THERMAL AND NONTHERMAL ENERGIZATIONS IN SOLAR FLARES: SOFT X-RAY SPECTROSCOPIC AND HARD X-RAY OBSERVATIONS

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Abstract

We have analyzed, using a moment method, the Ca XIX and Fe XXV spectra for 64 flares observed from BCS/Yohkoh together with simultaneous observations in hard X-ray to determine the physical relationship between the thermal and nonthermal energization processes. The results show that preflare heating, which produces the observed pre-impulsive blue-shifts in the Ca XIX and Fe XXV lines, is needed for the nonthermal acceleration of electrons during the impulsive phase.

1. Introduction

Central the understanding the physics of solar flares is the question of the relationship between the thermal and nonthermal energizaitons as manifested in soft and hard X-ray emissions. Previous soft X-ray spectroscopic observations using Bragg Crystal Spectrometer (BCS) on board P78-1, SMM, and Hinotori have shown that blue wings and blue-shifted components often exist in the Ca XIX and Fe XXV lines during the rise phase of flares (cf. Feldman et al. 1980, Antonucci et al. 1982, Tanaka 1987). Because of the low sensitivity of the previous BCS instruments, soft X-ray spectra were not recorded earlier in the pre-impulsive phase, and the precise temporal relationship between the blue-shifted X-ray lines and the impulsive hard X-ray (HXR) emission remains largely unclear. In an attempt to sorting out this relationship, we have analyzed the Ca XIX and Fe XXV spectra of 64 flares obtained from the BCS/Yohkoh. together with simultaneous hard X-ray observations from either BATSE/GRO or HXT/Yohkoh. The BCS/Yohkoh is about an order of magnitude more sensitive than those flown on earlier missions and is, therefore, able to observe the pre-impulsive phase on many flares. A detailed description of the instrument has been given by Culhane et al. (1991). In this paper, we present the results of a time comparison between the BCS spectra and the corresponding HXR emission, with particular emphases on the pre-impulsive phase.

2. Analysis of BCS Spectra by Moment Method

Sufficiently intense spectra of the resonance lines Ca XIX ($\approx 3.17\AA$) and Fe XXV ($\approx 1.85\AA$) in the earlier phase of many flares were taken with a time cadence of 3 sec by BCS/Yohkoh. Since the spectra are generally not Gaussian, a proper decomposition of the observed spectra requires elaborate spectral fitting in order to derive the physical parameters that characterize the constituting plasmas, such as the temperature, [EM], line shift, and line broadening (cf. Antonucci, 1989). While such a program is useful for a detailed look for a particular event, it is impractical for a large amount of spectra for many flares. In this paper, we have applied the moment method to deduce the dynamic properties of the flaring plasmas. The moment method has been previously applied to the analysis UV observations from OSO 8 and SMM (White and Athay 1978, Cheng et al. 1982). The first moment, $\sum(\lambda_i - \lambda_0)I_i/\sum I_i$, give the averaged line shift relative to a chosen standard wavelength at λ_0. The second moment, $\sum(\lambda_i - \lambda_0)^2 I_i/\sum I_i$, gives the equivalent width of the line. We have chosen the reference wavelength as that of the central line wavelength of the spectra taken at late decay phase. Therefore, the mass motion velocity derived from the first moment is relative to the decay phase, when the spectra are observed to be "stationary" with negligible blue wing. This kind of a "poor man's" spectral fitting is particularly useful to study the temporal evolution of flare dynamics.

Since the first moment is a mean wavelength shift weighted by the intensity, the derived mass motion velocity is dominated by plasmas with small line shifts near the "rest wavelength", which have generally higher intensity than those in the far blue wing. Thus, higher velocity components in the far blue wing contribute negligibly to the averaged mass motion. For our studies, the largest mean mass motion velocity derived from the moment method is around 100 km s^{-1}, indicating the dominating contribution from slow moving plasmas. Another way of investigating the mass motion in flares, particularly the higher velocity components (~300-600 km s^{-1}), is to plot the intensity of selected wavelength interval in the far blue wing as a function of time and compare it with the corresponding HXR emission (Bentley et al. 1993). These two ways of looking at the observed Ca XIX and Fe XXV spectra reveal different aspects of the mass motion in flares and the results compliment with each other.

3. Observational Results form BCS/Yohkoh

We have calculated the line shift and line width as function of time for 64 flares, using the moment method. All these flares are disk flares located less than 50^0 within the disk center. Figure 1 shows the time change of the mass motion as derived from the Ca XIX resonance line and compares it with the corresponding hard X-ray emission for the 22 April 1993 flare. The figure shows that at some 3 min before the onset of the hard X-ray emission, there is already an upflow of $\sim$ 100 - 150 km s^-1. When the HXR starts, the upflow increases somewhat and then decreases before the HXR and BCS light curves reach their peak. In Figure 2, we compare the Ca XIX line profiles taken at different times during the flare. We see that the line profiles taken before and during the impulsive phase are blue-shifted relative to that in the late decay phase, just as that shown in Figure 1. This is also true for the Fe XXV profiles.

Figure 3 (upper panel) shows the behavior of the mass motion velocity in the 21 August 1992 flare. We see that there is noticeable upflow ($\approx$ 30 km s^-1) a few minutes before the onset of the hard X-ray burst. Comparison of the line profiles show that both the CA XIX and Fe XXV line profiles are blue shifted before and during the impulsive phase. Another example of upflow observed before the onset of the impulsive hard X-ray burst is the 30 September 1992 flare (lower panel, Figure 3). Again, we see that the upflow starts before the impulsive hard X-ray burst.

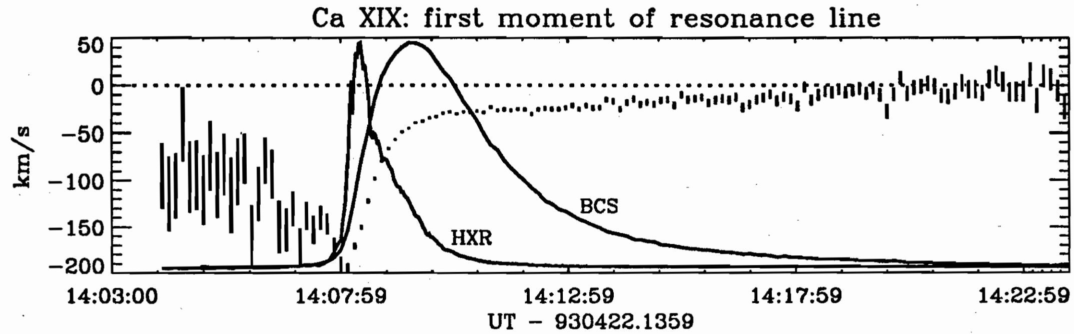

Fig. 1. Mass motion velocity derived from Ca XIX for the 22 April 1993 flare. Negative values represents upward motion. Length of the vertical line gives the uncertainty in the calculated mass motion velocity. HXR (15-24 keV) is from HXT/Yohkoh.

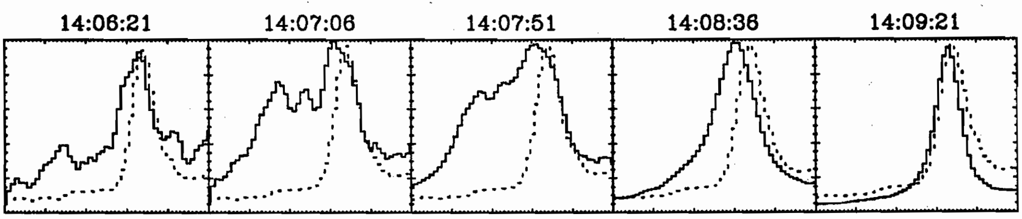

Fig. 2. Normalized Ca XIX line profiles for the 22 April 1993 flares. The dotted profile is at 1419:06 UT, late in the decay phase. Horizontal axis is in wavelength scale.

Out of 64 flares we studied, 47 show blue shifts in the Ca XIX and Fe XXV line profiles, 11 show shifts that are due to spatial effect, 1 shows possible red shift, and 5 show no shift or are multiple flares whose spectra are complex. For the 47 flares that show blue shifts, we find the following results: 1) All upflow starts before or at the same time as the onset of the HXR. 2) For majority of the flares, the blue shift peak occurs before the HXR peak. 3) There is no correlation between the Ca XIX/Fe XXV blue shifts and the HXR intensity. 4) There is no correlation between the line width and the HXR intensity.

4. Discussion

Above, we see that, except for a few flares that are multiple or due to spatial effect, almost all flares show some blue shift during the impulsive phase. In particular, there are many flares that show detectable upflow before the onset of the impulsive hard X-ray burst. This and that the mean blue shift (upflow) for majority of flares reaches its maximum value before the hard X-ray peak indicate that there is thermal heating before the nonthermal acceleration of the electrons. Indeed, SMM observations in X-ray (3.5-8 keV) and in the UV line of Fe XXI ($T \approx 10^7$ K) have shown that, for many flares, there is a low level intensity enhancement before the impulsive phases (Machado et al. 1982, Poland et al. 1982, Cheng et al. 1985). Such a pre-impulsive heating likely will generate an upflow as that observed in the Ca XIX and Fe XXV lines. Our results of a mean upflow observed before the impulsive phase with a magnitude of about 100 km s^-1 can be compared with that obtained by Bentley et al. (1993). As mentioned above, their results pertain to the high velocity components ($\sim$ 300–600 km s^-1) of the mass motion. A physically plausible flare energization process that incorporates both results can be stated as follows. Due to current heating or other heating mechanisms, the temperature in the pre-flare plasma is increased to around 1-2$\times 10^7$ K. This thermal heating not only produces an upward mass motion as that observed, but also provides a seed population of electrons with higher energies, which are accelerated later at the onset of the impulsive phase. Indeed, for a

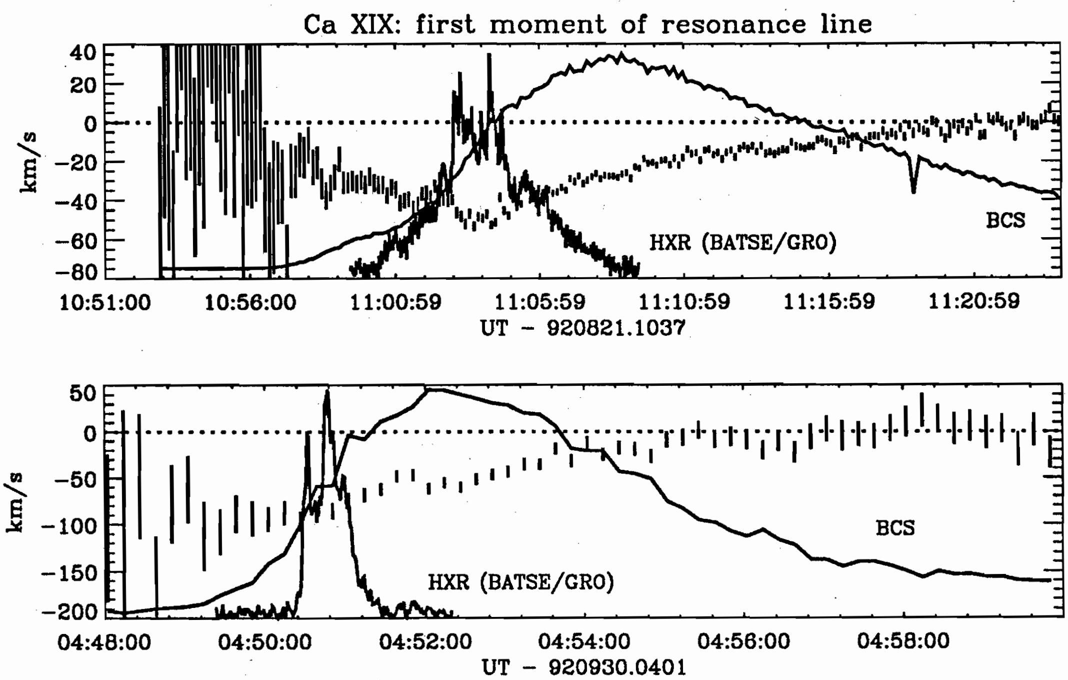

Fig. 3. Mass motion derived from Ca XIX line profiles for the 21 August 1992 flare (upper panel) and the 30 September 1992 flare (lower panel). HXR (25-50 keV) is from BATSE/GRO.

stochastic type particle acceleration mechanism, such as the Fermi mechanism, only particles whose energies exceed a certain threshold are efficiently accelerated; the pre-impulsive heating naturally provides such electrons with sufficient energies to be accelerated further, When the electrons are accelerated to nonthermal energies at the onset of the impulsive phase, they not only produce hard X-ray emission, they also heat the chromospheric plasma to such a extent as to produce large velocity upflows as that observed by Bentley et al. (1993). Further investigation of the per-impulsive phase, especially the evolution of the magnetic structures in the pre-flare active region, is needed to better determine the physical conditions that are favorable to the occurrence of flares.

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