THE CORRELATION OF SOLAR FLARE HARD X-RAY BURSTS WITH DOPPLER BLUEShiftED SOFT X-RAY FLARE EMISSION

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ABSTRACT

We have investigated the temporal correlation between hard X-ray bursts and the intensity of Doppler blueshifted soft X-ray spectral line emission. We find a strong correlation for many events that have intense blueshifted spectral signatures and some correlation in events with modest blueshifts. The onset of hard X-rays frequently coincides to within a few seconds with the onset of blueshifted emission. The peak intensity of blueshifted emission is frequently close in time to the peak of the hard X-ray emission. Decay rates of the blueshifted and hard X-ray emission are similar, with the decay of the blueshifted emission tending to lag behind the hard X-ray emission in some cases. There are, however, exceptions to these conclusions, and, therefore, the results should not be generalized to all flares. Most of the data for this work were obtained from instruments flown on the Japanese Yohkoh solar spacecraft.

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

1. INTRODUCTION

The relationship of the soft X-ray flare to the hard X-ray flare has been the subject of some controversy. In one view the energetic particles produced at the onset of solar flares propagate down to the chromosphere and heat the chromospheric gas, driving it into coronal loops where it appears as the soft X-ray flare. In this picture the soft X-ray thermal plasma with a temperature of about 20 MK is mostly the result of chromospheric evaporation induced by high-energy, nonthermal particles (the beam-heating model). This view has been espoused in both observational (e.g., Dennis 1991) and theoretical papers (e.g., Mariska, Emslie, & Li 1989). In contrast, others have suggested that the hard X-ray and soft X-ray flares are both the result of a common energy release mechanism but that the electrons which produce the nonthermal hard X-rays do not energize the soft X-ray emitting plasma (e.g., Feldman, Cheng, & Doschek 1982).

Previous solar flare missions that contained Bragg crystal spectrometers discovered blueshifted emission wings on the X-ray spectral lines of highly excited ions that are produced in the soft X-ray flare plasma (Doschek et al. 1980; Antonucci et al. 1982). This emission has been interpreted by some as direct evidence in support of the beam model, but this interpretation has been challenged (e.g., Doschek et al. 1986) and is not universally accepted. Simnett (1991) pointed out that if chromospheric evaporation were driven by ion beams, then the onset of the evaporation should be decoupled from the onset of the hard X-rays. However, since both the largest blueshifts and the hard X-ray production arise near the time when the energy flux deposition is greatest, then in large flares a significant correlation between these quantities is expected.

One way to help resolve these issues is to determine whether temporal correlations exist between the blueshifted emission and the hard X-ray bursts. Numerical simulations of chromospheric evaporation, as well as other theoretical attempts to model the interaction of nonthermal particle beams with the chromosphere, make explicit predictions regarding such correlations. Previous studies using Bragg crystal spectra from the Solar Maximum Mission (SMM), Hinotori, and P78-1 showed that blueshifted emission occurred roughly over the same time interval as the hard X-ray bursts, but timing details remained unclear because of either low instrument sensitivity or inadequate time resolution. The same comment applies to correlations between the intensity of the blueshifted emission and hard X-ray bursts.

The recent launch of the Japanese Yohkoh spacecraft has enabled us to take a major step forward in the search for hard X-ray/blueshift correlations. Yohkoh contains four high-resolution and high-sensitivity Bragg crystal spectrometers specifically designed to investigate the impulsive phase of flares. These spectrometers are significantly more sensitive than instruments flown on earlier missions. In this Letter we report the results of a first survey of correlations between hard X-ray and blueshifted emission.

2. THE DATA AND ANALYSIS TECHNIQUES

The two bent Bragg crystal spectrometers (BCSs) on Yohkoh cover narrow wavelength windows centered on lines of highly ionized iron (Fe XXV–Fe XXVI, 1.7597–1.8121 Å), Fe XXIII–Fe XXV, 1.8284–1.8957 Å), calcium (Ca XVIII–Ca XX, 3.1633–3.1933 Å), and sulfur (S XIV–S XV, 5.0163–5.1143 Å). The spectrometers are uncollimated and therefore view the entire Sun continuously during spacecraft day and outside the South Atlantic Anomaly. The BCS sensitivity is high enough to record spectra with statistical significance in 9 s integration times at the onset of the soft X-ray flare. A detailed description of the instrument is given by Culhane et al. (1991).
Hard X-ray data are available from the hard X-ray Fourier transform imaging telescope (HXT) on *Yohkoh*. The imaging capabilities of this instrument are not used in this work since only a temporal correlation between hard and soft X-ray emission is being investigated. Three hard X-ray channels are used in this work: 13.9–22.7 keV, 22.7–32.7 keV, and 32.7–52.7 keV. The lowest energy channel may contain some emission due to the Maxwellian tail of the thermal soft X-ray emission. In the examples to be discussed later we illustrate the results using the 22.7–32.7 keV data. The HXT is described in detail by Kosugi et al. (1991). If available, the hard X-ray data have been supplemented by data from the BATSE experiment on the *Compton Gamma Ray Observatory*, when the initial onset phase of a flare was not observed by HXT.

Since launch at the end of 1991 August, the BCS has recorded rise phase spectra of more than 200 flares. These flares range in class from weak C events to X class flares. BCS is sensitive enough to investigate C flares with good statistics. Preliminary results concerning certain general characteristics of the Ca xix resonance line profiles during the rise phase have been published by Mariska, Doschek, & Bentley (1993). This survey has resulted in a list of flares with known line profile characteristics and forms the starting point for the selection of most of the flares examined in the present investigation.

We have used two methods for investigating a hard X-ray/blueshift correlation. In one method, we have constructed contour plots of the blueshifted soft X-ray line emission as a function of time for computer interactive comparison (by eye) with the hard X-ray emission time profile. Ten fixed levels were chosen at the following detector count levels: 1.67, 3.33, 6.67, 13.3, 26.7, 53.3, 107, 213, 427, and 853. The lowest level, 1.67, is quite low, and therefore the method is sensitive to very weak blueshifts. The data were also smoothed using the standard Interactive Data Language (IDL) boxcar averaging technique. This smoothing is over both time and wavelength with a width of 3.

The contour method allows us to investigate a large number of events in a short time. For this study, only events that were well observed during the impulsive phase, and which have either a clear blueshift signature at flare onset and/or a hard X-ray signature, were selected from the list published by Mariska et al. (1993). Sixty-three such events were found that occurred between 1991 November and 1992 mid-July. Events with blueshift signatures do not occur at the limb, as we found from previous analyses of SMM spectra. An example of a contour plot is shown in Figure 1.

The contour inspection method is not intended for quantitative work; it allows the simple processing of a large number of events. It has an added advantage in that it gives an overall picture of the data which clearly reveals problems such as false line features caused by the presence of more than one event simultaneously on the Sun, as well as possible detector effects. It also provides an indicator for events that are worthy of a more detailed examination.

The second technique is similar, but not exactly the same, as the technique used by Doschek et al. (1993) in their investigation of the 1992 January 5 flare near 13 UT observed by *Yohkoh*. First, the continuum is subtracted from all the spectra. Then the spectral intensity at a selected line-of-sight velocity is simply plotted as a function of time. A comparison of this intensity with the hard X-ray intensity reveals whether or not a correlation exists. In practice, in order to improve statistics, the spectral intensity is summed over a velocity range. The velocity range is chosen by selecting spectral regions where the blueshifted intensity is large, but an attempt is made to choose the largest velocities for which good statistics can be obtained. This minimizes, but does not eliminate, contamination from the nonmoving spectral component. For the study using the second technique, events were selected from the Mariska et al. (1993) list that have particularly strong blueshift signatures at flare onset. This biasing criteria was used to obtain good statistics. Note, however, that many events have either very weak dynamical signatures, or no obvious dynamical signatures, at flare onset.

The second technique does not in principle distinguish between a blueshift and strong resonance line broadening; however, visual inspection of the line profile was made to establish that the flares we studied did indeed have asymmetric profiles during the rise phase, although inevitably there is some contribution to the signal from turbulence in the stationary component. Because of the asymmetric appearance of the line at flare onset, we are confident that the majority of the blueshifted emission at early times near flare onset is due to a bulk motion along the line of sight and is not due to symmetric turbulent broadening. At later times, when the stationary component weakens, there may be some contamination of the blueshifted signal due to the stationary component.

As the BCS views the whole Sun, coincident activity from elsewhere on the Sun could simulate a blueshift. However, the dispersion relation for the two spectrometers is such that an event which moved the Ca xix spectrum to the blue would move the Fe xxv spectrum to the red. All events were checked...
against this criterion to establish that the blueshifts are genuine.

Finally, we note that the second technique as used to obtain the results obtained in this Letter, refers primarily to large blueshift velocities. Small velocities, for example a shift of the entire resonance line by 20 km s\(^{-1}\), would not be detected by the second technique.

3. RESULTS AND DISCUSSION

From the contour survey of the 63 events obtained from the Mariska et al. (1993) list we find the following:

1. For simple, energetic hard X-ray bursts, the blue wing enhancement appears to begin at flare onset and almost coincident (to within a few seconds) with the hard X-ray burst.
2. Flares without significant impulsive, rapidly varying hard X-rays, the blue wing can first appear several minutes after the start of the flare.
3. Sometimes the blue wing persists after the decay of the hard X-ray burst.
4. The intensity and velocity range of the blue wing do not seem strongly related to the intensity of the hard X-ray burst.
5. There may be a relationship between the structure of the hard X-ray burst and the time profile of the blue wing: more impulsive (harder) X-ray events are associated with stronger blue wings.
6. In a few cases (roughly 7%), at the very start of the flare, the entire line profile is shifted, i.e., there is no rest component. However, for many flares there is an intensity enhancement of the "rest" component prior to the onset of hard X-rays which might represent preflare energy input.

7. Flares with a hard X-ray signature but no blue wing are mostly near the limb. Ten of 12 events of this type occurred at longitudes greater than 45\(^\circ\). Although there is a general consistency with the cosine law, i.e., radial flows, there are many departures from the cosine law.

We have examined about 30 events which have a large blueshifted component using the second technique described in § 2. More events continue to be investigated. Plots of the blueshifted emission versus time are shown in Figure 2 for four of these events. Also shown are the counts in the 22.7–32.7 keV HXT energy channel.

The blueshifted emission in Figure 2 has been smoothed over time with a width of 3 using the same IDL smoothing routine mentioned above. In some cases there appears to be a correlation between the more minor intensity variations in the blueshifted and hard X-ray time profiles. However, inspection of the error bars for the blueshifted emission shows that these apparent correlations might not be real and instead might only be coincidences.

A brief description of the results obtained from Figure 2 is given below.

**The 1992 September 12 flare.**—There is a strong temporal correlation between the intensity of the blueshifted emission in the indicated line-of-sight speed range and the intensity of the hard X-ray bursts. The intensities are expressed in arbitrary units to show the time correlation. A detailed investigation of the ratio of hard X-ray to blueshifted emission intensity is also interesting but is beyond the scope of this Letter. The onset time of the blueshifted emission and the time of peak intensity of the blueshifted emission coincide closely with the times of

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**Figure 2.** Ca xix resonance line blueshifted emission intensity in the indicated line-of-sight speed ranges and HXT hard X-ray intensity in the 23–33 keV channel. (solid curve) Average blueshifted intensity; (dotted curve) hard X-ray intensity. The light curves are normalized relative to each other. The vertical error bars are 1 \(\sigma\) standard deviations, assuming Poisson statistics.

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onset and peak of the hard X-ray emission (This has been verified from the BATSE data for this event.)

The blueshifted emission decay rate for the September 12 event is similar to, but not as rapid as, the decay rate of the 23–33 keV energy band. There appears to be a second weaker burst superposed on the decay of the first hard X-ray burst. This second burst is weaker in the highest energy HXT channel relative to the first burst than in the lowest and middle energy channels, which indicates that it is produced by a softer electron spectrum. Thus, the blueshifted emission decays slower than the highest energy hard X-rays.

The 1992 February 2 flare.—The results for this event differ substantially from the September 12 event. The hard X-ray burst is extremely impulsive with a temporal width (width at half-maximum intensity) of less than 10 s. The blueshifted emission begins at about the same time as the hard X-ray burst (as inferred from the lowest channel HXT data) and peaks about 15 s after the peak of the hard X-rays. The temporal width of the blueshifted emission is about 30 s at half-peak intensity, and its intensity behavior with time looks more thermal than impulsive. However, the width of the stationary component for this flare is rather large, and the blue wing sum may be contaminated by the stationary component.

The 1992 August 20 flare.—The blueshift intensity increases with the hard X-ray burst, and they appear to have similar onset times. The peak blueshift emission occurs within 30 s of the peak hard X-ray emission.

The 1992 June 23 flare.—This event resembles the September 12 event. The onset time and time of peak intensity of the blueshifted emission appear to be about the same as for the hard X-ray times. The overall time profile of the blueshifted emission resembles the hard X-ray time profiles in general appearance.

The four events we have discussed above were selected on the basis of a strong blueshift. We have also studied a sample of 14 other events selected solely because they could be compared with a hard X-ray burst detected by BATSE. Of these, seven had good correlations with the dominant features of the hard X-ray burst, five showed onsets of the blueshifted component some tens of seconds before the hard X-ray onset, and for two events the correlations were not clear. In the cases where the blueshifts might occur before the hard X-ray onset, the blueshifts are very weak prior to the onset of hard X-rays, and it is possible that hard X-rays are not detected because of a hard X-ray detector sensitivity threshold.

The results of the general survey of 63 events are qualitatively similar to the specific results discussed above. In many cases the occurrence of blueshifted emission is an impulsive phenomenon in the sense that it is linked strongly to the hard X-ray emission in terms of onset times, peak emission times, and decay rates. However, some of our observations, and some previous observations, indicate that this strong correlation does not always hold, e.g., the correlation is weak for the February 2 event discussed above. There are also many flares that do not have an obvious blue wing enhancement, even when they occur at disk center.

The ability with the Yohkoh BCS to make high time resolution comparisons between hard X-ray and blueshifted emission intensities is what is new compared to previous results. We have established timing correlations to within a few tens of seconds between the blueshifted emission in a specified velocity range and hard X-ray emission for many events. For some of the events, the blueshifted time history appears quite similar to the hard X-ray time history. The results presented in this Letter can be used for direct comparison to beam-model numerical simulations of evaporation. Flare images of all of our events are available from the soft X-ray telescope on Yohkoh and can be used to determine morphological input parameters for the simulations.

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