts/pixel, the digonal line shows the limb location, and the two arcs sketch the presumed loop outlines. The SXT image shown on the lower right panel was taken nearly two minutes after the HXT image.

We determine the relative fluxes of the LT and FP sources and obtain rough measures of some of the spectral characteristics (e.g. power-law indexes). Figure 3 shows the M1 channel ($\sim 23 - 33$ keV) counts of the FPs vs LT sources for all flares (left panel) and the distributions of the count ratio $R = \text{FPs}/\text{LT}$ (right panel). We use a representative time period around an impulsive peak and avoid the later stages (the third periods of the histograms shown along the light curves) which can be contaminated by thermal emission. Note that some flares (those connected by dashed lines contribute more than one data point.

Analysis of these results lead to the following very important conclusions (see also PDM).

- The LT hard X-ray emission seems to be a common characteristic of the impulsive phase of solar flares, appearing in some form in 15 of the 18 selected flares. The absence of LT emission in the remaining cases (those indicated by the horizontal arrows in Figure 3) is most likely due to the finite dynamic range of the imaging technique which is about 10. The hatched diagonal regions show this range. Flares outside the area between these two bounds will have either a too weak a FP or LT source to be detected by HXT. From
Fig. 3. (**Left Panel**): Counts from two FPs vs LT counts, in the M1 channel. The diagonal lines show lines of constant ratio \( R = \text{FPs}/\text{LT} \) and represent detection thresholds arising from the finite dynamic range of the instrument which is about 10. Flares with undetected LT source are denoted by an arrow placed on the upper bound of detection of \( R = 10 \). The dotted curve shows the event selection threshold of 10 counts at the M2 channel. (**Right panel**): The differential distribution of the ratio \( R = \text{FPs}/\text{LT} \) of all flares. The arrows indicate ratios greater than the dynamic range. Some of the flares in the shaded area with \( R < 1 \) may be occulted or be dominated by a superhot thermal component.

this we conclude that LT emission is present in all flares. However there are very few flares with \( R < 1 \) and there are indications that the three such cases seen in Figure 3 are either partially occulted or are dominated by a superhot LT source. Thus one may conclude that, in general, the ratio \( R \) has a relatively flat distribution between 1 and 10, with few cases outside this range. A larger sample with a wider dynamic range will be required for a better determination of this distribution.

Figure 4 shows the distribution of the overall spectral index (left panel) and the distribution of the difference between low (\( \sim 13 – 28 \) keV, L and M1 channels) and high (\( \sim 28 – 53 \) keV, M1 and M2 channels) energy indexes. Clearly with only a four channel data one must be cautious in the interpretation of these histograms. Nevertheless, some significant conclusions can be drawn from these results as well.

- The overall distribution of the power-law spectral index \( \gamma \) rises rapidly above 2, peaks around 4 and then declines gradually thereafter. This is similar to previous determinations of these distributions from HXRBS on board the Solar Maximum Mission (see e.g. McTiernan & Petrosian 1991), but contains a few more steep spectra, specially for LT sources. This difference could be due to thermal contamination and/or because HXT is sensitive to lower photon energies than HXRBS. On the average, the spectral index of LT sources is larger (i.e. spectra are steeper) than that of the FP sources by one unit; \( \bar{\gamma}_{LT} = 6.2 \pm 1.5 \), \( \bar{\gamma}_{FP} = 4.9 \pm 1.5 \).

- The physics of the acceleration process must certainly play a role here.

- The spectra tend to steepen at higher energies (spectral index \( \gamma \) increases by 1 to 2), especially for sources with \( \gamma < 6 \), for which the thermal contribution should be the lowest. This is the opposite of what is observed at higher energies, where spectra tend to flatten above 100’s of keV (McTiernan & Petrosian 1991). The directivity of the X-ray emission and the albedo effect for the limb flares under consideration could play some role here, especially for the FP sources.
Finally, we note that solar flares occur in many different morphologies, the most common being a simple flaring loop with one LT and two FP sources. However, interacting loop models and even more complicated structures are frequently observed. There is a hint that the frequency of occurrence of complex morphologies may be different for the declining and growing phases of the solar cycle.

THEORETICAL IMPLICATIONS

The above results can be used to constrain the model parameters describing the plasma in the acceleration site and those describing the acceleration mechanism. These parameters define several important timescales: The acceleration time scale is related to the energy diffusion coefficient $D_{EE}$ as $\tau_{ac} \sim E^2 / D_{EE}$. The mean scattering time is inversely proportional to the pitch angle diffusion coefficient, $\tau_{sc} \sim 1 / D_{\mu\mu}$. The time for a particle with velocity $v$ to cross the acceleration site of size $L$ is $\tau_{tr} \sim L / v$; these two timescales determine the escape time from the acceleration site (for $\tau_{sc} < \tau_{tr}$, $T_{esc} \sim \tau_{tr}^2 / \tau_{sc}$, otherwise $T_{esc} \sim \tau_{tr}$). Finally the energy loss timescale for an electron of energy $E$ is $\tau_L = E / \dot{E}_L$, which for the non relativistic electrons under consideration here is dominated by the Coulomb losses, $\tau_{\text{Coul}} = vE / (4\pi\epsilon_0^2 n \Lambda m c^4)$, where $4\pi\epsilon_0^2 \ln \Lambda = 2 \times 10^{-23}$ cm$^2$ and $m$ is the mass of the electron. The values of these time scales depend on the plasma density $n$, magnetic field $B$, plasma turbulence energy density $w_{\text{turb}}$ and size $L$, and their variations with energy depend on these parameters and the spectrum of the turbulence (for details see PPS and PD and reference cited there).

For example, if $T_{esc}$ is large the accelerated electron spend a long time in the acceleration site or at the loop top giving rise to a strong LT source. Inversely, a weak LT source is expected for a short $\tau_{\text{Coul}}$. Very roughly, the ratio of the FP to LT emission is expected to vary as $R = J_{FPs} / J_{LT} \sim \tau_{\text{Coul}} / T_{esc}$, where the $J$’s refer to the expected bremsstrahlung fluxes. Furthermore, the spectral shape of these fluxes are also related to the above mentioned parameters. It is clear, for example, that if the acceleration time is short compared to the escape time, then more electrons get to higher energies resulting in a flat accelerated electron spectrum and LT hard X-rays. For a power law accelerated spectrum, $f(E) \propto E^{-\delta}$, the LT (thin target) hard X-ray
spectrum at photon energy $k$ is $J_{LT} \propto k^{-\delta - 1/2}$. On the other hand, the spectrum of the electrons that escape the acceleration region and reach the footpoints is $f(E)/T_{esc}(E) \propto E^{-\delta - s'}$, assuming that for the small energy range of the HXT we can use the approximation $T_{esc}(E) \propto E^{s'}$. These electrons will emit a thick target spectrum at the footpoints with $J_{FPS} \propto k^{-\delta - s' + 1}$. Thus, for LT spectra that are steeper than the FPS spectra we require $s' < 3/2$. When the escape is determined by the traverse time $s' = -1/2$ and this condition is satisfied. And when scattering dominates, this requires $\tau_{sc} \propto E^s$, with $s > -5/2$. The energy dependence of $\tau_{sc}$ depends on the characteristics of the turbulence. In general, one expects a positive value for $s$, and even for for a very steep spectrum of the turbulence one has $s > -1$ (see e.g. Pryadko & Petrosian 1997).

However, it should be noted that these relations are very approximate and valid only for a limited energy range and very steep electron spectra; they breakdown completely for $\delta < 2.5$. Nevertheless, this exercise demonstrates that using the observed values of the spectral indexes and FP and LT counts we can determine the plasma and acceleration characteristics. As shown in PD the values of the parameters such derived from the YOHKOH high spatial resolution data are very reasonable, and agree with those derived by PPS from fits to large dynamic range overall spectra. It is clear then that a more refined and simultaneous observations of the flare characteristics can yield important information about the the acceleration mechanism, the energy release and the evolution of solar flares. We eagerly anticipate the increased spectral, temporal and spatial resolution possible with the instruments of the RHESSI satellite.

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