Observations of Several Small Flares with the Bragg Crystal Spectrometer on Yohkoh


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Abstract

We have analysed data from two flares of GOES class C7.1 and C8.5 observed by the Yohkoh Bragg Crystal Spectrometer. The high sensitivity of the Yohkoh instrument allows us to observe the very early stages of flare development and to study small events with a high signal-to-noise ratio. Spectral fitting programs have been used to derive plasma temperatures, emission measures and velocities from spectra of S XV, Ca XIX and Fe XXV. Large plasma motions indicative of chromospheric evaporation have been found. A more detailed analysis of a flare which occurred on 1991 October 30 is presented.

Key words: Plasma motions — Sun: flares — Sun: X-rays — X-rays: spectra

1. Introduction

Among questions relating to flare development in soft X-rays which can be advanced by the Yohkoh data, line broadening and chromospheric evaporation attract particular interest. The observations from previous missions left several questions unanswered, particularly those relating to the distinction and relative timing between turbulence and chromospheric evaporation. Moreover, previous missions were better suited to studying the larger M and X class flares. Although events of class C were also observed by the Solar Maximum Mission, the statistical quality of the data did not allow the study of either the detailed time history of the initial phase or the late decay of small flares. The high sensitivity of the Yohkoh Bragg Crystal Spectrometer (Culhane et al. 1991) makes it an ideal instrument to extend our knowledge of energy release and plasma dynamics to small flares.

The BCS registers spectra in four wavelength ranges and the sensitivity in each channel (see Lang et al. 1992) is significantly greater than for previous flare missions. In the following sections data are presented from two flares which occurred on 1991 October 30 and 1991 November 19. The method of analysis is described and results for velocity and temperature are given for the flare impulsive phases. The possibilities of plasma upflows and turbulent line broadening are discussed and data from the flare decay phases are used to infer the duration of the energy input and to constrain the dimensions of the loops which contain the emitting plasma.

2. Observations

Among 12 small flares which we have examined, we have analysed in detail data from two events which occurred on 1991 October 30, at 150 UT and on 1991 November 19, at 930 UT. Spectra of S XV, Ca XIX and Fe XXV have been recorded, with time resolution of 3 s. These two events give examples of line profiles observed early in the rise phase. We combine the observations from three channels to derive information on chromospheric evaporation in a wide range of temperatures from 5 to $25 \times 10^6$ K.

The flare on 1991 October 30, at 150 UT, is classified as a class C7.1 flare and was located at S12 W23. It began about 30 min after the peak of an M4.3 flare which had occurred in the same active region. The entire flare has been recorded, except for a two minute gap in the decay phase. Plots of intensity against time (lightcurves) are shown in figure 1a where the curve for S XV has had the background due to the first flare subtracted. The intensity of Fe XXV spectra increases in 90 s and decays

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Fig. 1. Time histories for the flare of 1991 October 30 in the S xv, Ca xix and Fe xxv spectral channels. 
a) total intensities – a constant background due to emission from elsewhere on the Sun has been subtracted from the S xv data. b) electron temperatures derived from fitting the individual spectra. 
Error bars show 1σ statistical errors. The Fe xxv value at 195409 UT is an upper limit.

Fig. 2. Time histories for the flare of 1991 November 19 in the S xv, Ca xix and Fe xxv spectral channels. 
a) total intensities, b) electron temperatures derived from fitting individual spectra.

tal effects and integrated for the required time intervals. The spectra have been analysed using spectral fitting programs written for the Yohkoh BCS and employing a method described by Lemen et al. (1984) and Fludra et al. (1989). The atomic data for Ca XIX and Fe XXV are from Bely-Dubau et al. (1982a, b) and are discussed by Lemen et al. (1984). The programs have also been extended to fit S XV spectra using atomic data for dielectronic satellites from J. Dubau (1992, private communication) and the ratios of the intercombination and forbidden lines to the resonance line from McCam and Keenan (1988). The effects of the numerous dielectronic and inner-shell excitation lines have been included, in order to estimate correctly the intensity of the resonance lines. The synthesized spectra are then convolved with the crystal rocking curve and a least squares fit is performed to adjust the electron temperature, emission measure and line widths in order to obtain the best agreement with the observed spectra. Also, a second spectral

3. Data Analysis

The BCS data are taken from the reformatted database (Morrison et al. 1991) and are corrected for instrumen-
component, representing plasma moving along the line of sight, has been applied in cases where there is evident asymmetry of line profiles, indicating plasma upflows. For such spectra, an average upflow velocity and emission measure of the moving component are also calculated. A detailed description of the data reduction and fitting techniques will be given elsewhere.

3.1. The Flare of 1991 October 30

The first sign of line broadening or upflows can be seen at 194821 UT, and at 194839 UT upflows with velocities above 300 km s\(^{-1}\) are observed. A substantial blue-wing appears at 194851 UT. Until this time the intensity rises slowly, but in the six seconds between 194857 UT and 194903 UT the intensity of the calcium spectrum increases by a factor two.

These spectra were analysed by representing line profiles as consisting of two components. We assume that the temperatures of the plasmas responsible for both components are the same. Typically, the main component represents the stationary plasma and the second component represents the moving plasma. However, a standard approach was to allow the position of both components to vary to obtain the best fit to the spectrum. Figure 3 shows a two-component theoretical spectrum fitted to the observed rise phase Ca XIX and Fe XXV spectrum at 194852 UT (integration time = 15 s). The position of the first component in the Ca XIX spectrum is shifted by about 2.5 to 3 detector bins relative to the decay phase rest position, which corresponds to upflow velocity of about 70 km s\(^{-1}\), and the second component has velocity of 230 km s\(^{-1}\) higher than the first component, i.e., 300 km s\(^{-1}\) with respect to the decay phase rest spectrum. There is no stationary component in this rise phase spectrum. The intensity ratio of the fast moving plasma to the slow moving plasma is 0.85. This intensity ratio in the three subsequent calcium spectra has the values of 0.48, 0.35, and 0.25, while the velocity difference between the two components stays around 230 km s\(^{-1}\).

Simultaneously with the upflows, the first spectral component emitted by the slowly moving plasma has a much larger than thermal width. The excess over the thermal width is expressed as a turbulent velocity (Fludra et al. 1989), although the nature of this broadening is open to interpretation. It represents a broadening of symmetric profiles, as expected in a plasma with isotropic turbulence, hence we use the term “turbulent velocity” for convenience. The excess width of the first component over the thermal width gives the value of the turbulent velocity of 130 km s\(^{-1}\) in the early rise phase spectra. However, a superposition of directed flows could under certain circumstances also lead to such broadening (Emslie and Alexander 1987).

The width of the second component is even larger (\(v_t = 200–250\) km s\(^{-1}\)). However, in this case we in-
interpret the broadening as due mainly to the superposition of a range of velocities. The spectral fitting method used indicates that a range of velocities from 0 to at least $2 \times v_{up}$ may be present where the derived average upflow velocity of the second component is equal to $v_{up}$. The presence of the velocity distribution is qualitatively in agreement with numerical models of flaring loops (e.g., Pallavicini et al. 1983). The above interpretation of the asymmetric profiles of Ca XIX lines indicates that all the plasma at 194852–194924 UT is moving upwards with large broadening of the low velocity component. It is not clear whether this broadening is caused by isotropic turbulence alone or by a superposition of different velocities. However, we are considering another way of decomposing the spectra, which assumes that there is a stationary component in the rise phase spectra with the turbulence at the same low level as in the decay phase. With this assumption, for the spectrum shown in figure 3a, at least two moving components with the same small widths as that of the stationary component are necessary to explain the shape of the blue wing of the resonance line. This alternative way of interpreting the data is being investigated.

The Yohkoh BCS also allows us to extend the analysis of flare spectra to lower temperatures by using the sulphur spectra. We have subtracted the pre-flare spectrum from two rise phase spectra recorded at 194852 UT and 194906 UT and have found that the sulphur spectrum at 194852 UT can be represented by a stationary component with the same position and width as in flare peak or in the decay phase, and the moving component with an average velocity of 120 km s$^{-1}$ and intensity of at least 1.5 of that of the stationary component. For the spectrum at 194906 UT the velocity of the second component is similar and the intensity ratio is 1.0. In addition, the shape of the blue wing of the S XV resonance line indicates a presence of upflows with line of sight velocities of about 400 km s$^{-1}$ and very low intensities.

The electron temperature derived from S XV, Ca XIX and Fe XXV spectra is shown in figure 1b. When fitting the spectra in each channel, we assume that the plasma detected by each channel is isothermal. If this assumption is true, the temperatures derived from all channels would be identical. The differences of 3–5 million K between these temperatures indicate that the plasma is multi-thermal with a broad distribution of emission measure as a function of temperature and our calculated values represent an average temperature weighted by the emissivity functions of the lines in each channel. The greatest temperature differences are during the rise phase and the difference decreases as the flare decays. However, due to the fact that sulphur spectra also have a contribution from a cooler plasma from other sources, the S XV temperature in figure 1b is underestimated during the beginning of the rise phase and in the decay. The dependence of line intensity ratios of sulphur, calcium and iron.
lines on electron temperature has also been discussed by Doschek et al. (1990, 1992).

The temperature in all channels increases or stays constant until 1950 UT. This period of energy release is accompanied by upflows. The profiles become narrower when the temperature starts decreasing, however, the emission measure increases for further 30 s which indicates continued upflows. The dependence of the upflow velocities on temperature is such that the upflow velocity increases with temperature in spectra recorded between 194852 and 194921 UT.

The time history of turbulent velocity $v_t$ derived from the width of the first component is typical: lines are broadest at the beginning of the rise phase, with $v_t \approx 130$ km s$^{-1}$, then the turbulent velocity decreases until the flare maximum and levels out. It has been a controversial point whether the line widths in the decay phase are purely thermal. The SMM and P78-1 data have always shown that the lines have been wider than their thermal widths (Doschek et al. 1980; Fludra et al. 1989), and this difference in SMM data remains even after subtracting the effect of the source size (Moorthy, private communication). Yohkoh BCS spectra also support the existence of non-thermal motions persisting in the decay phase. Unless the source size is much larger than $30''$ across in the North-South direction, the observed line widths in excess of the thermal width are most likely to be due to Doppler effects, explained by plasma turbulence or directed flows.

The decay of the 1991 October 30 flare was sufficiently fast to assume that the energy input ceased at about 1950 UT and that the flare underwent conductive and radiative cooling which caused the decrease of temperature. If we further assume that the flare occurred in a single loop, we can estimate the loop length by using the results of Serio et al. (1991), who investigated cooling of a loop from an initial static condition and calculated the rate of decay of the maximum temperature.

The Fe XXV temperature at 1950 UT is $20 \times 10^6$ K. Although there is a data gap during decay, we use the fact that a very faint Fe XXV spectrum is last seen at 195354 UT and no Fe XXV lines are seen in the next spectrum at 195409 UT and hence place an upper limit of $9 \times 10^6$ K on both the Fe XXV temperature and the maximum temperature at 195409 UT. Fitting an exponential function $\exp(-t/\tau)$ to the Fe XXV temperature we obtain the $1/e$ time scale of its decay, $\tau = 300$ s. Using this as an estimate of the decay time for the maximum temperature, from the numerical simulations of Serio et al. (1991) we derive an estimate of a loop semi-length of $L_s \approx 2.8 \times 10^9$ cm. Since the maximum temperature in the flare is greater than the temperature derived from Fe XXV spectra, the actual loop length is shorter. For example, if the maximum temperature were $30 \times 10^6$ K at 1950 UT, the estimated semi-length of the loop would be $L_s \approx 2.2 \times 10^9$ cm. The Soft X-ray Telescope image of this flare was not available to verify this.

### 3.2. The Flare of 1991 November 19

This flare was well observed by the BCS. The lightcurves and variation of electron temperature in all three channels are shown in figure 2. As in the 1991 October 30 flare, the plasma is multi-thermal, but differences between the S XV, Ca XIX and Fe XXV temperatures at the flare peak are smaller.

An image from the Yohkoh Soft X-ray Telescope which was made available to us shows that the flare probably occurred in a single loop, inclined at a significant angle to the line of sight; we estimated the loop length to be $4 \times 10^9$ cm. For this loop length, the expected decay time of the maximum temperature to its $1/e$ value, if the energy input ceased abruptly after the maximum, would be about 180–230 s (Serio et al. 1991).

The observed Fe XXV temperature decays at a much slower rate, starting from $18 \times 10^6$ K and staying above $14 \times 10^6$ K for 15 min. Qualitatively, this indicates that the energy input after the peak of this flare decreased gradually and heating continued at a lower rate sufficient to maintain the Fe XXV temperature above $14 \times 10^6$ K throughout the decay phase. The line intensities decreased mostly due to the decrease of the observed emission measure.

The line profiles in the rise phase show only a moderate asymmetry. We have analysed the spectra using our standard two-component fitting method described above. The Ca XIX spectrum with the largest asymmetry at 92730 UT has the ratio of moving to stationary plasma of 0.3 and the upflow velocity of 270 km s$^{-1}$. In the subsequent spectra this ratio is 0.22, 0.18 and 0.15. These small intensity ratios of moving to stationary plasma can be explained by the inclination of the loop relative to the line of sight, if the shifts are due to plasma motions along the loop.

The width of the stationary component exhibits a typical behaviour throughout the flare: the turbulent velocity reaches its maximum value of 150 km s$^{-1}$ early in the rise phase, then continues to decrease until the peak of emission measure and stays at a level of 75 km s$^{-1}$ through the whole decay.

### 4. Conclusions

We have shown examples of class C7.1 and C8.5 flares in which rise phase line profiles have variety of shapes: highly asymmetric characteristic of chromospheric evaporation and mostly symmetric with only moderate upflows. The two-component representation of rise phase profiles is only a convenient simplification. The large width of the moving component may result from a super-
position of components with a range of velocities. The width of the main component might also be a superposition of directed flows or it might be due to isotropic turbulence. This represents a fundamental problem in the way to interpret the existence of turbulence and the proportion of moving and stationary plasmas and is being investigated.

We have shown that electron temperatures calculated from the S XV, Ca XIX, and Fe XXV spectra indicate a broad multi-thermal distribution. The upflow velocities derived from simultaneously recorded S XV, Ca XIX, and Fe XXV spectra are larger for spectra emitted by hotter plasma.

In both flares the moving component is largest at the time when the electron temperature increases in the rise phase and the upflows significantly decrease simultaneously with the decrease of temperature. The relatively small upflows in the November 19 flare can be explained by the inclination of the flare loop relative to the line of sight.

The 1991 October 30 event had a fast decay of temperature, indicative of a fast decay of the energy input, and we used this to estimate a loop length from the rate of decay of the Fe XXV temperature. The energy input in the 1991 November 19 flare lasted at a slowly decreasing rate throughout the decay phase.

These events, together with other class C flares, will be analysed in more detail in a future paper.

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References


