HARD AND SOFT X-RAY OBSERVATIONS OF SOLAR LIMB FLARES

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ABSTRACT

Using observations from the Yohkoh Bragg Crystal Spectrometer, hard X-ray telescope, and soft X-ray telescope, we have examined eight limb flares. Four of the flares have the footpoints occulted by the solar limb. We find that the occulted flares generally have softer hard X-ray spectra and smaller peak values of the nonthermal broadening velocity than nonocculted flares. All other physical parameters show no differences between occulted flares and nonocculted flares. The hard X-ray spectra support a model in which the footpoint emission is due to thick-target sources, while the loop top emission is due to thin-target sources. High spectral resolution hard X-ray observations should thus show a break in the hard X-ray spectrum of the loop top source. We can find no obvious explanation for the differences in nonthermal broadening velocity.

Subject headings: Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

At the conceptual level, solar flares are generally thought to be the result of magnetic reconnection. Some kind of initiating event causes reconnection at a site in the corona, leading to rapid acceleration of electrons and protons, which then follow the field lines of one or more magnetic loops downward to the chromosphere. The rapidly varying impulsive-phase hard X-ray emission is then just the result of thin- or thick-target bremsstrahlung as the suprathermal electron beam propagates. These same electrons heat the ambient plasma collisionally, resulting in the more gradually varying emission observed in soft X-rays. There may also be additional heating in the corona associated with the reconnection site. In this picture, most of the hard X-ray emission observed during the impulsive phase should originate from the thick-target bremsstrahlung emission at the loop footpoints.

Recent observations of limb flares in hard and soft X-rays from the Yohkoh satellite provide a more complete picture of the early phases of a flare in hard and soft X-rays (Masuda et al. 1994; Masuda 1994b). These observations show that early in the rise phase the soft X-ray flare consists of one or more loop-like structures with emission concentrated at the loop footpoints and at a loop-top source. Soft X-ray filter ratios suggest that there is also a high-temperature region with relatively low emission measure just above the soft X-ray loop. Spatially coincident with the soft X-ray footpoints are strong hard X-ray sources. Above the soft X-ray loop is a third hard X-ray source, which has no clear counterpart in the soft X-ray images.

Many disk flares also show a concentrated soft X-ray emission source at the assumed location of the loop top (e.g., Acton et al. 1992; Feldman et al. 1994). This source appears early in the flare and persists well into the decay phase. Since hydrodynamic simulations of electron beam-heated flares predict that shortly after heating begins a flaring loop should be uniformly filled with nearly isothermal plasma (e.g., Mariska, Emslie, & Li 1989), the existence of these loop-top soft X-ray sources presents a challenging contradiction to current conceptual flare models. Indeed, any simple energy input model should have this problem.

While ratios of soft X-ray images taken through different filters with the soft X-ray telescope (SXT) on Yohkoh can in principle be used to determine the temperature and emission measure at all locations in a flaring loop, these values are of necessity somewhat crude. They rely on the assumptions that the plasma is isothermal and changes little between the successive images required to construct the diagnostic ratio. The Bragg crystal spectrometer (BCS) on Yohkoh provides high temporal and spectral resolution data at selected wavelengths that allow a more refined determination of the physical conditions in the flaring plasma. Unfortunately, the BCS views the entire Sun, and thus for most flares it cannot isolate individual components of the flaring plasma. For some flares, however, the solar limb occults part of the flaring plasma, allowing an examination of only the loop-top source. In this paper we examine the time evolution of the physical parameters that characterize the loop-top-emitting source by studying Yohkoh observations of four limb flares with occulted footpoints and four limb flares with exposed footpoints.

2. YOHKOH INSTRUMENTATION

For this study we use data from three instruments on the Japanese Yohkoh spacecraft. Yohkoh was launched in 1991 August and has been operating continuously since then. Ogawara et al. (1991) provide an overview of the entire mission.

The Yohkoh BCS uses four bent crystals to cover narrow wavelength ranges centered on emission lines of Fe xxvi, Fe xxv, Ca xix, and S xv. Radiation from each crystal is registered in a one-dimensional position-sensitive propor-
The *Yohkoh* hard X-ray telescope (HXT) uses 64 pairs of grids in front of 64 hard X-ray detectors to synthesize hard X-ray images of solar flares. These detectors have a total effective area of about 70 cm² and cover an energy range from 15 to 100 keV in four bands. In flare mode, the HXT has a time resolution of 0.5 s. Images synthesized with the HXT have an angular resolution of about 5″. Kosugi et al. (1991) provide further details on the design and performance of the HXT. In this study we use data from the L (14–23 keV), M1 (23–33 keV), and M2 (33–53 keV) bands.

The *Yohkoh* SXT uses a grazing incidence telescope and filters to image soft X-rays on a 1024 × 1024 CCD camera. Five X-ray analysis filters transmit selected portions of the soft X-ray wavelength range to provide temperature and emission measure determination capability through filter ratios. Each pixel on the CCD covers 2.45 × 2.45 arcsec². For a point source, the FWHM of the image produced by the telescope is ≤3″. Tsuneta et al. (1991) provide further details on the SXT.

3. OBSERVATIONS

Masuda (1994a) has surveyed data from the entire *Yohkoh* mission to produce a list of flares observed near the solar limb, which are suitable for analysis using the HXT. In addition, he has also constructed a list of flares observed with *Yohkoh* for which there was no Hα emission observed from the ground. Among this list are several flares which occurred at the limb but had occulted footpoints, resulting in no Hα emission. Using these lists and *Yohkoh* SXT observations, we selected the eight flares listed in Table 1 for detailed analysis.

Figures 1 and 2 show SXT images taken during the rise phase through the Be 119 μm filter for the eight flares listed in the table. Using spacecraft pointing data, we have added the position of the solar limb. The contours on each plot show an image synthesized at the same time using the data from HXT. In Figure 1 we show those flares which we believe are not fully occulted by the solar limb. In Figure 2 we show those flares which are fully or nearly fully occulted. The Be 119 μm filter is sensitive to the shortest wavelength soft X-rays in the passband of the SXT and thus tends to

![SXT and HXT images of the nonocculted limb flares observed on (a) 1992 June 28, (b) 1992 August 11, (c) 1993 September 27, and (d) 1993 November 30. The SXT images were taken through the Be 119 μm filter. The HXT images were reconstructed from data in the M1 (23–33 keV) band for (a) and in the M2 (33–53 keV) band for (b–d).](image-url)
show the highest temperature emitting regions in a solar flare.

For each of the flares listed in Table 1 we have processed the BCS Ca xix and Fe xxv data to correct for instrumental effects and apply wavelength calibrations. In addition, the data were accumulated until the total number of counts exceeded 10,000 counts in the Fe xxv channel and 8000 counts in the Ca xix channel. This ensures that each spectrum contains sufficient detail for spectral fitting software to work successfully.

<table>
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4. ANALYSIS

Analyses of large numbers of flares observed with the BCS on Yohkoh show that on average Doppler-shifted components to the spectrum are not common in flares observed near the limb (Mariska, Doschek, & Bentley 1993; Mariska 1994). All the flares listed in Table 1 show no large Doppler-shifted component and no evidence for changes in the wavelength of the resonance line during the flare that would signify bulk mass motions. Therefore, we have fitted the Fe xxv and Ca xix spectra from each flare using a single-component isothermal model. Thus, each BCS spectrum is characterized by a temperature $T$, an emission measure $EM$, and nonthermal broadening $\xi$.

These parameters were determined by computing synthetic spectra and then varying the fitting parameters to locate a minimum in the $\chi^2$. The synthetic spectra for the Fe xxv BCS channel primarily use the atomic data computed by Bely-Dubau et al. (1982a). Those for the Ca xix BCS channel primarily use atomic data computed by Bely-Dubau et al. (1982b). Both sets of atomic data have been subjected to minor modifications in wavelengths and excitation rates (Doschek 1994).

Figures 3 and 4 show the time evolution of the HXT emission in the L, M1, and M2 bands, the total emission in the BCS Ca xix and Fe xxv channels, and the temperatures and nonthermal broadening velocities determined from the BCS spectra. All data are plotted centered on the time inter-
Fig. 3.—Temporal behavior of the HXT L, M1, and M2 channels; the BCS count rate in the Fe xxv and Ca xix channels; and the derived temperatures and nonthermal broadening velocities in the BCS Fe xxv and Ca xix channels for the non occulted flares observed on (a) 1992 June 28, (b) 1992 August 11, (c) 1993 September 27, and (d) 1993 November 30.
Fig. 4a—Temporal behavior of the HXT L, M1, and M2 channels; the BCS count rate in the Fe XXV and Ca XIX channels; and the derived temperatures and nonthermal broadening velocities in the BCS Fe XXV and Ca XIX channels for the occulted flares observed on (a) 1991 October 21, (b) 1992 October 5, (c) 1993 February 1, and (d) 1994 January 29.
val they cover. The count rates in the HXT plots are per subcollimator. To reduce clutter, we have not included error bars on the temperature and nonthermal velocity plots.

Assuming that the variation of each fitting parameter is independent of the values of the other fitting parameters near the values that yield the best fit to the data, the formal error for each fitting parameter is the square root of the corresponding element in the covariance matrix produced by the fitting procedure (e.g., Press et al. 1992, p. 696). For most of the flares in our study, the errors in temperature estimates for Fe xxv are \( \leq 4 \times 10^5 \) K, while those for Ca xix are \( \leq 6-8 \times 10^5 \) K. The errors are larger for the Ca xix channel because it does not include the most sensitive temperature diagnostic lines that are available for Ca xix. In one flare (1991 October 21), the temperature measured in the Ca xix BCS channel is near the limit of sensitivity for the diagnostic lines in the channel. Early in this flare, errors on the temperature determination in the Ca xix channel vary from 1–2 \times 10^5 \) K. The errors in the nonthermal velocity measurements for Fe xxv are usually 5–10 km s\(^{-1}\), while those for Ca xix are 3–8 km s\(^{-1}\).

Comparison of the data plotted for the nonocculted flares in Figure 3 with the data for the occulted flares in Figure 4 shows a number of similarities and differences between the two kinds of flares. These are summarized in Table 2.

The time variation of the HXT count rates shows the range of behavior typical for flares observed with Yohkoh. Early in each flare, all channels tend to show the rapid time variations characteristic of the impulsive phase. Later in the time variations become more gradual, and the stronger signal in the lowest energy channel relative to the higher energy channels suggests that we are observing the thermal flare plasma.

While the overall time variations appear to be the same in both the nonocculted and the occulted flares, the relative signal in the various HXT channels appears to differ between the two kinds of flares. In most of the occulted flares, the higher energy channels are noticeably weaker relative to the 14–23 keV channel compared with the nonocculted flares. This is shown by spectral fitting to the three lowest energy channels at the peak in the HXT emission in each flare. In Table 2 we list the values of the spectral index \( \gamma \) measured at the peak of the HXT L channel signal. These values suggest that the loop-top hard X-ray emission from occulted flares is softer than that from nonocculted flares in which the footpoint sources dominate. Another manifestation of this tendency for the HXT emission to be softer in occulted flares than in nonocculted flares is a tendency for the peak count rates in the HXT M1 channel to be lower in the occulted flares than in the nonocculted flares.

The time behavior of the total emission in the BCS Fe xxv and Ca xix channels shows no significant differences between nonocculted and occulted flares. In general, the count rates in the two channels are comparable, with the flare usually peaking in Fe xxv shortly before it peaks in Ca xix. Peak emission in the BCS channels, which are sensitive to the thermal plasma from the flare, always takes place after the peak in the hard X-ray burst, although, as the figures show, the length of that delay varies significantly from flare to flare.

Table 2 lists the peak temperatures reached in the BCS Fe xxv and Ca xix channels. For most of the flares, the time evolution of the temperature measured in these two channels is typical of that seen in disk flares. When the signal is strong enough to fit accurately the Fe xxv spectrum, the temperature is 16–18 MK. It then usually continues to rise until it reaches 20–24 MK. In the BCS Ca xix channel there is often enough signal to fit spectra at or sometimes before the onset of the hard X-ray burst. For most of the flares shown in the figures, the first Ca xix spectra show temperatures of 10–12 MK. Then it usually rises to 13–16 MK.

The occulted limb flare observed on 1991 October 21 shows unusual temperature behavior. This flare shows significantly higher Ca xix temperatures than are commonly seen with the Yohkoh BCS. Moreover, the temperatures measured from the Ca xix spectra are very close to those determined from the Fe xxv spectra, suggesting that the plasma we are observing is nearly isothermal. This is the only flare in the Yohkoh data for which we have seen this kind of behavior. A more detailed investigation of this flare will be the subject of a future paper.

Table 2 lists the peak values of the nonthermal broadening velocities for all the flares. In both the nonocculted and occulted flares, the nonthermal broadening is already large at the earliest time at which we can obtain a statistically meaningful spectrum. For some of the flares, particularly those in which there are Ca xix spectra available at or before the onset of the hard X-ray burst, the nonthermal broadening sometimes increases after the hard X-ray burst begins. In Fe xxv, which we generally only find useful spectra in after the onset of the hard X-ray burst, the first few spectra usually have the largest values of the nonthermal broadening. For the remainder of the flare, the nonthermal broadening measured in Fe xxv declines.

At high count rates, the BCS detectors suffer from a rate-dependent distortion (Trow, Bento, & Smith 1994). When a large number of counts are put into a small volume of the detector, for example at the position of the resonance line in a strong flare, a space charge effect develops. This affects the electrons in the detector toward the region of the strong line, resulting in lines that are taller and narrower than they should be and locally distorting the linearity of the detector. When this line narrowing becomes severe, the line widths fall to less than their thermal values. The 1993 January 1 event shows this effect in the Ca xix nonthermal broadening measurements. We believe that this effect is small below a count rate of between 3000 and 4000 s\(^{-1}\). Since the peak values of the nonthermal broadening velocity occur early in the flare, when the count rates are below these values, we believe that

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**TABLE 2**

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<th>DATE</th>
<th>( T ) (MK)</th>
<th>( \xi ) (km s(^{-1}))</th>
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the measured values are accurate. Note that even when line narrowing is severe, the total number of counts in each detector channel is conserved.

The nonthermal broadening velocities in Table 2 show a clear tendency toward smaller peak values in the occulted flares than in the nonocculted flares. This is true for both the Fe xxv and the Ca xix spectra. Late in each flare, beyond the times plotted in the figures, the nonthermal broadening velocities decay to between 150 and 200 km s\(^{-1}\) in the Fe xxv spectra and to near 50 km s\(^{-1}\) in the Ca xix spectra. Thus, late in the flare all the physical parameters derived from the BCS spectra appear to be the same for both the nonocculted and the occulted flares.

5. SUMMARY AND DISCUSSION

In summary, we have found that in most observational characteristics occulted limb flares are indistinguishable from nonocculted limb flares. Based on the average properties of what is admittedly a small sample of each kind of flare, we find that the occulted flares have softer hard X-ray spectra, lower peak count rates in hard X-rays, and smaller peak values of the nonthermal broadening velocity than nonocculted flares.

Softer hard X-ray spectra from a flare whose footpoints are not visible have been observed previously (Kane et al. 1979). In that observation the power law index of the above-the-limb component was greater by 2 than the power-law index of the complete flare. This result has been interpreted by Brown, Hayward, & Spicer (1981) as consistent with a thick-target model for downward injection of electrons. The hard X-ray emission from the loop-top source results from thin-target emission with \(\gamma = \delta + 1\), while the emission from the full flare is dominated by the footpoint thick-target sources with \(\gamma = \delta - 1\). Here \(\delta\) is the power-law index of the electron energy source function. In our nonocculted flares, the average value of \(\gamma\) is roughly 4.2, while the value for occulted flares is 6.5. Thus, our small sample of flares supports this interpretation.

Hard X-ray observations of occulted limb flares have also been reported by Frost & Dennis (1971) and Hudson (1978). Both these studies found that the hard X-ray spectra were harder than spectra of nonocculted flares. Thus, there is still considerable uncertainty about the nature of the hard X-ray sources observed at large heights in solar flares.

Masuda (1994b) analyzed HXT observations of several limb flares. He found that the impulsive loop-top source observed early in most flares showed a spectral index that was close to or a little softer than the spectral index for the footpoint sources. Both our results and those of Masuda are highly uncertain owing to the limited energy resolution of the Yohkoh HXT. Analysis of additional flares for which there are data from the Compton Gamma Ray Observatory BATSE experiment would aid in clarifying this result.

This picture of softer hard X-ray spectra higher in the flaring loop or loops is also supported by the height analysis of hard X-ray sources in solar flares performed by Matsushita et al. (1992). They found that the average height of hard X-ray emission observed with the Yohkoh HXT decreases with increasing X-ray energy. This is consistent with the thick-target model for downward injection of electrons.

High spectral resolution observations would allow us to search for breaks in the hard X-ray spectrum of the loop-top source. A break in the spectrum would mark the change from thin-target emission. The energy at which such a break takes place is related to the column density, which is the product of the density and loop length, corrected for the pitch angle of the field lines to the loop axis and the electron paths relative to the field lines (e.g., Tandberg-Hanssen & Emslie 1988). Thus, higher spectral resolution hard X-ray observations could ultimately yield improved density estimates. These density estimates are crucial for validating numerical models of electron beam-heated flares. For example, Emslie, Li, & Mariska (1992) have suggested that only a high-density preflare loop will result in Ca xix spectra that have characteristics similar to those seen in the Yohkoh BCS data.

The difference in intensity of the hard X-ray emission between the occulted and nonocculted flares may also provide useful constraints on flare models. The intensity of the hard X-rays is related to the amount of material the electrons that produced them have passed through. Thus, some estimate of the density may be possible from the intensity measurement. Kane et al. (1979) found that the coronal hard X-ray source they observed was about 600 times less intense than the full flare. Our observations show that the occulted flares tend to be about a factor of 2–3 less intense than the full flare. The coronal source observed by Kane et al. (1979) was, however, at a height of 25,000 km in the corona. We are likely to see more of the flaring loop. In addition, emission from the lower energy channels of the HXT, is probably a mixture of both thermal and nonthermal emission.

It is difficult to use this estimate, though, without some assurance that the occulted and nonocculted flares we are observing are all of the same GOES class and thus probably of roughly the same size. Recent work by Feldman et al. (1995) suggests that the temperature determined from an Fe xxv spectrum obtained near peak flare emission may be related to the GOES class of a flare. Thus, an analysis of additional limb flares may provide the information necessary to use the relative hard X-ray intensity to deduce the density in the flaring loop.

Interpreting the meaning of the nonthermal broadening velocities measured in flares has always been a challenge. Broadly speaking, there are two ways to view it: as a manifestation of the range of bulk velocities present in the plasma flowing in the loop in response to heating by the energetic electrons or as mass motions at spatial scales smaller than the scale of the bulk flows in the magnetic flux tubes, usually referred to as turbulent broadening or microturbulence. If the second view is correct, then the nonthermal broadening velocity probably contains more direct information about the plasma heating process. Combinations of the two are also possible.

If the nonthermal broadening velocities are simply due to bulk velocities, then we would expect their magnitude to diminish for flares at the limb relative to the values measured near Sun center. This assumes that on average the flows are roughly radial in a flaring flux tube. Mariska et al. (1993) and Mariska (1994) did not find any obvious center-to-limb dependence in line width measurements, suggesting that this simple interpretation is not correct.

If the plasma flows in flaring flux tubes were following helical magnetic field lines, the center-to-limb behavior would be altered and bulk flow might still explain the observations. In this case, the reduced nonthermal broadening velocity in the occulted flares would suggest that the
pitch angle of the field varied from the top of the loop to the bottom. If we imagine a loop with both footpoints at the limb, then the line-of-sight velocity would be the component of the velocity transverse to the loop axis. Smaller nonthermal broadening velocities at the loop top would thus indicate that this component is smaller there. This would suggest that a helical field has a smaller pitch angle near the top of the loop than at the base. If such a loop were observed near Sun center, the broadening measured near the footpoints would be reduced and those near the loop top would be large, which might then yield the observed lack of a center-to-limb dependence in the line widths.

Unfortunately, for a magnetic loop with field expansion from the base to the apex, the magnetic field should have a smaller pitch angle where it is strongest near the base (Parker 1974). Thus, this picture does not appear to apply. If, however, the field is not helical and the flow velocity is related to the variation in the cross-sectional area of the flaring flux tubes, then in a simple mass-conserving flow view, we would expect the velocities to be highest near the base, where the cross-sectional area is small, and smaller near the loop top, where the cross-sectional area is larger. In this view, the difference in nonthermal broadening velocities is a measure of the change in cross-sectional area from loop base to loop top. Reconciling this picture with the center-to-limb variation of the blueshift velocity and the lack of center-to-limb variation of the line widths would present a new challenge.

If the nonthermal broadening velocities are due to turbulent broadening, then they are probably related more directly to the heating process than bulk flow produced line broadening. In this case, the reduced nonthermal broadening velocity in the occulted flares suggests that the plasma is being heated differently near the loop tops than at the footpoints. Since the density is lower and the temperature is higher near the loop tops than at the sites at which the bulk of the energy in the energetic electrons is deposited in the upper chromosphere, we might expect that any heating at the loop tops would result in larger mass motions there. Our observations show that this is not the case. Moreover, since most flare initiation processes are related to magnetic field changes, we would expect that any velocities produced would tend to be on the order of the Alfvén speed. Our observations suggest that the nonthermal velocities are only a fraction of the sound speed.

Of course, the microturbulence could also be the result of the movement of energy to higher wavenumbers as the energy in the bulk flow is converted to thermal energy. In this case, measurements of the nonthermal broadening velocity would not provide any direct measure of the flare heating process. It is not clear, though, why there should be a difference in the nonthermal broadening velocity between occulted and nonocculted limb flares.

Khan et al. (1995) have analyzed Yohkoh data for four occulted limb flares which occurred in a single active region over a period of about 10 hr. These flares, which varied from GOES class C5.4 to C6.9, were not part of our study. Khan et al. found no obvious differences between the temperatures and nonthermal velocities measured for the four flares and those quantities determined for disk flares observed with spectrometers flown on earlier satellites. Our observation of differences in the nonthermal broadening velocity between nonocculted flares and occulted flares thus disagree with their observations. In both studies, the numbers of flares examined are relatively small, and our flares were generally stronger than those observed by Khan et al. Additional analyses of occulted and nonocculted limb flares will be necessary to understand the different results.

We thank S. Masuda for sharing his lists of limb flares with us. J. T. M. thanks A. G. Emslie, J. A. Klimchuk, and S. K. Antiochos for useful discussions and P. Cargill for useful discussions and for his comments on the manuscript. J. T. M. was supported by a NASA Yohkoh Participating Scientist grant and by the Office of Naval Research. R. D. B. was supported under the MSSL rolling grant provided by the UK Particle Physics and Astronomy Research Council.

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