Yohkoh Bragg Crystal Spectrometer Observations of the Dynamics and Temperature Behavior of a Soft X-Ray Flare

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Abstract

We describe X-ray spectra of an M1.5 flare that occurred on 1991 November 9, starting at about 0313 UT. This flare is unusual in that very intense blueshifted components are observed in the resonance lines of Fe XXV, Ca XIX, and S XV. During the onset of the flare, the resonance lines of Ca XIX and Fe XXV are primarily due to this blueshifted component, which from the Doppler effect indicates line-of-sight speeds and turbulent motions that in combination extend up to 800 km s^{-1}.

Key words: Sun: flares — Sun: X-rays — X-ray spectroscopy

1. Introduction

The source of the soft X-ray flare plasma, and the manner in which the electron density in coronal flux tubes increases during solar flares by several orders of magnitude over quiet coronal values, are important unresolved problems in solar flare physics. One explanation is ablation of heated chromospheric gas (evaporation is the more common term) into magnetic flux tubes (Neupert 1968). Suggested sources of the chromospheric heating are conduction fronts and/or energetic particles. Another explanation is that mass is driven into flux tubes by a magnetodynamic process called a “sweeping pinch” effect (Uchida and Shibata 1988). Other explanations for the soft X-ray flare plasma are that it is heated transition region plasma, which is already at a high density, or that it is coronal or transition region plasma that is compressed during a flare by a pinch mechanism (Feldman et al. 1980a; Doschek et al. 1986).

The dynamics of the soft X-ray flare can be studied by analyzing the profiles of X-ray spectral lines of highly ionized atoms. Numerical simulations of evaporation predict that the effect of evaporation will be largest on X-ray spectral lines at the very onset of flares (e.g., Mariska et al. 1989; Li et al. 1989). At this time spectral lines from disk flares should be blueshifted by velocities on the order of 300 km s^{-1}. However, as evaporation proceeds, the density in the flux tube increases and an intense stationary component is predicted to develop, which dominates the blueshifted component shortly after flare onset. Only at the very onset of flares, when line intensities are quite low, is the blueshifted plasma component expected to be the dominant feature of a spectral line.

Analyses of flare spectra obtained by previously flown Bragg crystal spectrometers did in fact reveal a blueshifted plasma component in many flares (e.g., Feldman et al. 1980b; Antonucci et al. 1982), but it was usually weak relative to the stationary spectral component. The centroids of the resonance lines of Ca XIX and Fe XXV were not Doppler shifted from their rest wavelengths in almost all cases, and, in the few cases where such shifts were reported, the velocities were about 100 km s^{-1}, which is smaller than predicted from chromospheric evaporation simulations. However, the X-ray spectrometers on previous solar flare missions did not have the necessary sensitivity to detect the evaporating plasma at times close to flare onset. Neither the cases for nor against evaporation are conclusive, and thus a controversy developed which is still not resolved (e.g., Doschek et al. 1986).

One of the scientific goals of Yohkoh is the investigation of the dynamics of soft X-ray flares at flare onset. For this purpose Yohkoh contains a four-channel Bragg crystal spectrometer (BCS), each channel of which has a sensitivity about an order of magnitude larger than the spectrometers flown on previous missions. The chan-
nels of the BCS cover narrow wavelength ranges centered on spectral lines of highly ionized sulfur (S XV, 5.0160–5.1143 Å), calcium (Ca xix, 3.1631–3.1912 Å), and iron (Fe xxv, 1.8298–1.8942 Å; Fe xxvi, 1.7636–1.8044 Å). The BCS instrument package is described in detail by Culhane et al. (1991).

In this paper we discuss a flare that exhibits intense blueshifted spectral components at flare onset. So far, only this event and one other flare, out of about 60 events examined, have been found with blueshifted components that are sufficiently intense to dominate clearly from eye inspection a stationary, or near-stationary, plasma component at times very close to flare onset.

2. The 1991 November 9 Flare

The flare we discuss occurred on 1991 November 9 at about 0313 UT, and is classed as M1.5 from Geostationary Operational Environmental Satellite (GOES) observations. The GOES X-ray light curves are typical of many flares and did not exhibit any obvious complexities. The rise time of the event is about 220 s. Ground based observations place the flare at N20, E08.

The time evolution of the total intensities in the Fe xxv, Ca xix, and S xv resonance lines (1s2 1S0–1s2p 1P1), observed by the BCS, along with sample spectra recorded at flare onset and near peak flux, are shown in figure 1. Each of the spectra in figure 1 is a sum of three spectra, in order to improve the signal to noise ratio. Each spectrum in a sum was recorded over a 3 s time interval. The onset spectra are considerably less intense than the peak flare spectra, and have been scaled in intensity by the factors indicated for display purposes.

The spectra in figure 1 show that the centroid of the resonance line of Ca xix is blueshifted by roughly 200 km s⁻¹ early in the flare compared to the centroid position in the peak emission spectrum, and is greatly Doppler broadened relative to the peak flare spectrum. At flare onset the S xv resonance line is highly asymmetric and wide and the Fe xxv resonance line is extremely broad. (Wavelength shifts due to spatial effects are much smaller than the Doppler shifts and will be discussed in a longer paper.)

We have deconvolved a moving plasma spectral component from an assumed stationary or slowly moving component using theoretical synthetic spectra. The individ-
Table 1. Plasma parameters.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Ion</th>
<th>$V$ (km s$^{-1}$)</th>
<th>$v_m$ (km s$^{-1}$)</th>
<th>$v_s$ (km s$^{-1}$)</th>
<th>$I_m/I_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>S XV</td>
<td>200</td>
<td>380</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>S XV</td>
<td>160</td>
<td>310</td>
<td>70</td>
<td>3.5</td>
</tr>
<tr>
<td>45</td>
<td>S XV</td>
<td>140</td>
<td>310</td>
<td>90</td>
<td>2.1</td>
</tr>
<tr>
<td>117</td>
<td>S XV</td>
<td>140</td>
<td>310</td>
<td>50</td>
<td>0.40</td>
</tr>
<tr>
<td>0</td>
<td>Ca XIX</td>
<td>270</td>
<td>330</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>Ca XIX</td>
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<td>280</td>
<td>110</td>
<td>6</td>
</tr>
<tr>
<td>45</td>
<td>Ca XIX</td>
<td>210</td>
<td>290</td>
<td>110</td>
<td>2.5</td>
</tr>
<tr>
<td>129</td>
<td>Ca XIX</td>
<td>200</td>
<td>270</td>
<td>90</td>
<td>1</td>
</tr>
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<td>Fe XXV</td>
<td>350</td>
<td>580</td>
<td>130</td>
<td>25</td>
</tr>
<tr>
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<td>Fe XXV</td>
<td>400</td>
<td>430</td>
<td>120</td>
<td>2.5</td>
</tr>
<tr>
<td>117</td>
<td>Fe XXV</td>
<td>210</td>
<td>380</td>
<td>120</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Notes: Times are given in seconds after 131308 UT. $V$ is the line-of-sight speed of the moving component, and $v_m$ is the most probable speed of the moving (stationary) component. $I_m/I_s$ is the intensity of the moving (stationary) component.

Ultraviolet lines were fit with Voigt functions with damping parameters determined by the crystal rocking curve widths. The synthetic spectra for Fe and Ca were generated using atomic data discussed in Lemen et al. (1984), and Bely-Dubau et al. (1982a,b).

The results of the spectral synthesis are given in table 1. Times are expressed in seconds after the first summed onset spectrum at 131308 UT. Inspection of table 1 shows that: (1) At flare onset almost all of the plasma is moving with average line-of-sight speeds ranging from 200 to 350 km s$^{-1}$. (2) A stationary component rapidly develops. (This component is called stationary, but motions on the order of 50 km s$^{-1}$ could exist for this component. These motions must be deconvolved from spatial effects, and will be considered in a longer paper.) Note the change in relative intensity of moving and stationary plasma in just 18 or 45 s. The stationary component is comparable in intensity to the moving component after about 2 min. (3) The nonthermal turbulent (most probable) motions of the moving component are substantially greater than the most probable motions characterizing the stationary component. These large motions reflect the extent of the blueshifted wing out to line-of-sight speeds of 800 km s$^{-1}$. (4) The moving component line-of-sight speeds and nonthermal motions for iron appear to be greater than for sulfur and calcium, implying that the speeds increase with temperature of line formation. We note that a really good synthetic fit could not be obtained for the iron spectra, implying that a single blueshifted component is a poor representation for the early iron spectra and that the isothermal assumption is not valid.

The Doppler shifts and turbulent speeds reported in table 1 are very large, although the Doppler shift speed of the moving component is comparable to values found previously (Antonucci et al. 1982). However, the Doppler shift of the entire profile centroid is larger than previously reported. In a few cases from previous missions, a Doppler shift of about 100 km s$^{-1}$ was observed for a line centroid (Antonucci et al. 1990; Watanabe 1990). Also, typical turbulent speeds reported for flare onset were about 160 km s$^{-1}$ (e.g., Doschek et al. 1986).

The large blueshifts seen in the early rise phase spectra are qualitatively consistent with evaporation models, but the nonthermal mass motions of the blueshifted component are very large. It is possible that the blueshifted component is not really symmetric at all times during a flare, i.e., perhaps the spectral broadening towards short wavelengths is due to the superposition of plasma ejected over a continuum of speeds between 0 and about 800 km s$^{-1}$. In this situation there would be no appreciable contribution of the blueshifted plasma to the red side of the stationary component. A similar suggestion has been made by Emmslie and Alexander (1987) in the context of an evaporation model.

Because of the higher sensitivity of BCS, we can measure spectra of highly ionized iron obtained closer to flare onset than was possible using high resolution spectra from previous missions. Inspection of all the iron spectra during the rise phase of this flare shows that the temperature of the plasma increases for 2 min after the first recorded spectrum, and then begins to decrease. The temperature decrease begins before peak flux in the Fe XXV line is achieved. This can be seen in figure 2, from the ratio of the Fe XXV to Ca XIX resonance lines, and from the Ca XIX to S XV resonance line ratios, which are increasing functions of temperature (Doschek et al. 1990). At the peak of the flare in Fe XXV emission, the Fe XXV temperature is about 20 x 10$^6$ K, as determined from the ratio of the dielectronic line j to the resonance line.
line w. (See Gabriel 1972 for details on temperature determinations using dielectronic satellite lines and for the widely adopted letter notation for the X-ray lines. Also, note that in these temperature estimates we are not distinguishing between blueshifted and stationary components, and therefore the results in figure 2 represent an average over the entire high temperature soft X-ray emitting flare region.)

Doschek et al. (1990) have investigated the line ratios shown in figure 2 for flares observed from P78-1 and SMM. From figure 8 in that paper, the $20 \times 10^6$ K peak temperature found from the Fe j/w ratio implies a temperature of about $17 \times 10^6$ K for the onset iron spectrum and for the spectra obtained at the end of the observations that have the same Fe XXV(w)/Ca XIX(w) ratio as the onset spectra. This prediction agrees with the j/w temperature derived from the decay phase spectrum. However, an interesting result is that the intensities of lines of lower iron ionization stages (e.g., Fe XXII) are greater relative to Fe XXV lines in the onset spectrum than in the decay phase spectra. This implies that the differential emission measure is different at flare onset than during flare decay.

It is very difficult to obtain an Fe XXV temperature for the early Fe spectra using a dielectronic to resonance line ratio, because of the large line broadening which blends the many individual Fe lines. The synthetic fits to the data imply a temperature of about $15 \times 10^6$ K, not far from the temperature obtained from the ratio of the Fe XXV to Ca XIX resonance lines. However, these fits are obtained by assuming an isothermal source and adjusting the ion abundances until a best fit is obtained. It turns out that the resulting ion abundances do not agree with the calculated ionization equilibrium abundances of Arnaud and Rothenflug (1985). (The possibility of transient ionization needs more investigation and is beyond the scope of this Letter.)

If instead we assume a multithermal source at onset, then a differential emission measure solution can be estimated from the iron lines. Assuming a power law distribution for the differential emission measure, a negative power law index of $-7$ with a high temperature cutoff of $18 \times 10^6$ K can fit the data about as well as the isothermal fits with variable ion abundances.

3. Summary

The BCS results for this flare are supportive of the idea that mass is injected into the corona by a process such as evaporation or a "sweeping pinch" effect. However, we have by now observed about 60 events with BCS covering longitudes from Sun center to the limb. Most of these events have an X-ray class of about M1. So far, only the November 9 event and one other event (1991 December 16, 0500 UT) show total bulk shifts of emission lines in excess of 100 km s$^{-1}$. It is important to point out that the November 9 event, while intrinsically interesting, appears to be exceptional in its dynamical signatures. Other events near Sun center show weaker blueshifted features, and a near-stationary component (< about 50 km s$^{-1}$) that appears comparable in intensity or stronger than the blueshifted component, even at flare
onset. This non-detection of completely blueshifted spectral lines in most events, many of them superficially quite similar to the November 9 event, cannot be an effect due to sensitivity.

Many of the flares we have observed show spectral signatures that do not appear to be consistent with the standard evaporation scenario, because of their weak blueshifted signatures. However, the results may be consistent with a “sweeping pinch” mechanism, if the mass driven into the flare loop or loops is cold until it is heated at the top of the loop. In this case the moving mass may not be observable in high temperature X-ray lines, or only part of it may reach temperatures high enough to be observable. In addition, it appears possible that in situ plasma heating, such as might be produced by compression, may play an important role in these events. The energy transport problem in flares is evidently more complicated than assumed by standard models.

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References


