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Broadening of soft X-ray lines during the impulsive phase of solar flares: Random or directed mass motions?

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Summary. We present spectroscopic data for three flares obtained with the Bent Crystal Spectrometer flown in the Solar Maximum Mission in 1980. This data is concerned with the structure of the Ca XIX resonance line at 3.176 Å during the impulsive phase of flares. On the basis of high time resolution (6 s.) data, we suggest that the previous published results concerned with the excess broadening of the resonance line being due to bulk random mass motions may give an over-simplified picture. Instead we suggest that during this stage of the flare, the resonance line consists of many discrete features, which we interpret as mass flows.

Key words: solar flares – soft X-ray emission – directed mass motion – electron beams

1. Introduction

The solar flare is a complex phenomenon, but it has now become usual to crudely refer to it as a two stage process; the impulsive phase which is characterised by a rapid time structure best observed in hard X-rays ($E > 20$ keV) and the more gradual thermal phase best observed in soft X-rays ($E < 10$ keV). The relationship between these two phases is clearly crucial to our understanding of the flare process, thus the simultaneity of data from these different energy bands is of obvious importance. As a result of spectroscopic data obtained from instruments on three different satellites, the Bent Crystal Spectrometer (BCS) on the Solar Maximum Mission, the Solflex Spectrometer on P 78-1, and the Soft X-ray Spectrometers on Hinotori, soft X-ray observations of the impulsive phase have substantially increased in recent years. With this high temporal and spectral resolution data, our understanding of the flare phenomena has seen substantial advances. In particular, the observations of the He-like ions Ca XIX and Fe XXV have shown a wealth of different phenomena, e.g. line shifts of 80 km s^{-1} for the principal soft X-ray source (Antonucci et al., 1985), the existence of a blue-shifted component in the main Ca XIX and Fe XXV resonance lines and substantial broadening of the resonance lines themselves (Doschek et al., 1980; Feldman et al., 1980; Tanaka et al., 1982; Strong et al., 1984; Antonucci et al., 1982, 1985). These mass upflows have been interpreted in terms of chromospheric evaporation, a process which can explain the appearance of a hot 10^7 K plasma in the corona during the flare (Antiochos and Sturrock, 1978). The broadening of the lines in excess of their thermal widths has been interpreted in terms of random mass motions, with velocities in the range 50 to 200 km s^{-1}.

Here, we discuss the soft X-ray spectra data taken during the impulsive phase of three different flares. For these three events, previous analyses have shown the existence of mass upflows of several hundred kilometers per second and substantial broadening of the main Ca XIX resonance line during the first few minutes of the flare. In the work reported here we look again at these spectra, but with a shorter integration time than used previously. Section 2 contains a brief discussion of the observational data and our method of reduction, while in Sect. 3 we discuss and compare our results with those published previously.

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2. Observational data and reduction

The three flares discussed here were all observed by the BCS instrument (and other instruments) onboard SMM in 1980; 21 May, 31 August and 1 November. The Ca XIX BCS data for all of these events have been analysed previously. For the first two of these events, substantial broadening of the resonance line was reported. Here, we consider only the Ca XIX data, paying particular attention to the spectral region around the resonance line. In the previous analysis, large integration times were used to accumulate the data during the impulsive phase. Although the BCS is capable of a time resolution of 128 ms, this has never been used because the sensitivity of the instrument was not sufficiently high. In this analysis we consider integration times of 6 seconds, but because of the poor statistics, we applied a running-mean smoothing technique, using a Gaussian filter of 2 bins (i.e. 0.6 mÅ), for each spectra. The spectrometer bin spacing of 0.301 mÅ was preserved (see Acton et al., 1980 for a discussion of the instrument parameters). Below we briefly outline a few details on each of the above events, however for a full discussion see the references quoted.

2.1. *May 21*

This event was a 2B/X1 two-ribbon flare which occurred in AR 2456 at S 13 W 15. A filament was observed to break-up at 20:50 UT, and started to rise at 20:52 UT. By 20:54:50 UT, Hα kernels were first observed. The hard X-ray emission, normally considered an indicator of the impulsive phase of the flare was also observed to begin to increase at around this time, reaching maximum at 20:56 UT. The rise time of the flare in Ca XIX was some 12 minutes, while the decay time was approximately 50 minutes. The blue-shifted component observed in Ca XIX indicated material moving at 370 km s^{-1} in the impulsive phase, while the broadening of the line indicated a turbulent velocity as high as 220 km s^{-1}. See Hoyng et al. (1981), Duijveman et al. (1982) and Antonucci et al. (1985) for further details of this complex event.

2.2. August 31

This flare occurred in AR 2646 and was discussed in detail by Strong et al. (1984). It consisted of two separated bursts in a compact loop, the first started at 12:48 UT and the second at 12:51 UT. There was a large variation in the relative peak intensities of the two events, e.g. in the first event the hard X-ray emission was a factor of two more intense while in the soft X-rays the second event was more intense in Fe XXV by a factor of 8. Line shifts of 60 km s^{-1} and zero were indicated for the first and second flare, with Doppler widths of 200 km s^{-1} and 100 km s^{-1} respectively.

2.3. November 1

This flare was classified as a 1B/M1 two ribbon event which began at approximately 19:15 UT in AR 2776 (N 17, E 64). Discussion on the morphology and energetics can be found in Tandberg-Hanssen et al. (1984) and Doyle (1985). The overall magnetic structure of this flare was that of a fairly simple, closed bipolar loop, with perhaps significant substructure. In hard X-rays the flare consisted of two spikes of emission. These two hard X-ray bursts are thought to have occurred within different subsets of field lines within the loop. Mass upflows with a mean velocity ranging from 80 to 250 km s^{-1} was observed. Little or no evidence was found for broadening of the Ca XIX resonance in excess of its thermal width.

3. Results and discussion

In Figs. 1, 2 and 3, a time series of the spectral region close to the Ca XIX resonance line is shown. It is clear that substantial variations in the line profile are occurring on a time scale of seconds, although the statistics are poor. Evaluation of the statistical uncertainties of the features in Figs. 1 to 3 is rather difficult, as most of them have only a peak count of 3 to 5 during the first few seconds of the flare. However, looking at, for instance Fig. 1, we see the same feature at bin ~205 repeating in three different spectra from 20:55:08 UT to 20:55:23 UT. Furthermore, the three largest features at 20:55:22 UT have 3 bins contributing in its un-smoothed state with a separation of 3 bins between each

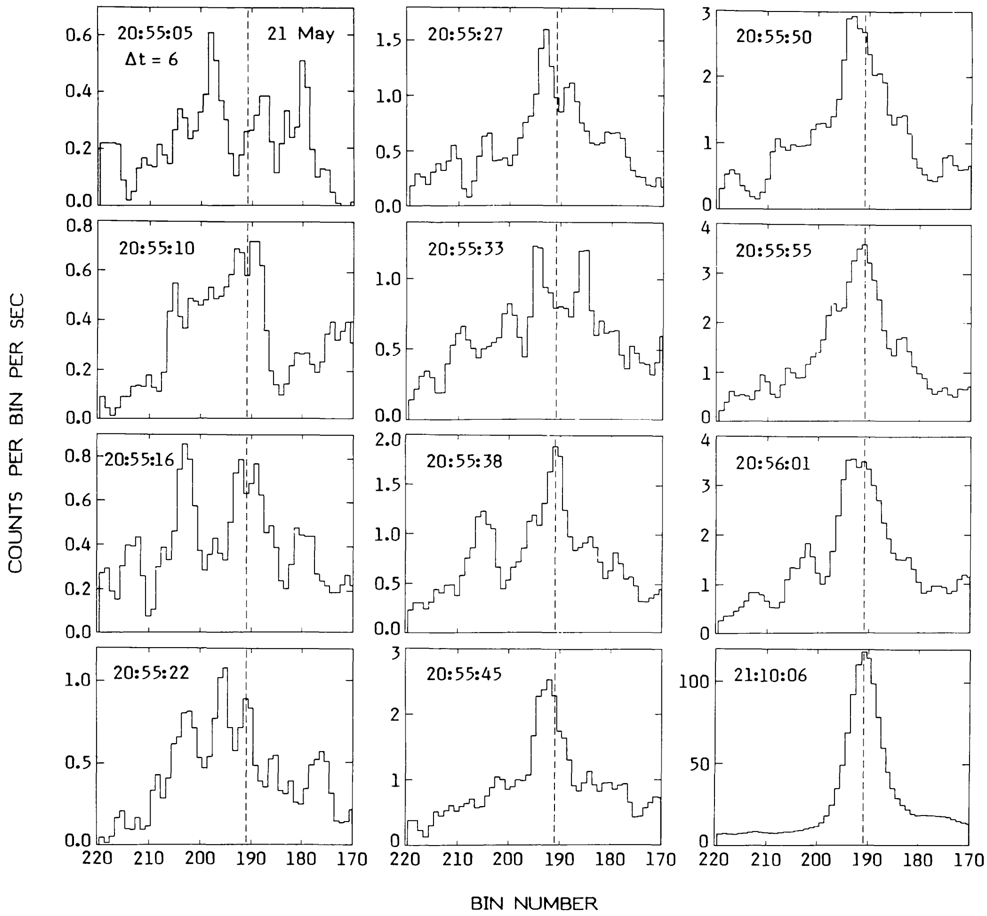

Fig. 1. A time series of the spectral region around the Ca XIX resonance line during the impulsive phase of the 21 May 1980 flare. The spectra during the impulsive phase were integrated over 6 seconds, for comparison we also show on the bottom right-hand corner a spectra taken during the decay phase (integrated over 11 seconds). The mean time of each spectra is given in the top left-hand corner. The vertical line (– – –) indicates the central wavelength of the resonance line as measured in the decay phase

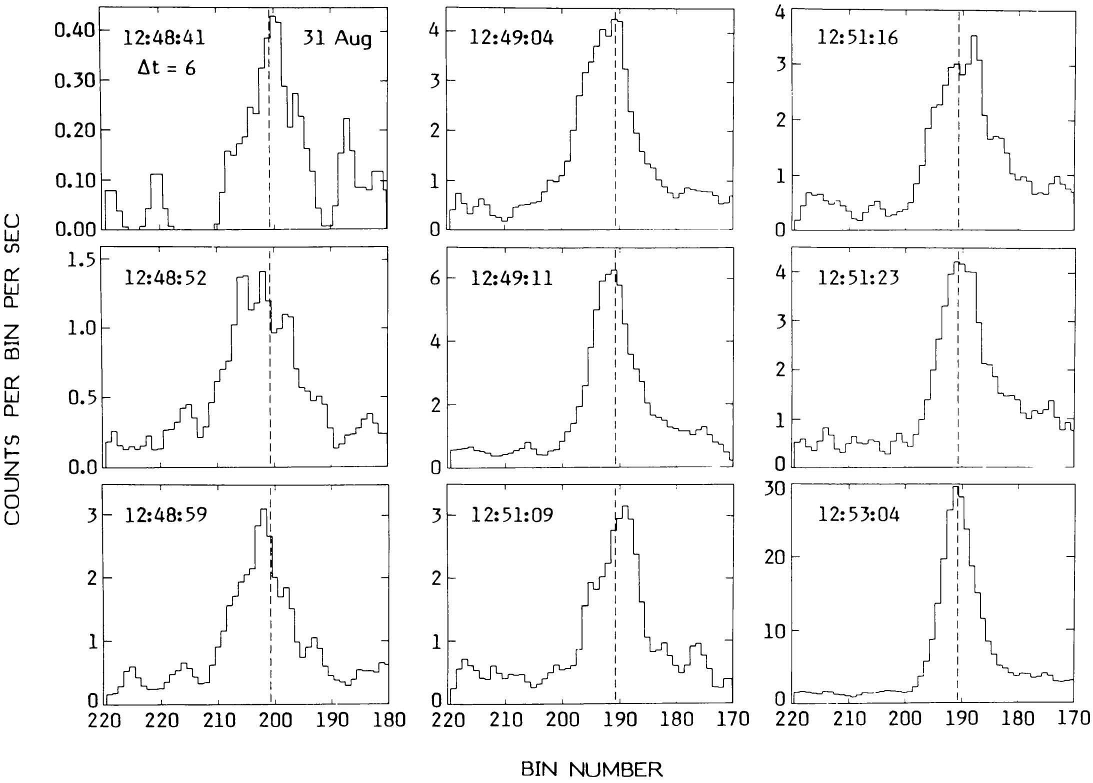

Fig. 2. Same as Fig. 1 except for the 31 August 1980 flare

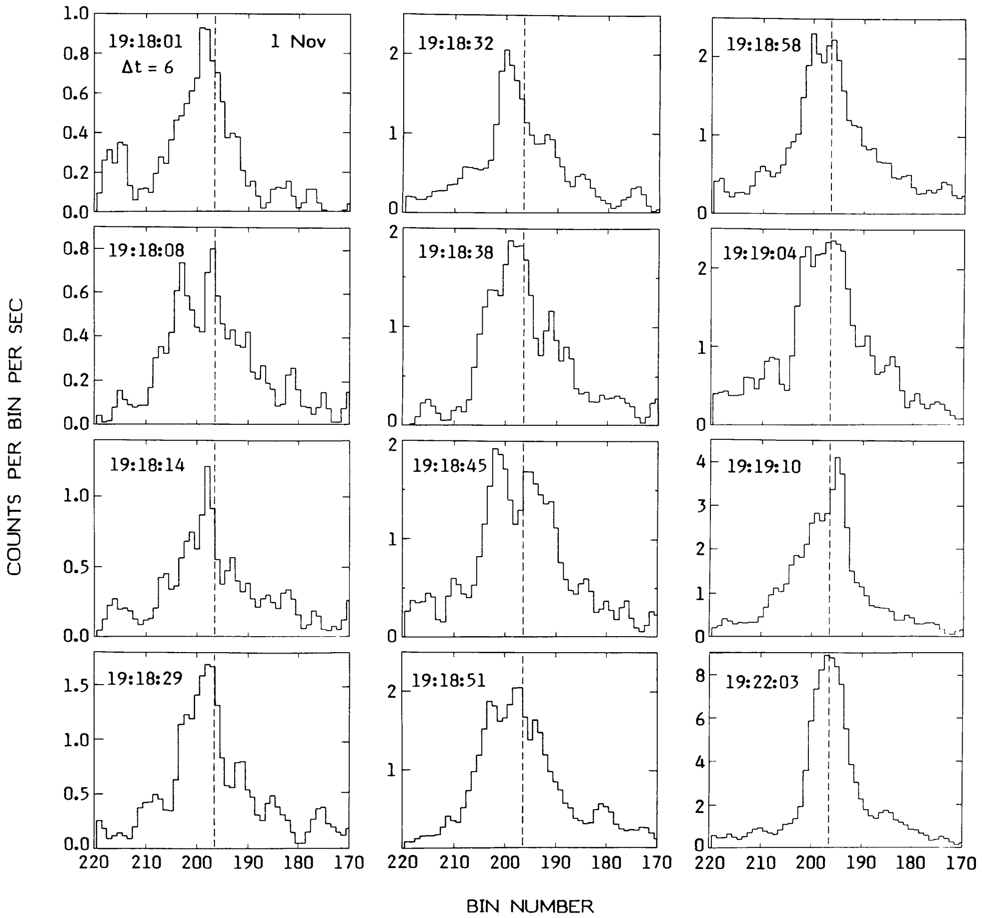

Fig. 3. Same as Fig. 1 except for the 1 November 1980 flare

of the features. Hence, features such as these are highly significant, although positive confirmation of just how much structure is present in these high temperature lines during the impulsive phase of flares must await an instrument with a much high sensitivity.

In previous analyses, much larger integration times were used, e.g. in Fig. 4 we show a plot of the spectra for the 21 May flare from 20:55:10 to 20:55:43 UT, i.e. over a 34 second interval. In this figure we see only two profiles, the main resonance line and a blue-shifted component moving at 320 km s^{-1}. We may calculate the thermal full width at half maximum (FWHM) of the Ca XIX resonance line in Angstroms from

$$\mathrm{FWHM} = [4(\ln 2)(\lambda(\text{Å})/c)^2[2\,kT/M] + \delta\lambda(\text{Å})^2_{\mathrm{sp}}]^{1/2}$$

where λ is the rest wavelength in Angstroms, c the velocity of light, M the atomic mass and $\delta\lambda_{\mathrm{sp}}$ the contribution to the line broadening from the spatial extent of the plasma. During this phase of the 21 May flare, the electron temperature is of the order of 10^7 K (Antonucci et al., 1985), and assuming the spatial extent of the source (i.e. the size of the kernels) to be less than 30″, we derive a thermal width of approximately 1.1 mÅ (i.e. 4 bin widths as measured by the BCS instrument). However, in Fig. 4 the FWHM of the resonance line is substantially greater than 1.1 mA. If this excess broadening is interpreted in terms of random mass motions, it would imply a mean velocity of 175 km s^{-1}. In Fig. 1, however, the width of the resonance line is very close to the thermal value (i.e. 1.1 mÅ), implying that mass motions during the impulsive phase of flares may be mostly directed rather than random. A similar argument may be made for the other two flares (Figs. 2 and 3).

This result is in direct contradiction with the published results for these flares and similar results obtained by other authors for different flares, e.g. Doschek et al. (1980), Feldman et al. (1980) and Tanaka et al. (1982), since these authors reported large turbulent velocities, plus a single blue-shifted component. However, from our analysis we find that the inferred Ca XIX resonance line profile comprises of several discrete components of varying velocities with essentially little or no evidence for random mass motion (turbulent velocities). The mass upflow velocities given previously for these and other flares are therefore only an averaged mean value and do not represent the rather complex and widely ranging mass upflows (and perhaps downflow) velocities which are present during the impulsive phase of flares. The hard X-ray light-curve of the typical flare usually shows a lot of fast time-structure. This hard X-ray emission may be interpreted in terms of energetic beams of electrons colliding with the chromosphere, as has been suggested by several authors (e.g. Strong et al., 1984; Doyle et al., 1985 and Antonucci et al., 1985). Then the observed Ca XIX resonance line profile would be expected to show a wide range of different components, if these are interpreted in terms of chromospheric evaporation, caused by the impact of the electron beams.

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References

Acton, L.W., Culhane, J.L., Gabriel, A.H., Bentley, R.D., Bowles, J.A., Firth, J.G., Finch, M.L., Gilbreth, C.W., Guttridge, P., Hayes, R.A., Joki, E.G., Jones, B.B., Kent, B.J., Leibacher, J.W., Nobles, R.A., Patrick, T.J., Phillips, K.J.H., Rapley, C.G., Sheather, P.H., Sherman, J.C., Stark, J.P., Springer, L.A., Turner, R.F., Wolfson, C.J.: *Solar Phys.* **65**, 53

Antiochos, S.K., Sturrock, P.A.: 1978, *Astrophys. J.* **220**, 1137

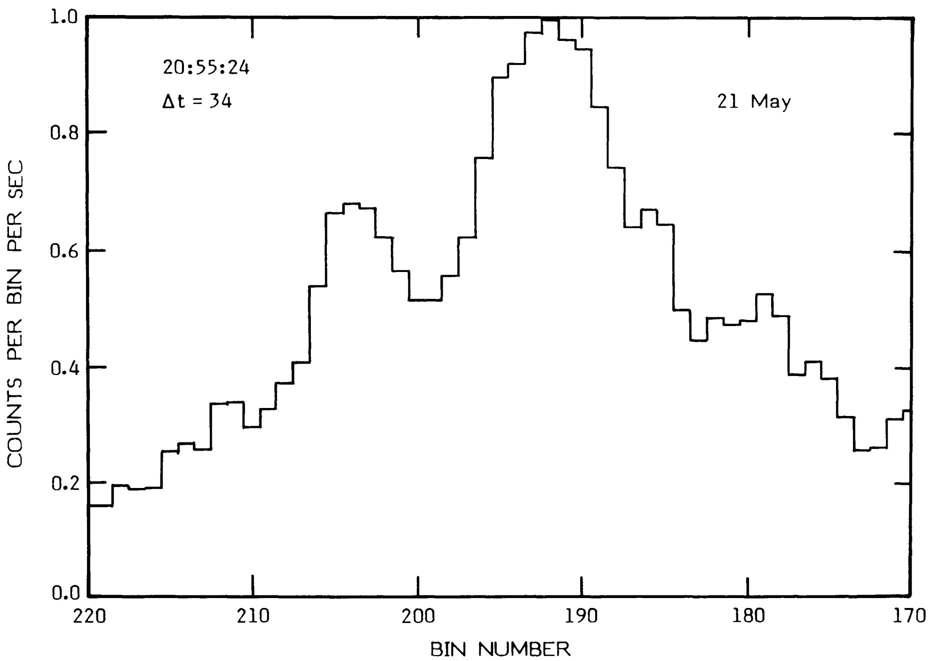

Fig. 4. The Ca XIX spectral region for the 21 May flare integrated over a 34 second interval during the impulsive phase showing a broadened main resonance line implying a turbulent velocity of 175 km s^{-1} and a blue-shifted component with a velocity of 320 km s^{-1}

Antonucci, E., Gabriel, A.H., Acton, L.W., Culhane, J.L., Doyle, J.G., Leibacher, J.W., Machado, M.E., Orwig, L.E., Rapley, C.G.: 1982, *Solar Phys.* **78**, 107
Antonucci, E., Dennis, B.R., Gabriel, A.H.: 1985, *Astrophys. J.* **287**, 917
Doschek, G.A., Feldman, U., Kreplin, R.W., Cohen, L.: 1980, *Astrophys. J.* **239**, 725
Doyle, J.G., Byrne, P.B., Dennis, B.R., Emslie, A.G., Poland, A.L., Simnett, G.M.: 1985, *Solar Phys.* (in press)
Doyle, J.G.: 1985, (in preparation).
Duijveman, A., Hoyng, P., Machado, M.E.: 1982, *Solar Phys.* **81**, 137
Hoyng, P., Duijveman, A., Machado, M.E., Rust, D.M., Svetska, Z., Boelee, A., de Jager, C., Frost, K.J., Lafleur, H., Simnett, G.M., vav Beek, H.F., Woodgate, B.E.: 1981, *Astrophys. J.* **246**, L155
Feldman, U., Doschek, G.A., Kreplin, R.W., Mariska, J.T.: 1980, *Astrophys. J.* **241**, 1175
Strong, K.T., Benz, A.O., Dennis, B.R., Leibacher, J.W., Mewe, R., Poland, A.L. Schrijver, J., Simnett, G.M., Smith, J.B. Jr., Sylwester, J.: 1984, *Solar Phys.* **91**, 325
Tanaka, K., Watanabe, T., Nishi, K., Akita, K.: 1982, *Astrophys. J.* **254**, L59
Tandberg-Hanssen, E., Kaufmann, P., Reichmann, E.J., Teuber, D.L., Moore, R.L., Orwig, L.E., Zirin, H.: 1984, *Solar Phys.* **90**, 41