OBSERVATION OF CHROMOSPHERIC EVAPORATION DURING THE SOLAR MAXIMUM MISSION

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ABSTRACT. A sample of flares detected in 1980 with the Bent Crystal Spectrometer and the Hard X-Ray Burst Spectrometer on the Solar Maximum Mission satellite has been analysed to study the upward motions of part of the soft X-ray emitting plasma. These motions are inferred from the presence of secondary blue-shifted lines in the Ca XIX and Fe XXV spectral regions during the impulsive phase of disk flares. Limb flares do not show such blue-shifted lines indicating that the direction of the plasma motion is mainly radial and outward. The temporal association of these upward motions with the rise of the thermal phase and with the impulsive hard X-ray burst, as well as considerations of the plasma energetics, favour the interpretation of this phenomenon in terms of chromospheric evaporation. The two measureable parameters of the evaporating plasma, emission measure and velocity, depend on parameters related to the energy deposition and to the thermal phase. The evaporation velocity is found to be correlated with the spectral index of the hard X-ray flux and with the rise time of the thermal emission measure of the coronal plasma. The emission measure of the rising plasma is found to be correlated with the total energy deposited by the fast electrons in the chromosphere by collisions during the impulsive phase and with the maximum emission measure of the coronal plasma.

1. Introduction

The Soft X-Ray Polychromator observations during the Solar Maximum Mission (SMM) have shown a systematic presence of upward moving, high temperature plasma in the corona during the impulsive phase of many flares (Antonucci et al., 1982; Antonucci, 1982). Part of the plasma at a temperature exceeding 10^7 K rises in the solar atmosphere at a velocity of the order of 400 km/sec or less at flare onset. This plasma flow presumably results from the chromospheric evaporation process, which was proposed to explain the appearance of large amounts of hot plasma in the corona during flares (Neupert, 1968; Hudson, 1973; Sturrock, 1972). In fact,

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evidence for rising hot plasma is observed from the beginning of the impulsive phase until the peak of the thermal phase. The rate of increase of the fractional emission measure of the thermal coronal plasma is found to be proportional to the velocity of the upward motion. For a few flares whose characteristics can be more accurately determined, the energy and mass transferred by the upward moving plasma are sufficient to account for all of the thermal coronal plasma at the peak of the gradual phase on the assumption of magnetic confinement of the rising plasma. The observations suggest that chromospheric evaporation is a common occurrence in X and M class flares.

The soft X-ray data for this analysis were obtained with the Bent Crystal Spectrometer (BCS) on SMM in the spectral regions containing atomic lines of Ca XIX (3.165 - 3.266 Å) and Fe XXV (1.843 - 1.896 Å) in the period from March to November 1980. The BCS integrates the soft X-ray emission over the whole flaring region, but it was the first spectrometer to measure X-ray spectra simultaneously in various wavelength regions with a time resolution of 1 to 6 seconds (Acton et al., 1980). Hence, it was the first instrument capable of studying the rapidly changing dynamic conditions of the soft X-ray plasma during the impulsive phase of flares. For this paper, we have considered the 36 largest flares detected by BCS, all of which were class M or X. Only results from the calcium spectral region will be reported although similar results are obtained by analysing other high temperature emission lines.

The hard X-ray data were obtained with the Hard X-Ray Burst Spectrometer (HXRBS, Orwig et al., 1980) also on SMM. Power-law fits to the 15 channel spectra measured every 0.128s were obtained for all 36 flares studied. The hard X-rays are assumed to be produced in thick-target interactions as the fast electrons deposit their energy in the chromosphere. This hypothesis is supported by correlations found between the hard X-ray spectral index and the upward velocity of the evaporating plasma, and between the total energy deposited by the electrons and the maximum emission measure of the hot coronal plasma.

2. Role of Mass Flows in the Development of the Thermal Phase of Flares

A typical spectrum obtained with the BCS in the Ca XIX region during the impulsive phase of a disk flare is shown in Figure 1. This is an observation at $03^h05^m04^s$ UT of a class M4 flare on April 8, 1980. The data are averaged over 27 seconds. This spectrum shows a secondary component which is blue-shifted and reduced in intensity with respect to the principal component. The best fit to the data, shown as a continuous line in the upper part of the figure, is obtained by superposing two syn-

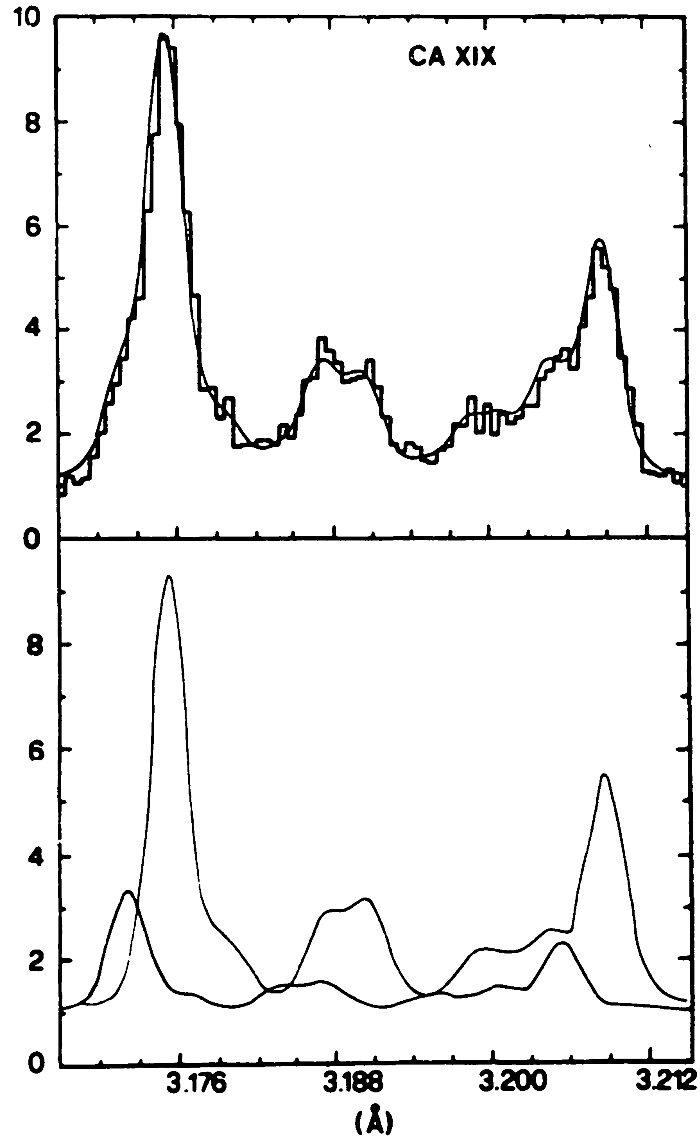

Figure 1. Ca XIX spectrum during the April 8, 1980 flare at $03^h05^m04^s$ UT. The intensity is expressed in counts/sec and has been averaged over a period of 27 seconds.

thesised spectra computed for the same set of physical parameters. These two spectra are shown in the lower part of the figure. The secondary spectrum is shifted by 3mÅ towards shorter wavelengths and its intensity is a factor of 0.17 lower than that of the principal spectrum. The method for computing these synthesised spectra is described by Antonucci et al. (1980). Both spectra are computed for a plasma electron temperature of 1.4×10^7 K and a Doppler temperature of 5.6×10^7 K. The additional parameters determining the emission line intensities are the population ratio of the Li-like to He-like ions, taken to be 0.2, and the ratio of the H-like to the He-like ions, taken to be 0.08. This spectral analysis indicates that 17% of the plasma at 1.4×10^7K moves upward with a velocity of 310 km/sec. In addition, the high non-thermal broadening of the emission lines of the principal spectrum, which is also a characteristic of the early phase of flares (Doschek _et al._, 1980; Antonucci _et al._, 1982), is likely to be due to turbulent motions in the coronal plasma at 130 km/sec.

The belief that the plasma motions are systematically upward is supported by the absence of blue-shifted secondary spectra in all of the flares occurring at longitudes exceeding 60°, while blue-shifted spectra are detected in 90% of all disk flares. As a consequence of this difference between limb flares and disk flares, the upward velocity derived from the observed blue-shift must be corrected for the longitude of the flare site.

According to the above results, the soft X-ray plasma at the flare onset consists of two basic components, a dynamic component that later disappears, and a stationary component that is present throughout the event. The dynamic component, we believe, is due to chromospheric evaporation resulting from the energy deposition during the impulsive phase. The stationary component is formed at coronal heights by the accumulation of the plasma flowing into the corona from the chromosphere. Moreover, the increase of the soft X-ray emission of the stationary coronal plasma should continue as long as chromospheric evaporation continues. Therefore, the emission measure and the thermal energy of the stationary coronal plasma should continue to increase as long as blue-shifted X-ray spectra are observed.

The temporal evolution of the emission from the dynamic and stationary plasma components for the May 21, 1980 class X1 flare is shown in Figure 2. The velocity of the rising plasma decreased from 380 km/sec at $20^h55^m20^s$ UT, the time of the main hard X-ray burst, to 120 km/sec at $21^h06^m48^s$ UT. Any upward motion with a velocity below this limiting value is not detectable since, for such a case, the shifted and principal spectra would not be resolved. The emission measure of the stationary plasma continues to increase as long as plasma motions are detected, and begins to decrease when the upward motion disappears, as expected from the plasma accumulation hypothesis. Emission measures are computed on the assumption that the calcium atoms contributing to the emission are at the temperature derived for each time interval from the spectral analysis discussed above (Antonucci _et al._ 1980). Only in 25% of the events considered is the emission measure of the coronal plasma still increasing after plasma flows are no longer observed. However, in those cases the increase stops within two minutes after the disappearance of the plasma flow. An analysis involving higher temperature emission lines than calcium XIX would tend to improve the temporal association between the plasma flow and the increase in the amount of coronal plasma. In fact, we are making the simplifying assumption of isothermal plasmas even though it is known that the intensity of such higher temperature lines as Fe XXV and Fe XXVI peak earlier than the intensity of the Ca XIX line.

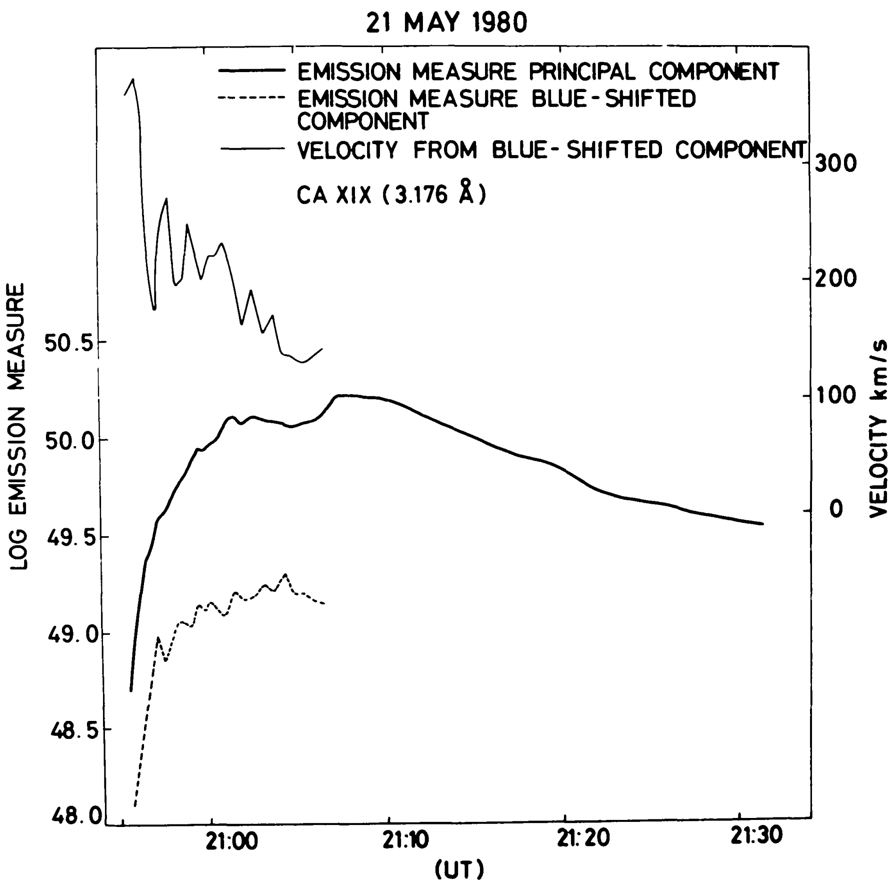

Figure 2. Time evolution of the velocity and emission measure of the dynamic component compared to that of the emission measure of the stationary plasma component during the May 21, 1980 flare.

For some of the flares analysed, the Hard X-Ray Imaging Spectrometer on SMM has resolved separate sources of hard X-ray emission in the energy range 16-30 keV (Hoyng et al., 1981). It is suggested that these sources are at the footpoints of magnetic loops where the electron energy is deposited, and that this is where chromospheric evaporation occurs. For these flares, the magnetic configuration can be inferred by assuming that the hard X-ray sources are at the footpoints of semicircular loops.

The fact that different footpoints may be activated successively during flares is not crucial to our treatment since the BCS observes the integrated emission of the whole flaring region. Once the magnetic configuration is inferred, the mass and energy input to the corona due to evaporation can be derived on the hypothesis of magnetic confinement and continuous mass flow through the footpoints during the impulsive phase. However, since the electron temperature, T_e', and the density, n_e', of the upward moving plasma are unknown, this coronal input cannot be derived directly. Note that the electron temperature has been considered to be the same for both the principal and the secondary spectrum in the analysis of the data shown in Figure 1, but it is, in fact, accurately determined only for the principal component. The emission measure, EMB, and the velocity, V, of the dynamic plasma are, however, determined directly from the spectral analysis. We have inferred values for T_e' and n_e' from the measured quantities by requiring that the input rates of mass and energy, integrated over the time that chromospheric evaporation is taking place, account for the increase in the number of coronal electrons, ΔN_e, and in their thermal energy, ΔE_{th} (Antonucci et al., 1982). Since the time of evaporation coincides with the rising part of the gradual phase, ΔN_e and ΔE_{th} correspond to the total mass and thermal energy increase in the corona during the flare.

In Table I the peak values of electron density, $n_{e,max}$, and temperature, $T_{e,max}$, of the coronal plasma compared with the average values of the density, $\overline{n_e'}$, and temperature, $\overline{T_e'}$, derived for the evaporating mass. The observed coronal plasma in a flare can be easily explained for reasonable physical conditions of the evaporating material. Therefore, we suggest that the accumulation process following chromospheric evaporation is the main mechanism that builds up the thermal phase of flares.

TABLE I

Date of Flare (1980)	Start Time (UT)	$n_{e,max}$ (10^{11} cm^{-3})	$\overline{n_e'}$ (10^{10} cm^{-3})	$T_{e,max}$ (10^6 K)	$\overline{T_e'}$ (10^6 K)
8 April	0303	3.1	3.6	15.5	20.0
10 April	0917	3.3	7.5	16.0	15.0
9 May	0711	6.9	11.0	18.0	17.0
21 May	2055	2.7	3.6	16.6	20.0
5 November	2233	2.0	9.9	20.4	16.0

We have searched for correlations between the two measurable parameters of the plasma flow, V and EMB, and parameters of the coronal plasma. We find that V is associated with R, the average rate of increase of the fractional emission measure of the coronal plasma. This parameter, R, is defined by the relation, $R = 100\ (E_{max} - E_{pre})/(E_{max}\Delta t)$ % min^{-1}, where E_{max} is the maximum emission measure recorded during the flare, E_{pre} is the emission measure existing prior to the flare, and Δt is the time taken to reach E_{max}. The maximum value of V, V_{max}, is plotted versus R in Figure 3, where the positive correlation can be seen. The correlation coefficient is 0.8. The peak emission measure of the upward moving plasma, EMB_{max}, is also positively correlated with EM_{max} with a correlation coefficient of 0.7.

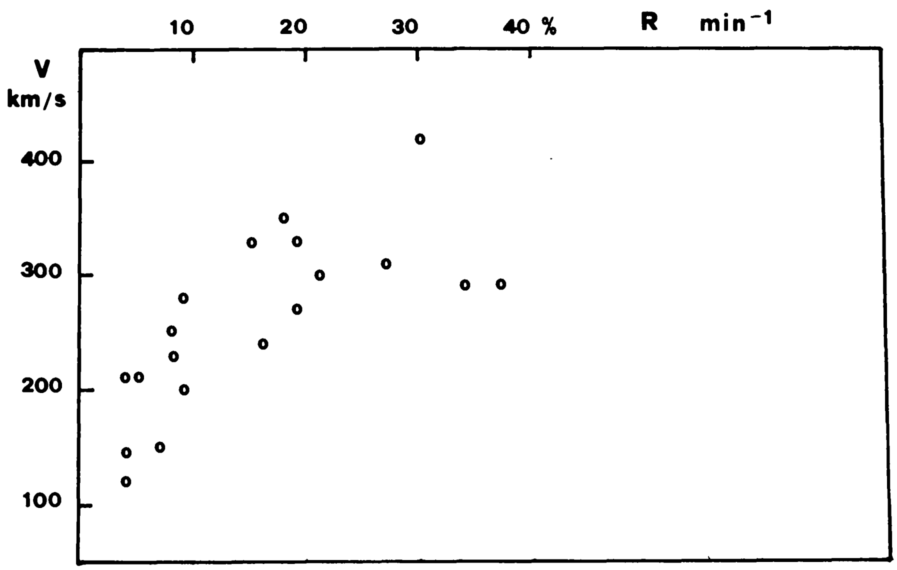

Figure 3. Evaporation velocity versus rate of increase of the emission measure of the coronal plasma.

3. Association of Primary Energy Release and Plasma Motions.

The secondary, blue-shifted lines in the soft X-ray emission appear in coincidence with the start of the hard X-ray emission. The hard X-ray power-law spectral index, γ, and the photon flux at 50 keV have been computed throughout each flare from the HXRBS data. The energy deposited in the chromosphere by the primary non-thermal electrons that are assumed to produce the observed hard X-rays is still quite low - a few times 10^{27} erg s^{-1} - at the time of the first observation of chromospheric evaporation. However, energies of this order are sufficient to sustain the process at this stage. This can be deduced by comparing the energy deposition rate and the rate of energy transferred into the corona by the evaporating plasma at the onset of the flares listed in Table I, for which the evolution of the energy transfer is known. For these flares, the total energy of the non-thermal electrons (> 25keV) assumed to produce the hard X-rays in thick-target interactions appears to be sufficient to power the thermal flare. Qualitatively, for all flares, chromospheric evaporation lasts throughout the time of the impulsive hard X-ray burst.

The velocity of the evaporating plasma is not correlated with the energy deposited in the chromosphere assuming the thick-target model. It is, however, correlated with the spectral index of the hard X-ray flux. Figure 4 shows that the highest value of the evaporation velocity during a flare is correlated with the lowest value of the power-law index of the hard X-ray spectrum with a correlation coefficient of -0.6. This result, together with the correlation found between V_{max} and R, implies that R should also be correlated with the hardness of the X-ray spectrum. This correlation between R and γ can be see! in Figure 5 and the correlation coefficient is -0.7. Limb flares have been included in Figure 5 since observations of blue-shifted lines are not required to determine a value for R.

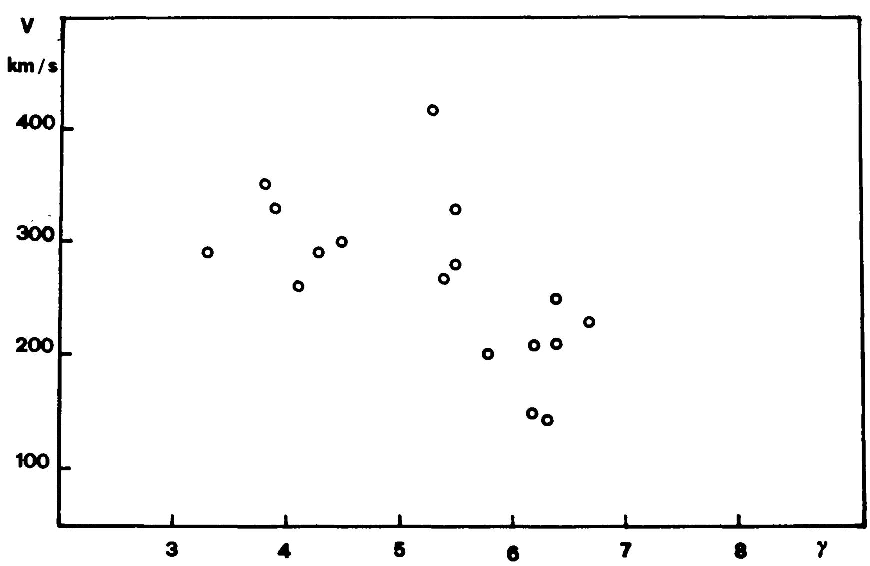

Figure 4. Evaporation velocity versus the lowest, hard X-ray spectral index, γ, measured during the flare.

The total energy deposited in the chromosphere by fast electrons (>25 keV) assuming a thick target model appears to be related to the peak emission measure of the evaporating plasma, but the correlation coefficient is only 0.4. This correlation together with the dependence found between the emission measure of the dynamic and stationary components implies a positive correlation between the total energy deposited by the electrons in the chromosphere and the peak emission measure of the thermal coronal plasma. This correlation has been tested, including also limb flares, and the coefficient is found to be 0.7.

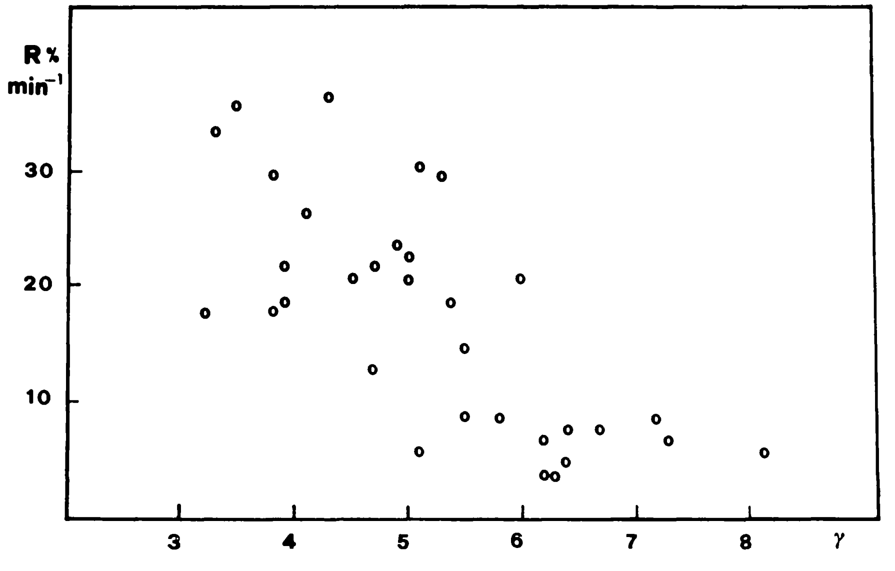

Figure 5. Rate of increase of the fractional emission measure of the coronal plasma versus the lowest hard X-ray spectral index, γ, measured during the flare.

4. Conclusion

We conclude that upward motions of the soft X-ray plasma are temporally associated with the build up of the thermal phase of flares and with the period of energy deposition as indicated by the hard X-ray emission. Moreover, the hardness of the hard X-ray spectrum, the evaporation velocity, and rate of increase of the gradual phase are correlated. The total electron energy deposited in the chromosphere, the peak emission measure of the evaporating plasma, and the peak emission measure of the thermal coronal plasma also appear to be correlated.

Acknowledgments

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DISCUSSION

HIEI: Evaporation may occur not only in one flare loop, but in several loops, successively. Could you find such an evidence in the SMM soft X-ray data?

ANTONUCCI: The Bent Crystal Spectrometer detects the soft X-ray emission integrated over the flare plasma, therefore single loops cannot be spatially resolved. It is also difficult to extract this information from the time structure of the profile of the evaporation velocity during the impulsive phase.

EMSLIE: If the data to which you refer are indeed to be explained by chromospheric evaporation, then the instantaneous rate of increase of the emission measure of the stationary component should be proportional to the product of the emission measure in the upward moving component times its velocity. The data you present do not appear to satisfy this requirement, even though the event-integrated meission measure in the moving component does correspond with the emission measure in the stationary component, for reasonable densities of this moving material.

ANTONUCCI: The data presented do satisfy this requirement. The instantaneous rates of increase of the thermal energy and mass observed in the stationary component are indeed consistent with the computed energy and mass input rates, due to the moving component. For instance, at 2100 UT of the 21st of May flare, the increase in thermal energy and mass observed in a 20 interval is 3×10^{29} ergs and 2.4×10^{37} electrons. For the same interval, the computed energy input would be 2.6×10^{29} ergs and the mass input 3.6×10^{37} electrons.

PRIEST: If the heating were at the top of a loop you would expect a downflow in the initial stages. Is the lack of an observed redshift due to a lack of sensitivity to that particular plasma or is it because of heating at footpoints?

ANTONUCCI: Redshifts at the onset of flares were not observed during the SMM period. In some events, there is a significant soft X-ray emission in pre-flare conditions, but no redshift is observed; however non-thermal broadenings of spectral lines can precede the appearance of blueshifts. Hence, it seems reasonable to think in terms of heating at the footpoints.

PALLAVICINI: It is true that the conduction front moves very fast from the loop top to the footpoints. However, in addition to that, there is also a pressure wave which moves downwards much more slowly. This pressure wave may produce a redshifted component. The problem is that the flare loop is initially almost empty, before evaporation starts, so that the emission measure corresponding to the redshifted component is very small and you may not see it with the Bent Crystal Spectrometer.

BRUECKNER: Have you (or anybody) considered the charge imbalance and resulting electric field caused by an electron beam?

BROWN: The problem of charge imbalance in electron beams was solved 10 years ago by recognition that a neutralizing return current is established in the background plasma, just as in the laboratory beam experiments. This point has beem made in some tens of papers already.