CHROMOSPHERIC EVAPORATION IN SOFT X-RAY FLARES

Ester ANTONUCCI
Space and Astrophysics Division
Rutherford Appleton Laboratory
Chilton, Didcot, U.K.

On leave from the University of Torino, Italy

Abstract

The chromospheric evaporation process, as observed with Doppler velocity measurements in the soft X-ray emission by the X-Ray Polychromator of the Solar Maximum Mission, is discussed. Plasma at a temperature exceeding 1.10^7 K, starts flowing into the coronal region of a flare at the onset of the impulsive phase. The flow persists during the period of the main hard X-ray emission and lasts approximately until the peak of the thermal phase is reached. It is suggested that the evaporation process represents the main mechanism for transferring to the coronal region the mass and energy responsible for the soft X-ray emission during the thermal phase of flares. The values of density and temperature of the evaporating plasma, sufficient to account for the increase in the density and temperature of the coronal thermal plasma during the impulsive phase, are derived.

1. Introduction

Flows of hot plasma from the chromosphere to the corona have been suggested to justify the observed sudden appearance of large amounts of plasma at coronal heights during solar flares. Evaporation of chromospheric material can be easily induced by a sudden local heating of the dense chromosphere (Antiochos and Sturrock, 1978, Somov et al., 1981). The energy required to initiate and sustain the process of evaporation can be deposited at chromospheric level either by bombardment by energetic electrons, accelerated during the primary energy release of a flare, or through heat conduction from the corona to the chromosphere. Conditions for both mechanisms are likely to occur during the impulsive phase of solar flares.

Although mass motions in the chromosphere and transition region are often observed during flares, as discussed by Canfield et al. (1980), direct observations of upward flows of plasma at coronal temperatures have been made only recently, during the last solar maximum. Feldman et al., (1980), reported the observation of blue-shifts of soft X-ray lines in the rising phase of two M flares detected on March 22, 1979, by the SOLFLEX spectrometers on board the P-78 satellite. The measured shifts are compatible with outward motions at 400 km/sec, which are interpreted as a possible indication of chromospheric evaporation, or as a high temperature spray. The Solar Maximum Mission (SMM) observations, during 1980, have systematically shown the presence of continuous mass flows into the corona during the impulsive phase, with characteristics compatible with the process of chromospheric evaporation. In the majority of the flares of class M and X, detected during the Solar Maximum Mission by the Soft X-ray Polychromator (XRP), plasma at a temperature within the range 1.3 - 2.3 10^7 K is observed to rise in the solar atmosphere at approximately the sound velocity. The mass flow starts at the flare onset and lasts throughout the impulsive phase, until the peak of the thermal phase is reached.

The XRP observations indicate also the existence of a small class of events which do not show chromospheric evaporation. That is, the process of energy transfer from the impulsive to the gradual phase is not observed. It can be suggested that in this case the mechanism of energy release may be substantially different.

2. Soft X-Ray Observations During the Impulsive Phase

The soft X-ray emission in the spectral regions of Ca XIX and Fe XXV resonance lines and associated satellites have been recorded by the XRP in the period February - November 1980. The instrument characteristics and early results on the dynamics of flaring plasmas are reported by Culhane et al. (1981) and Gabriel et al. (1981, a and b).

At the onset of flares, the soft X-ray spectra show a secondary component which is blue-shifted and reduced in intensity with respect to the principal one. The effect is evident in the spectrum of the Ca XIX region detected at 20.55.32 U.T., shown in Figure 1. This spectrum has been recorded in coincidence with the beginning of the impulsive phase of the May 21, 1980 flare, a large class X1 flare. The secondary component of the spectrum disappears later on, at the peak of the thermal phase, as shown by the measurements at 21.07.06 U.T., in Figure 1. In this second spectrum, the spectral lines no longer exhibit large non-thermal broadenings, which are another characteristic of the impulsive phase. Figure 1 also shows the time variation of the intensity of the calcium emission integrated over the entire spectral region from 3.165 to 3.231 Å. The gradual emission in soft X-rays is compared with the impulsive hard X-ray emission in the range 28-386 keV, detected by the Hard X-ray Burst Spectrometer of SMM.

These observations suggest that the thermal plasma during a typical flare consists of a stationary component present throughout the event and a dynamic component existing only during the impulsive phase (Antonucci et al.: 1981, 1982). The physical parameters relating the two components can be derived by fitting a theoretical spectrum to the observed one. Theoretical spectra are synthesized, according to the method developed by Antonucci et al. (1982), using the calculations of atomic parameters made by Bely-Dubau et al. (1982). A spectrum detected during the impulsive phase of the April 8, 1980 flare at 03.05.04 U.T., is shown in Figure 2. The observed emission is fitted by a superposition of two synthesised

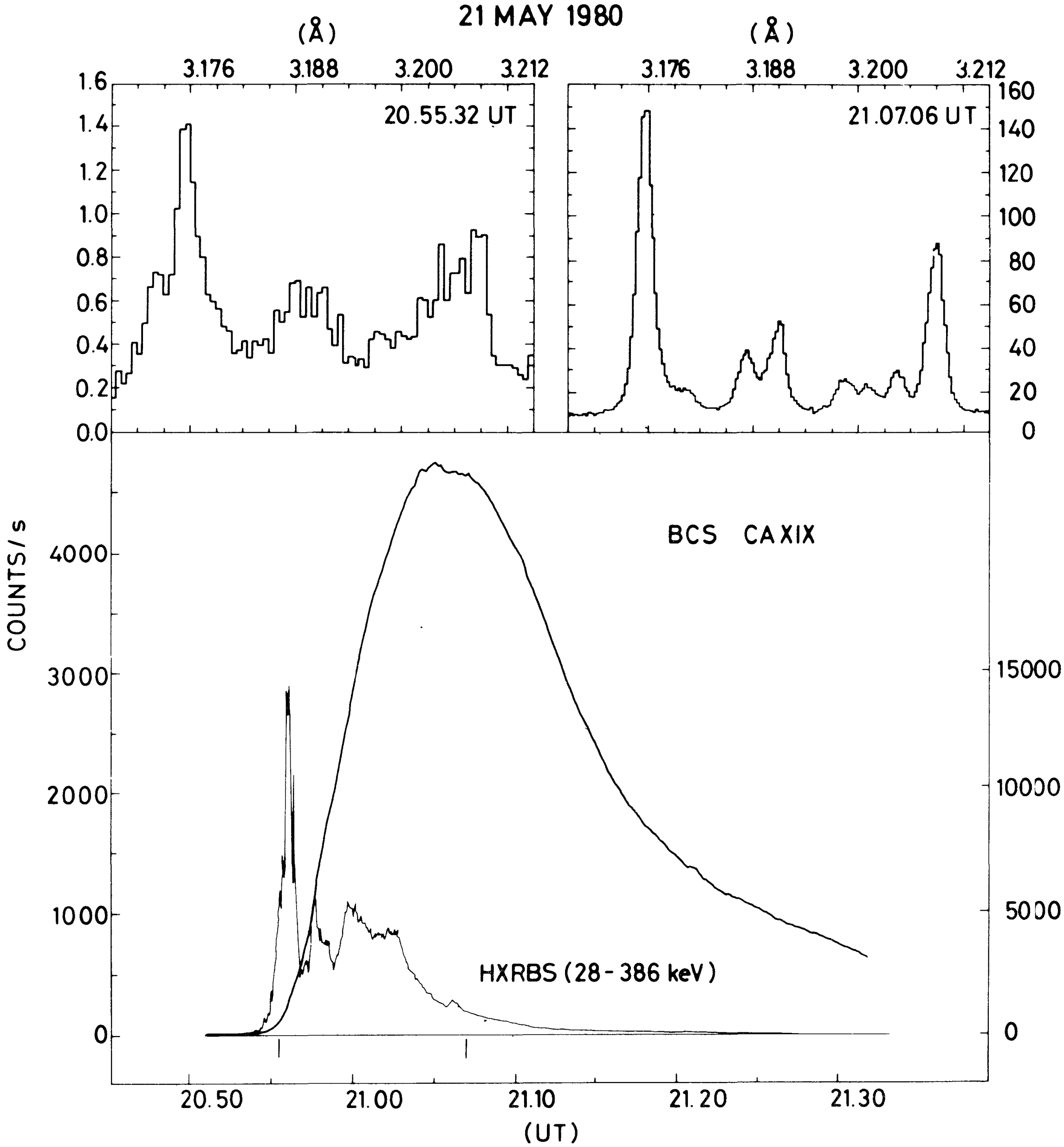

Figure 1. Ca XIX spectra observed by the Bent Crystal Spectrometer of the XRP at different times of the flare, the emission is measured in counts/secend. In the lower part of the figure: the emission of the soft X-rays in the calcium channel (relative scale or the left) and the emission in the hard X-rays (relative scale on the right) are shown.

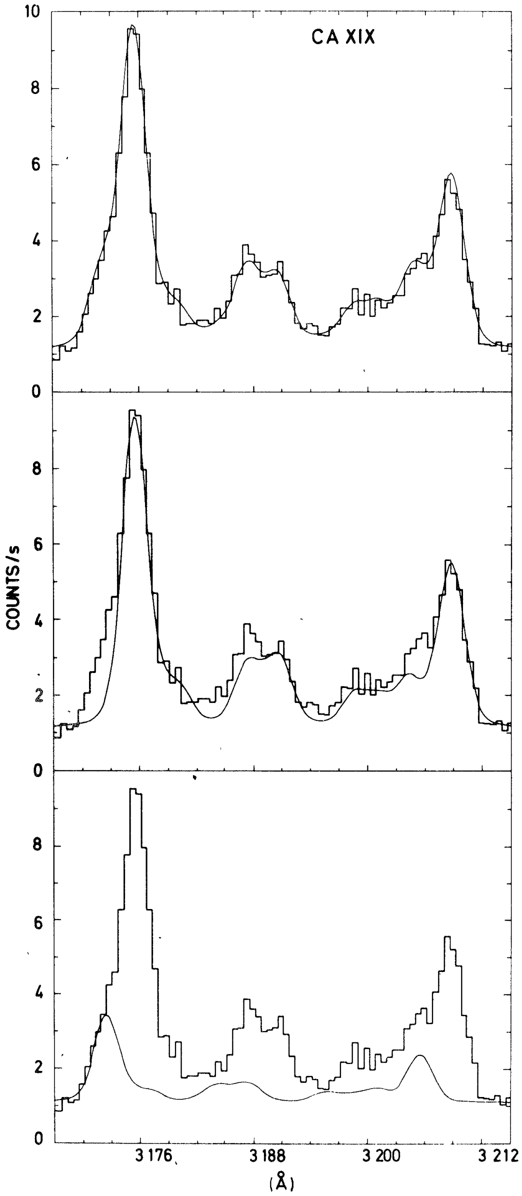

Figure 2. Ca XIX spectrum detected at 03.05.04 U.T. on April 8, 1980. Continuous lines refer to theoretical synthesised spectra. The upper one is given by the sum of the middle (principal component) and the lower (secondary component) synthesised spectra. They are computed for: electron temperature equal to 1.4 10^7 K, equivalent ion temperature, measuring the line width, equal to 5.6 10^7 K, lithium-like to helium-like ion ratio equal to 0.02 and hydrogen-like to helium-like ion ratio equal to 0.08. The secondary spectrum is blue-shifted by 3 mÅ.

spectra (upper part of the figure) separately shown below, which represent the principal and secondary components (middle and lower figures). The set of parameters (electron temperature, Doppler temperature, ion population ratios) determining the shape of the Ca XIX spectrum, is assumed to be the same for both components. This is a simplifying assumption, since the parameters can be accurately derived just for the principal component. The values providing the best fit are consistent with the following interpretation. The principal spectrum is emitted by a plasma at a temperature of $1.4\ 10^{7}$ K in the coronal volume. In this region turbulent motions with velocities of the order of 130 km/sec can be derived from the observed non-thermal broadening. The secondary spectrum is emitted by a plasma, which is assumed to have the same temperature, flowing into the coronal region at 310 km/sec/ The emission measure is approximately 3.10^{49} cm^{-3} for the coronal plasma and 7.10^{48} cm^{-3} for the mass rising in the solar atmosphere.

3. Temporal Behaviour of the Mass Flows

A number of large flares of class M and X, observed by the XRP, have been chosen for analysing the occurrence of the mass flows in relation to the gradual and impulsive phase. They have been selected on the basis of the intensity (total counts in the calcium channel exceeding 500 sec^{-1}), and of the coverage of the early phase of the event. For the resulting 36 events, the time variation of the electron temperature, the emission measure of the different plasma components (assumed isothermal) and the velocity of the dynamic component have been derived.

The 11 flares occurring at longitudes exceeding approximately 60°, do not exhibit any secondary component of the soft X-ray spectrum during the impulsive phase. A longitude dependence is expected for line shifts due to changes in the line-of-sight velocity component. While in the majority (90%) of the disk flares, blue-shifted lines are observed early in the flare.

The durations of the hard X-ray emission, the mass flow and the rise of the soft X-ray emission, and their temporal relationships, are qualitatively important in relation to the role of the mass flows in flare development. Soft X-ray spectra emitted by highly ionised heavy ions, such as calcium and iron, in most cases are not observed in an active region until the onset of a flare. Hence, blue-shifts are often observed in the first statistically significant spectrum of a disk flare. In all cases, however, they appear at the very beginning of the hard X-ray emission and persist throughout the main hard X-ray burst, or series of bursts in temporally complex events. As an example, during the May 21, 1980 flare, the mass flow is continuous from 20.55.20 to 21.06.48 U.T., covering the main hard X-ray emission (Figure 1). Mass motions of the thermal plasma are generally not observed during the slow decay of the hard X-ray emission, observed in some flares (for instance, in the May 21 event after approximately 21.07 U.T.).

The duration of the upward flows can also be compared to that of the rising phase of the soft X-ray emission. This can be defined as the interval from the flare onset to the peak in emission measure of the plasma emitting soft X-rays. The time variation of the velocity and emission measure of the plasma dynamic component for the May 21 event, is plotted in Figure 3. The flow lasts approximately until the emission measure of the stationary plasma in the coronal region peaks. During this period the velocity decreases from 380 to 120 km/sec, which is approximately the lower limit for detecting blue-shifts of the resonance line in the calcium spectrum. Since the temperature of the plasma changes from 13 to 17 million degrees in the same time interval, the velocity of the plasma is equal to or less than the sound speed. The decrease in velocity of the mass flow is accompanied by an increase in the emission measure of the moving plasma.

In the analysis of the time variation of the plasma parameters, the soft X-ray emission has been integrated in intervals from 30 sec to 120 sec depending on the total duration of the flare. The first sampling time is used when the thermal phase is of the order of 10 minutes, while the second is more appropriate when it exceeds 40 minutes. In 75% of the events, associated with mass flows, the emission measure reaches its maximum value in the last time interval during which blue-shifts are observed, or in the next one. In the remaining cases, the rise of the thermal phase is completed in an interval not exceeding 2 minutes from the last

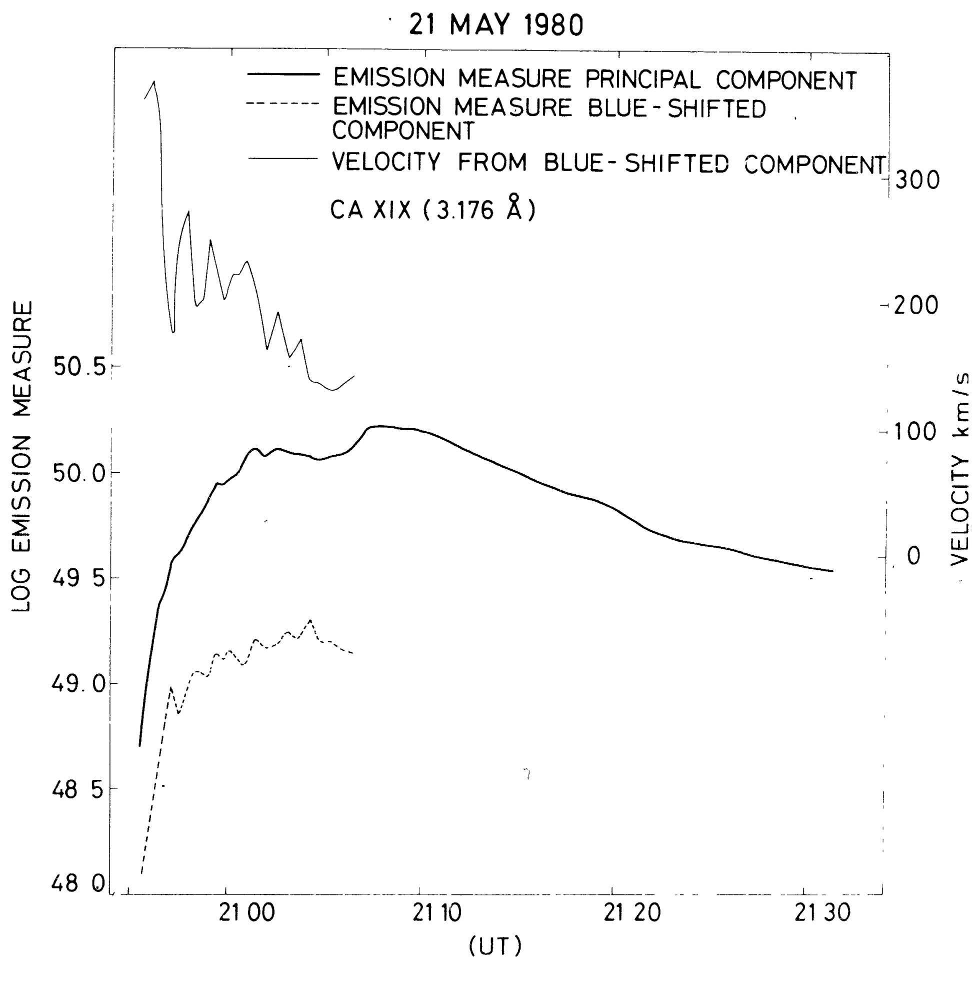

Figure 3. Time variation of the emission measure for the principal and blue-shifted components of the calcium spectra observed during the impulsive phase of the flare. The upward velocity of the plasma, derived from the blue-shift of the secondary component, is also plotted. The short-time variations in velocity are mainly due to statistical uncertainty.

observation of mass flows. Hence, upward motions last substantially throughout the rise of the thermal phase. It is to be noted that, except in one case, the peaks of the emission measure and the thermal energy content of the coronal plasma (proportional to the product of the emission measure and the electron temperature) are simultaneous.

Thus, qualitatively, the onset and duration of the mass flows suggest that such flows are a response to the same mechanisms which excite the hard X-ray emission. In addition, they might be a manifestation of a process through which energy is transferred to build up the thermal phase. Observations from the Hard X-ray Imaging Spectrometer (HXIS) on SMM, prove the existence of electron beams bombarding the chromosphere at least in the early part of the impulsive phase. There is evidence for accelerated electrons during the first hard X-ray spike of May 21 flare, before 20.57.30 U.T. (Hoyng et al., 1981). Hence, mass flows can indeed be interpreted as the chromospheric response to the energy deposition by accelerated particles, at least at the very beginning of the impulsive phase.

Furthermore, it is possible to investigate whether chromospheric evaporation represents the main energy transfer process from the impulsive to the thermal phase. In this case, the mass and energy input into the coronal region should be sufficient to provide the observed mass and thermal energy and account also for the radiation and conduction losses from that region. In turn, the energy deposited by the accelerated electrons at chromospheric heights should be sufficient to sustain the evaporation process, unless very hot coronal regions are postulated. The discussion in the next section will be limited to testing in which conditions chromospheric evaporation provides enough energy for the build up of the gradual phase.

4. Energy Transferred by Chromospheric Evaporation

A quantitative discussion of the energy transferred to the corona during the impulsive phase is complicated by the lack of complete information on the structure of the region, the density of the plasma and the temperature of the flowing mass, which are not precisely determined. This aspect of the flare energy balance has been discussed for the April 10, 1980 event by Antonucci et al. 1982. On the assumption of continuous flow and confinement of the plasma in the coronal region, chromospheric evaporation was found to be the main process of energy and mass transfer to account for the thermal plasma observed during the flare.

The same approach has been used to extend the study to all the flares which show evidence for hard X-ray emission initiated by electron beams. The chromospheric footpoints of the magnetic flux tubes, confining the accelerated particles, are observed as distinct sources in hard X-rays, in the 16-30 keV channels of the HXIS. A list of these events is reported in Table I, together with the linear extent of the hard X-ray footpoints (d) and their separation (ℓ), not yet corrected for longitudinal effects (Machado, 1981 private communication). A discussion of a few of these events can be found in the papers by Hoyng et al. (1981), Machado et al. (1981) and Duijveman et al. (1982).

The region containing the flaring plasma is approximated by a semicircular loop of diameter (ℓ), with uniform cross-section (d^2). In all flares one single loop has been assumed, except for the November 5 event, since in this case two loops are seen to be present simultaneously (Duijveman et al., 1982). The electron density n'_e and temperature T'_e of the evaporating plasma, not accurately determined from the observations, can be derived from the mass and energy continuity equations in the flare region. The increase in electron total content ΔN_e, and in thermal energy ΔE_{th}, corrected for energy losses, has to be consistent with the mass and energy input through the chromospheric footpoints, integrated over the evaporation period Δt.

The mass continuity equation is:

$$\int_{\Delta t} n'_e \, v' \, A \, dt = \Delta N_e$$

where v' is the flow velocity, and ΔN_e is the increase in total electron number in the coronal volume. The energy continuity equation is:

$$\int_{\Delta t} (P'_{EN}+P'_K)dt=\Delta E_{th} + \Delta E_{turb} + \int_{\Delta t} (P_R+P_C)dt=\Delta E$$

TABLE I

Flare	Start (U.T.)	Class	ℓ	d	ΔE (ergs)
8 April 1980	03.03	M4	20"	$\leq$ 8"	$4.3\ 10^{30}$
10 April 1980	09.17	M4	16"	8"	$1.7\ 10^{30}$
9 May 1980	07.11	M7	10"	$\leq$ 8"	$2.2\ 10^{30}$
21 May 1980	20.55	X1	40"	$\leq$ 10"	$1.1\ 10^{31}$
5 November 1980	22.33	M4	28"	8"	$2.4\ 10^{30}$

The first integral is the enthalpy and kinetic energy flowing into the coronal region in the interval Δt. ΔE_{turb} is the increase in turbulent energy, which is usually negligible compared with the variation in thermal energy content ΔE_{th}. The last integral accounts for the radiative and conductive losses from the coronal region. For radiative losses the following approximation, valid in the range of measured temperatures, is used:

$$P_R \cong 1.5\ 10^{-19}\ n_e^2\ T_e^{-1/2}\ V \text{ ergs/sec}$$

(Summers and McWhirter, 1979). The quantities n_e and T_e are respectively the electron density and temperature of the stationary plasma and V is the volume. The energy loss by classical heat conduction can be expressed by:

$$P_C \cong \frac{2}{7}\ \psi\ T_e^{7/2}\ A/h \text{ ergs/sec}$$

where h is the height of the loop above the chromosphere, $A = d^2$ is the footpoint cross-section and ψ is the coefficient of thermal conductivity.

The total energy ΔE, which has to be supplied to the coronal region of the flare, has been computed for each flare and reported in Table 1. The value of ΔE reported for the April 10 event differs from that published in Antonucci et al. (1982), because of a different assumption of the geometry of the region, the volume being smaller in this case. The total energy ΔE can be provided by the evaporating plasma, if its density and temperature have the values shown in Table II. These values are averaged over the interval of the evaporation process. They are also compared with the density and temperatures of the plasma contained in the coronal region at the peak of the thermal phase. It is sufficient for the plasma evaporating to have densities smaller than those found in the coronal loop during the gradual phase, while the temperature is approximately of the same order.

Somov et al. (1981) have computed the hydrodynamic response of the chromosphere to an impulsive heating. Their model assumes a value for the energy deposited by an electron beam compatible with the hard X-ray burst observations and the

TABLE II

FLARE	LOOP PLASMA n_e (cm^{-3})	LOOP PLASMA T_e ($10^6 K$)	PLASMA FLOWS $\bar{n}'_e$ (cm^{-3})	PLASMA FLOWS $\bar{T}'_e$ ($10^6 K$)
8 April 1980	$3.1\ 10^{11}$	15.5	$3.6\ 10^{10}$	20.0
10 April 1980	$3.3\ 10^{11}$	16.0	$7.5\ 10^{10}$	15.0
9 May 1980	$6.9\ 10^{11}$	18.0	$1.1\ 10^{11}$	17.0
21 May 1980	$2.7\ 10^{11}$	16.6	$3.6\ 10^{10}$	20.0
5 November 1980	$2.0\ 10^{11}$	20.4	$9.9\ 10^{10}$	16.0

energy is deposited in 10 seconds. A comparison between the values of the physical parameters of the evaporating plasma derived in our analysis and the computed ones is limited because of the differences in energy inputs and the simplifying assumption on geometry of the flux tube. However, the density of the evaporating mass, reported in Table I, is consistent with that computed for the first few seconds of the evaporation process by Somov et al., while the temperature is found to be higher. For the set of flares analysed in this study the maximum velocity observed in each event is within the range 460 - 150 km/sec, these values are also consistent with the model by Somov et al. The very high velocities, outside this range, predicted by the model correspond to plasma densities lower than observed. In the geometry assumed in our analysis, a density lower than 10^{10} cm^{-3} would lead to an emission measure for the dynamic component not detectable by the XRP.

As a conclusion the mass motions of hot plasma observed during the impulsive phase are likely to provide sufficient mass and energy to account for the thermal plasma observed during a solar flare in the corona.

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