HIGH-RESOLUTION X-RAY SPECTRA OF SOLAR FLARES. IX. MASS UPFLOW IN THE LONG-DURATION FLARE OF 1979 JUNE 5

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Received 1988 December 19; accepted 1989 April 12

ABSTRACT

We discuss blueshifted X-ray spectral line components in iron and calcium spectra of a large long-duration flare observed on 1979 June 5. The spectra were recorded by the Naval Research Laboratory X-ray SOLFLEX spectrometers flown on P78-1. We find that blueshifted emission exists for a time interval of at least 28 minutes indicating upflowing plasma at about 250 km s\(^{-1}\). We derive emission measures for both the blueshifted and stationary plasma and interpret the results in terms of chromospheric evaporation. We find that the total amount of hot upflowing plasma during the flare rise time exceeds the amount of stationary plasma contained in the loop close to the time of the peak of the flare. This result contradicts the simplest version of the evaporation model. Evaporation can account for the observations only if some of the upflowing plasma cools on time scales much shorter than the rise time of the event, which was about 40 minutes.

Subject headings: Sun: flares — Sun: X-rays — X-rays: spectra

I. INTRODUCTION

A discovery made with the SOLFLEX Bragg crystal spectrometer experiment on the P78-1 spacecraft is that X-ray line profiles of high-temperature solar flare lines usually have a blueshifted component during the rise phase of flares (Doschek et al. 1980; Feldman et al. 1980). This blueshifted emission is interpreted by some as evidence for the process of chromospheric evaporation or ablation (e.g., Antonucci et al. 1982; Antonucci, Gabriel, and Dennis 1984), but this conclusion is not universally accepted (e.g., Doschek et al. 1986; Batchelor 1986). Chromospheric evaporation is assumed to occur as the result of chromospheric heating by either conduction fronts or electron beams of coronal origin in response to the initial flare energy release. In this picture the heated chromospheric plasma “evaporates” into closed magnetic flux tubes, thereby producing the soft X-ray flare. Evaporation could therefore explain the high emission densities (and hence emission measures) found for the soft X-ray flare plasma at temperatures between 3 and \(2 \times 10^{6}\) K. It is believed by some that the blueshifted X-ray line components represent the Doppler-shifted signature of this evaporating plasma.

The SOLFLEX Bragg crystal spectrometer experiment on the P78-1 spacecraft was designed to obtain high-resolution spectra of the calcium and iron line groupings near 3.2 Å and 1.85 Å, respectively. The spectrometers were uncollimated and therefore viewed the entire Sun. The crystals were flat, and spectra were obtained by rotating the crystals over narrow wavelength ranges. The scan rate was such that complete spectra were obtained every 56 s. A description of the experiment is given by Doschek (1983).

A scan period of 56 s is insufficient for good temporal resolution of the rise phase for fast rising flares. For most of the large flares observed by SOLFLEX, the rise phase lasted less than 10 minutes, and about a half-dozen rise phase spectra were obtained. However, we observed one particular flare that had an unusually long rise time, i.e., the large flare of 1979 June 5. The rise time was about 40 minutes, and we were able to obtain about 30 spectra during the first 30 minutes of the rise phase. Furthermore, because of the long rise time, the effect of flux increase during each spectral scan is unimportant. We obtained spectra from the flare onset at about 0500 UT until about 0528 UT, when the spacecraft entered eclipse. Judging from the GOES X-ray data (Fig. 1), flare maximum occurred near 0540 UT. SOLFLEX resumed observations around 0606 UT, and much of the early part of the decay phase was also observed.

It is clear from Figure 1 and the decay phase extension of the X-ray light curve that the June 5 event belongs to a class of flares known as long-duration events (LDEs: e.g., Kahler 1977; Pallavicini, Serio, and Vaiana 1977). LDEs are associated with coronal mass ejections (CMEs), and the June 5 flare was associated with a large CME. Some characteristics of the CME are given in Sheeley et al. (1984), and an image of the CME is published in Poland et al. (1981). Hz observations of the flare have been obtained from the National Astronomical Observatory, Japan (NAOJ, formerly the Tokyo Astronomical Observatory; Watanabe 1988).

The June 5 flare is classified as X2 and was located about N18, E14. Although the rise time of the flare is unusually long, the X-ray spectra appear completely “normal” at first glance, i.e., they appear indistinguishable from spectra recorded from flares with much shorter rise times.

Hard X-ray data for the June 5 event are available from the High Energy Monitor (HEM) on P78-1 provided by the Aerospace Corporation. The HEM is a proportional counter with six energy channels covering the energy range from 18 to 230 keV. For the June 5 event, the energy bands in keV units were 18.2–23.5, 23.5–32.7, 32.7–44.7, 44.7–59.2, 59.2–84.4, and 84.4–226. The hard X-ray data are shown in Figure 2. The two lowest energy bands show a gradual rise in count rate that is very similar to the soft X-ray increase. Evidently, these channels reflect the tail of the Maxwellian that also produces the
thermal line and continuum emission. However, at about 0508:30 UT there was a spike burst that lasted about a minute and is most clearly observed in the highest two channels. Following this there were multiple smaller high energy bursts which strongly affected all but the lowest energy channel, although even in this channel these bursts are evident.

Aside from the flare under discussion, no other major Hα solar flare was reported in Solar Geophysical Data at the time of the high energy bursts. Also, there is no obvious evidence of the high-energy bursts in the soft X-ray spectra or in the full disk Hα images from NAOJ which have been examined over 2 minute intervals. The P78-1 spacecraft, which was launched in a polar orbit, encountered radiation belts between 0509:50 UT and 0512:59 UT and also between 0526:30 UT and 0529:32 UT. The soft X-ray SOLFLEX continuum increased during the 0526:30-0629:32 UT time interval, but no radiation belt effect in the SOLFLEX data was seen during the earlier time interval. It appears unlikely that the HEM burst data are due to radiation belts, as the times over which some of the burst data occurred are outside the time intervals of the radiation belts, e.g., the main spike burst occurred before the first radiation belt encounter.

It is possible that the high-energy bursts are associated with the June 5 flare. If this is assumed, the fact that they occur well after the onset of the soft-X-ray event and that they have no apparent effect on it would imply that, at least in this case, they are a by-product of the flare energy release mechanism just as the soft X-ray burst is a by-product. In this case the electron beam would not be the primary cause of the soft X-ray emission through beam deposition and consequent evaporation of chromospheric plasma. This argument has been stated before (Feldman, Cheng, and Doschek 1982), and evidence that at least some hard X-ray bursts have nothing to do with the soft X-ray flare has been given by Feldman, Liggett, and Zirin (1983). Unfortunately, we cannot state with certainty that the bursts shown in Figure 2 are related to the June 5 event.

The June 5 flare was included in our first survey of temperatures and nonthermal motions of X-type flares (Doschek et al. 1980). In fact, the June 5 flare was the discovery flare for the blueshifted component. X-ray light curves and temperatures for Ca xix and Fe xxv as a function of time starting at 0516 UT are presented in Figure 6 in Doschek et al. (1980).
II. DECONVOLUTION OF THE BLUESHIFTED COMPONENT

Before discussing the deconvolution of the blueshifted component, we consider whether or not the stationary component is really stationary, i.e., zero upward velocity. Recently Emslie and Alexander (1987) have suggested that none of the X-ray lines are at their rest wavelengths and that all the plasma is moving at substantial speeds (200 km s$^{-1}$) throughout most of the lifetime of a flare. Emslie and Alexander (1987) correctly note that none of the X-ray spectrometers have absolute wavelength calibration ability. However, if the Emslie and Alexander upward velocity for the "stationary" component were also correct, then limb flares would exhibit a substantial proper motion (the upward motion is perpendicular to the line of sight for a limb flare) that would be detected as a continuous change in Bragg angle of the diffracted radiation. Seely and Feldman (1984) have investigated this problem for limb flares and do in fact find a net upward motion during the decay phase of flares. But the upward motion is only about 20 km s$^{-1}$, rather than several hundred km s$^{-1}$. We conclude that the stationary component may not be completely stationary, but could be moving at low speeds of about 20 km s$^{-1}$. Also, according to Antonucci (see Doschek et al. 1986), sometimes larger speeds of about 80 km s$^{-1}$ may be present in the "stationary" component close to the onset of flares. However, the large velocities characteristic of the blueshifted component

Fig. 3.—Iron spectra for the times shown. The line ratio $i/w$ is used to calculate electron temperature. The notation, $i$, $w$, etc. (see also Fig. 4) is from Gabriel (1972). The smooth dashed curves are synthetic spectrum fits to the data. They are not constructed to fit the spectrum at wavelengths longer than 1.87 Å. The error bars are 1 σ errors for the peak counts in line w.

Figures 3 and 4 show spectra of iron and calcium recorded near the beginning of the event compared with spectra recorded well into the rise phase. Note the blue asymmetry on the wings of the resonance lines of Fe xxv and Ca xix (lines marked w in the figures), especially in the early spectra. (The synthetic spectral fits to these data [smooth lines] are discussed in §II.)

In this paper we deconvolve the blueshifted component from a presumed stationary component for most of the available rise phase spectra. We show that we can obtain an approximate temperature for the moving plasma as well as for the stationary plasma. Using the temperatures and absolute fluxes of the stationary and blueshifted components, we obtain emission measures for both components as functions of time during the rise phase. The deconvolution also gives the average velocity and the mean spread of velocities for the moving plasma. If we assume the evaporation model and use mass conservation, the average upflow velocity, and the emission measures, we can deduce the characteristic length of the flare loop or loops that confine hot plasma. We can then compare the deduced loop length with a loop length inferred from the Hα observations. In §III we argue that the June 5 event is composed of an arcade of hot flare loops.

Fig. 4.—Calcium spectra for the times shown. The ratio $k/w$ is used to calculate electron temperature. The smooth curves are synthetic spectrum fits to the data. The error bars are 1 σ errors for the peak counts in line w.
are not found for the stationary component and in this sense we regard the stationary component as not moving.

The iron and calcium spectra are actually rather complex. In addition to the obvious strong lines apparent in Figures 3 and 4, there are many weaker lines that are within the intrinsic line widths of the stronger lines. For example, there are weak satellite lines that blend and merge with the resonance lines of Ca xix and Fe xxv. These lines produce a red asymmetry to the resonance line profiles. Fortunately, the atomic physics of the spectra have been investigated in detail by a number of authors, and the effects of blending can be accurately accounted for.

We use the atomic data in Bely-Dubau et al. (1982a, b) to construct synthetic spectra of iron and calcium. These are the same data as used by Antonucci and colleagues in deconvolving bluelifted components. The calculated intensities for certain lines are in some disagreement (factors of 1.4 or less) with the observed intensities. These are the Fe-like forbidden and intersystem lines. They are not greatly sensitive to physical parameters such as temperature and are not used for diagnostic purposes. The source for the disagreements may be the ionization balance. It is possible to use decay phase spectra, which do not contain bluelifted components, to empirically adjust the calculated intensities of these lines to agree with the observations. Also, relative wavelengths cannot be calculated to the precision of the measured relative wavelengths. We have used decay phase spectra to determine empirical wavelength corrections such that the synthetic spectra closely match the observed spectra in appearance (Seely, Feldman, and Saffronova 1986; Seely and Doschek 1989).

To construct a synthetic spectrum of calcium requires the following information: the average electron temperature of formation in the plasma of Ca xvii and Ca xix, the average ratio of the number density of Ca xvii to Ca xix in the plasma, the ratio of Ca xx to Ca xix, and the full width at half-maximum of the lines (FWHM). The line profiles can be calculated using either Gaussian or Voigt functions. In addition, if the full range of the SOLFLEX spectra are used, we also need the average temperature of formation of Ca xvii and Ca xvii and the abundance ratio of Ca xvii to Ca xvii. However, the Ca xvii lines are not used in the present analysis, and we consider only the spectrum out to 3.22 Å. Note that the effect of a differential emission measure, i.e., multiethernal plasma, is taken into account by using average temperatures and abundance ratios of adjacent ions. The average emission measure of the plasma is derived by using the absolute sensitivity calibration of the spectrometer and requiring that the calculated photon fluxes agree with the observed fluxes.

To construct the entire iron spectrum shown in Figure 3 requires more information, because many more lines of ionization stages below Fe xxv and Fe xxv are present. However, the bluelifted component can only be clearly seen in the Fe xxv line profile, so it is not necessary to calculate the complete spectrum in Figure 3, but only the spectrum out to about 1.87 Å, for which only the average temperature of the Fe xxv and Fe xxv region need be specified, along with the abundance ratio of Fe xxiv to Fe xxv. Actually, it turns out that the entire iron spectrum is not very sensitive to the details of the differential emission measure in any case (Lemen et al. 1984). Furthermore, the ratio of ion abundances of Fe xxiv to Fe xxv and also Ca xviii to Ca xix only strongly affects the line marked q in Figures 3 and 4. This line is unimportant to the deconvolution process, and therefore precise values of the abundance ratios are unimportant for the work in this paper. Line q is empirically fitted to match the observations. Finally, we note that there is a weak contribution to the line intensities due to radiative recombination of Fe xxvi. This contribution is ignored.

In order to construct a synthetic spectrum that contains a bluelifted component, it is necessary to make some assumptions about it. First, it is not at all clear that the bluelifted component is in fact a single component. Feldman et al. (1980) found that a single component Gaussian approximation did not give particularly good fits to the spectrum under discussion in that paper, and they suggested that the actual line profile for the moving component might be much more complicated than a single Gaussian. This conclusion was also reached by Emslie and Alexander (1987) from their theoretical considerations. However, in the absence of a detailed model of the formation of the bluelifted component, the concept of a single bluelifted component is simplest and can be used to determine gross properties of the bluelifted plasma. We make this assumption in this work. The stationary and bluelifted components are described by single Voigt profiles, but the FWHM of the components may be different.

Another difficult quantity to specify before deconvolution is the electron temperature of the bluelifted component. We assume initially that the temperature of the bluelifted component is equal to the temperature of the stationary component. After deconvolution, this assumption can be checked. For the 1979 June 5 flare, the data suggest an effective temperature of the bluelifted component about $3 \times 10^6$ K lower than the temperature of the stationary component. This temperature difference does not produce a large enough effect on the spectra to significantly change the deconvolution results.

Matching a synthetic spectrum to a SOLFLEX spectrum is done interactively with a computer. Initial values of temperature and FWHM are guessed; spectra are computed and overlaid on plotted data. New parameters are estimated and the process is continued until a reasonable fit is achieved. The problem is slightly complicated because the spacecraft solar point was in raster mode during the June 5 flare, and this produces wavelength shifts of portions of the spectra, for some of the data. However, the intensities are usually unaffected by the raster process. We have found from the analysis of decay phase spectra that a Voigt profile provides a slightly better fit than a Gaussian to a single spectrum line. Both a Gaussian and a Voigt profile were used for the June 5 flare. The resultant values of emission measure using the two different fitting functions did not differ by more than about 25%. Temperature differences were much less. These differences do not alter any of the general results discussed in the next section. The appropriate damping constant in the Voigt function is about $a = 0.2$. The results given in the tables that follow were obtained using the Voigt function.

The following results were obtained from the fitting procedure: the absolute flux for the resonance lines of Ca xix and Fe xxv, the temperatures of the stationary component (the temperatures obtained from calcium are lower than the iron temperatures by a few million degrees because of the effect of the differential emission measure), the FWHM for both the bluelifted and stationary components, and the average upflow velocity of the bluelifted plasma. The emission measure of the stationary component can be calculated from the absolute fluxes, the electron temperature, the fractional ion abundances, and the element abundances of iron and calcium.
Ionization equilibrium is assumed, and the ionization equilibrium calculations of Arnaud and Rothenflug (1985) were used. We used the coronal element abundances given in Doschek, Feldman, and Seely (1985).

It remains to describe how the temperature of the blueshifted component is obtained. We can use the flux ratio of the resonance line of Ca xix to Fe xxv to obtain a rough temperature for Fe xxv. This temperature can in turn be used to obtain an approximate temperature for Ca xix. The relationship of the resonance line ratio to the Fe xxv temperature and the relationship of the Ca xix to the Fe xxv temperature, for the stationary emission line component, have been explored for a number of flares using SOLFLEX data. The results of this work are given in Doschek et al. (1989) and were used to obtain the blueshifted plasma temperatures. (We assume that the temperature relationships found for the stationary component are also valid for the blueshifted component.) It turns out that there is a fairly definite relationship between resonance line ratios and temperature, and between the Ca xix and Fe xxv temperature, for individual flares. There is some uncertainty because of the effect of the differential emission measure, but the uncertainty is not large enough to prevent us from estimating the temperature of the blueshifted component. The point is that the ratio of the blueshifted intensity to the stationary intensity is greater for calcium than for iron, an indication that the blueshifted plasma is somewhat cooler than the stationary component plasma.

The results of the deconvolution are given in Tables 1–4 for the rise phase spectra. Some examples of the fits used to derive the data in Tables 1–4 are illustrated in Figure 5, which shows the regions near the resonance lines of Ca xix and Fe xxv for the data shown in Figures 3 and 4. The quality of the fits near the resonance lines is illustrated better in this figure than in Figures 3 and 4. The fits to the remainder of the spectra are shown as the solid lines in Figures 3 and 4. Note that no attempt was made to accurately reproduce the emission from ions such as Fe xxii which are not relevant to the discussion. Note also that the fit in the Figure 3 spectrum recorded at 0512.3 is not satisfactory even for the Fe xxiv and Fe xxv lines between 1.85 and 1.87 Å. This probably indicates that the assumption of a single Gaussian-type profile for the blueshifted component is an oversimplification.

Tables 1 and 2 show that the FWHM of the blueshifted component is much greater than the FWHM of the stationary component (except for late times in the iron spectra). This extremely wide blueshifted component made it difficult to detect possible changes in the average upflow velocity. We found that the data could be fitted by a single upflow speed of between 200 and 250 km s$^{-1}$. An upflow speed of 250 km s$^{-1}$ is representative of most of the data, but changes of about 75 km

## Table 1

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**Note:** Widths ($W$) are in mÅ and refer to the Doppler input into the Voigt function with $a = 0.2$. The intensities are integrated and not peak intensities.

## Table 2

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**Note:** Temperatures are in millions of K. Emission measures are in units of 10$^{48}$ cm$^{-5}$.

## Table 4

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</table>

**Note:** Temperatures are in millions of K. The emission measures are in units of 10$^{48}$ cm$^{-5}$. 
s⁻¹ can give comparable fits to the data. Antonucci and Dennis (1983) found that the upward velocity decreased with increasing emission measure for a number of flares. We did not find a noticeable decrease for the June 5 flare. However, judging from the GOES X-ray data, the X-ray maximum (where the blueshifted plasma should vanish) occurred during eclipse of the spectrometers, about 14 minutes after the last spectrum analyzed. So perhaps the apparent constancy of ν is not inconsistent with the Antonucci and Dennis (1983) results.

As mentioned above, the temperature (Tables 3 and 4) of the blueshifted component for both calcium and iron is less than the temperature of the stationary component. This results in a larger ratio of blueshifted to stationary emission measure for both elements than implied by the intensity ratio of blueshifted to stationary emission. We also found a lower value of the ratio of blueshifted to stationary emission measure for iron than for calcium.

Tables 3 and 4 show that the ratio of blueshifted to stationary emission measure decreases with time during the rise phase. This result has been found previously for many other flares (e.g., Feldman et al. 1980; Antonucci and Dennis 1983).

It is important to note that the above results cannot be generalized to all flares. For example, Karpen, Doschek, and Seely (1986) found that the line widths of the blueshifted and stationary components were about equal for the large flare of 1980 November 7, for which the blueshifted emission was quite strong. It is also evident from inspection of Figure 5 of that paper that the temperature of the blueshifted component in the November 7 flare was about equal to or somewhat larger than the temperature of the stationary component at times near the onset of the event. This conclusion follows from the fact that the blueshifted component is stronger relative to the stationary component for iron than is the case for calcium.

### III. POSSIBLE MORPHOLOGY OF THE 1979 JUNE 5 EVENT

The interpretation of the results in Tables 1-4 could be considerably enhanced if the morphology of the flare could be inferred. This is possible by noting that the June 5 event is an LDE and that investigations of LDEs observed from Skylab allow us to reach some very reasonable conclusions concerning the morphology. In particular, we can infer the approximate maximum lengths of the flare loops from inspection of Skylab data coupled with the June 5 Hz observations.

First, we note that analysis of Skylab flares by Kahler (1977) has shown that LDEs are arcades of loops. The loops are large in size, several arcminutes, as compared with the loop sizes of so-called compact flares, which are typically less than 1’ in length and can be much smaller. We therefore assume that the June 5 flare was composed of several large and bright X-ray-emitting loops.

It would be most helpful if a well-observed Skylab flare could be found with a broad-band X-ray light curve similar in shape and intensity to the June 5 GOES light curve. It would seem fair to assume that while the details of such an event might be much different from the June 5 flare; nevertheless, the overall morphology of the two events should be quite similar. It turns out that there is such a flare, the large LDE of 1973 September 7. This is a famous Skylab event, and detailed analyses of some of the Skylab data have been given by Moore et al. (1980), Withbroe (1978), and Pallavicini and Vaiana (1980). The September 7 event had a long rise time, about 30 minutes, was of X-ray class X1 and had a decay time on the
order of 7 hr. The postflare loop system expanded during this
decay phase. The sizes of these loops were on the order of a few
arcing minutes. We can suppose that the June 5 event would have
exhibited a very similar morphology if images had been
obtained in X-rays.

The September 7 event produced a classical set of double
ribbons. Observations of the event unfortunately began a few
minutes after peak flux. Nevertheless, enough emission in high
temperature lines is present in the NRL S082-A Skylab
spectroheliograph data to show emission in the X-ray
lines of Fe xxv and Ca xix would have occurred. In the S082-A
Skylab data, four major loop systems are observed in lines of
Ca xvii, Fe xvii, and weakly in Fe xxiv, that bridge the double
ribbons. It is obvious that the XUV arcade is not composed of
a continuous set of loops that have a near continuous set of
footpoints at each point along the double ribbons. Rather,
there are just four major loop systems, and in fact most of the
area covered by the double ribbons as seen in Hα is not associ-
ated with any apparent footpoint of a high temperature loop.

Figure 6 (Plate 20) shows some of the Hα images of the June
5 event. The Hα images cover the preflare active region, the rise
phase, and the decay phase over which substantial emission in
Ca xix and Fe xxv is observed. There are some obvious similari-
ities and differences between the June 5 and September 7
events, as observed in Hα. First, the similarities are that both
events are very large, and that during the decay phase of the
June 5 event the June 5 ribbons (A and B in Fig. 6) appear to
move apart from one another as is similarly observed in the
September 7 event. However, a third ribbon (C in Fig. 6) of
emission is also seen in the June 5 event that is associated with
a filament. Inspection of a Kitt Peak magnetogram (a June 6
magnetogram; one was not available on June 5) indicates that
ribbons B and C were of the same polarity, and ribbon A was
of the opposite polarity. The June 5 event may have been
somewhat more complicated than the September 7 event;
however, we assume that the X-ray structures are similar in
overall numbers and sizes, despite the differences in Hα mor-
phology.

We assume that emission from Ca xix and Fe xxv in the
June 5 event arose from several loops with footpoints anchored
in ribbons A and B. In addition, there might have been loops
connecting ribbons A and C. Inspection of the earliest June 5
Hα images obtained near flare onset reveal pointlike bright-
ening in all three ribbons. We consequently conclude that
activation of at least some of the possible high temperature
loops connecting A and B and A and C occurred at about the
same time. By direct measurement of the separations of A and
B and A and C in the June 5 flare it can be seen that the
maximum lengths of the possible loops are about 2:5, assum-
ing a semicircular geometry and an interribbon separation of
about 1:6. This result is important for the interpretation of the
blueshifted emission given in the next section.

IV. INTERPRETATION OF RESULTS

In this section we interpret the results given in Tables 1–4
assuming that the blueshifted component is due to chromo-
spheric evaporation, i.e., we assume that the stationary com-
ponent is produced by evaporating plasma that is stopped and
trapped in closed magnetic flux tubes. Furthermore, from the
results of § III we assume that plasma is evaporated into a
small number (1–10) of large loops with a length of 2:5. Ini-
tially, we assume that evaporation occurs in each loop at about
the same time. This appears to be a reasonable assumption,
because if evaporation began at different times in different
loops, the small number of total loops would imply that the
X-ray light curve would exhibit changes of slope during the rise
phase when new loops were activated. This is not observed.
However, for the sake of a complete discussion, we consider a
sequentially activated loop scenario as well.

The equation of continuity for the evaporating plasma is

\[ \frac{d(N_b V_b)}{dt} = 2N_b v A - \frac{d(N_s V_s)}{dt}, \]

(1)

where \(N_b\) is the electron number density of the blueshifted
evaporating plasma, \(V_b\) is the volume occupied by the evapo-
rating plasma in all loops, the subscript \(s\) denotes similar quanti-
ties for the stationary plasma, \(v\) is the average upflow velocity
of evaporating plasma, and \(A\) is the total cross sectional area
of the loops through which plasma evaporates. This equation
expresses the fact that the plasma that evaporates over the area
\(A\) is eventually converted to stationary plasma. The factor of 2 in
the first term on the right-hand side of equation (1) arises
because there are two loop footpoints. If evaporation occurs
through only one footpoint, then an asymmetrical condition
arises in the loops and numerical simulations indicate that
downflows producing redshifts are expected in addition to the
blueshifts (Cheng, Karpen, and Doschek 1984). Since redshifts
are not observed, we feel that the factor of 2 is justified.

We eliminate one of the densities in equation (1) by using a
numerical simulation result (e.g., Cheng et al. 1983) that shows
that the densities of the moving and stationary plasmas are
comparable. Henceforth, we assume the same density \(N\) for
both moving and stationary plasmas. Two other useful equa-
tions are simply the definitions of the emission measures, i.e.,

\[ E_s = N^2 V_s, \quad E_b = N^2 V_b. \]

(2)

We proceed further by defining a total loop arcade volume
\(V = V_s + V_b = AL\), where \(L\) is the average length of a loop in
the arcade. For the present we regard the total volume of all
loops as a constant, i.e., we assume that all loops are activated
at about the same time. We also define a total emission
measure \(E = E_s + E_b\).

Equations (1) and (2) can be differentiated to get,

\[ (V_b + V_s) \frac{dN}{dt} = 2NaA, \]

\[ \frac{dE}{dt} = 2NV \frac{dN}{dt}, \]

removing that \(dV_b/dt + dV_s/dt = 0\).

Substituting for \(V \frac{dN}{dt}\) gives

\[ \frac{dE}{dt} = 4N^2 v A. \]

(4)

Using the fact that \(V = AL\), equation (4) becomes

\[ \frac{dE}{dt} = 4E/\dot{L}, \]

(5)

which can be integrated to give

\[ E_2/E_1 = \exp \left[ +4(s t_2 - t_1)/L \right], \]

(6)

where \(t_1\) and \(t_2\) are any two times during the rise phase.

Since \(L\) is known from the Hα observations, the assumptions
that are implied by equation (6) can be immediately checked
by using the results in Tables 1–4. Using the emission measures
and the upflow velocity in equation (6) yields unrealistically
large values of \(L\). For example, if we define \(t_1\) and \(t_2\) to be the
last two entries in Table 3, \(t_2 - t_1 \approx 160\) s, \(E_2/E_1 \approx 1.26\), and
using \(v = 220\) km s\(^{-1}\) gives \(L = 6.1 \times 10^5\) km, or about 6 times
larger than derived in § III. Similar results are obtained for other times during the rise phase for the calcium data, although the ratio of loop lengths decreases from 6 to about 2.0 for the earliest times given in Table 3. Similar results are also obtained for the iron spectra. The point is that the total emission measure is increasing too slowly relative to the amount of plasma that is evaporating into the arcade system. Note that this result is obtained without consideration of the relative emission measures of the blueshifted and stationary plasmas.

The above difficulty might be considerably reduced if we imagine a situation in which successive loops are excited along a magnetic neutral line such that the flare spreads along the double ribbon. Evaporation may cease in the earliest loops to be excited, i.e., cooling occurs in these loops, while it continues further along the neutral line. In this case the GOES X-ray light curve might be expected to show some departure from its smoothly increasing rise, which it does not.

However, even in the multiple activation case there is a difficulty in reconciling the observations with the model. Either in the fixed loop volume case or in the multiple activation case it is very useful to note that the amount of moving plasma observed at any given time must become stationary in a time τ that is roughly equal to the time that it takes the plasma to stop moving in the loop, i.e., travel a distance less than L/2. In fact most plasma must be stopped well before L/2 and from inspection of numerical simulation results it is reasonable to adopt a rough distance of \( \sqrt{L/2} = L/6 \).

The time limit τ for blueshifted plasma to become stationary means that the amount \( (N'V) \) of blueshifted plasma observed at any given time t must become stationary plasma in approximately the time, τ. That is, the number of stationary particles \( (N'V) \) must increase by at least \( N'V \) in the time τ. If we ignore the increase in electron density in τ (τ is short compared to the total rise time), then the above constraint can be expressed in terms of emission measures, i.e.,

\[
E_0(t)/N \approx \Delta E_0(t + τ)/N .
\]  

(7)

Equation (7) states that the observed blueshifted emission measure at time t must be converted to stationary plasma emission measure at time \( t + τ \), and that the increase in stationary emission measure \( \Delta E_0 \) in time τ must be approximately equal to \( E_0 \). For an upflow velocity of about 220 km \( s^{-1} \), τ is about 83 s for a loop of length 2.5. Interpolating (the time intervals in the tables are usually larger than τ) emission measures from Tables 3 and 4 and substituting into equation (7) shows that the stationary plasma emission measure fails to increase by \( E_0 \) in time τ near the end of the observed rise phase around 0524, although for the iron data the difference is not very large, about a factor of 2.

Alternatively, the plasma emission measures can be used to derive the actual time necessary for equation (7) to be satisfied. From this time a constant can be calculated using the observed upflow velocity. As an example, for calcium emission measures calculated near 0522 UT, the actual time needed to satisfy equation (7) is about 5.5 minutes. For an upflow speed of 220 km \( s^{-1} \), this corresponds to a distance of about 1.3 half-loop lengths, which is too large. The conclusion is that the assumptions used in the above discussion, whether or not successive loop activation is considered, need modification.

The simplest modification of the initial assumptions is that not all evaporating plasma is confined to closed magnetic structures. If part of the evaporating plasma escapes along open field lines in the form of a high-temperature surge-like phenomenon, then evaporation could still be valid and the derived loop sizes would be much smaller. The escaping plasma could cool on time scales much shorter than the flare rise time and therefore not contribute to the emission measure of the stationary plasma. We consider this to be one straightforward explanation of the above discrepancies. Another explanation is that all of the upflowing plasma is confined by closed structures, but that some of the loops cool quickly before the rise phase is over. This seems artificial in view of the constant and even slightly increasing temperature observed over the rise phase for the confined plasma, and the long time scales evident for both rise and decay phases. It is difficult to explain why some loops should cool while other loops remain hot. In the escaping plasma case this problem is not as apparent since the magnetic geometry of the cooling plasma is postulated to be different from that of the confined plasma.

However, the cooling loop picture is mathematically equivalent to the escaping plasma scenario, and is plausible physically since cooling times for conduction to the chromosphere are reasonably short for a 2.5 loop with a typical density (found for many coronal flares) of about \( 10^{11} \, cm^{-3} \). For example, using the conductive cooling expression given in Feldman, Doschek, and Kreplin (1982) we find that cooling from \( 18 \times 10^6 \, K \) to \( 10 \times 10^6 \, K \) can occur in about 100 s for an emission measure of \( 10^4 \, cm^{-3} \). The point is not that loops cannot cool quickly compared to a 40 minute rise time, but that this picture requires some loops to remain hot and others to cool, without any apparent physical reason for why some loops should cool. Thus, this explanation has the characteristic of an “epicycle.” Furthermore, there is no evidence of cooling in the average plasma temperature.

V. Summary and Conclusions

We have analyzed soft X-ray spectra for the intense flare of 1979 June 5, correlated the spectra with Hz and hard X-ray data, and have reached the following conclusions:

1. The blueshifted component was several million degrees cooler than the stationary component, and using this fact, emission measures for both the blueshifted and stationary components were determined for most of the rise phase.

2. If the blueshifted component is regarded as a single component characterized by a Voigt profile, then the average upflow speed was about 250 km \( s^{-1} \), with little evidence of a decrease in the speed over the time interval of the observations.

3. Unlike many events observed in the SMM data, and unlike the case for the large 1980 November 7 SOLFLEX event, the width of the blueshifted component was about 2 times greater than the width of the stationary component for early times during the rise phase.

4. A hard X-ray spike burst occurred well after the soft X-ray event had begun, indicating that the electrons responsible for this burst and subsequent high energy bursts were not responsible for energizing the soft X-ray source. Although it is not certain beyond a doubt that these bursts are associated with the June 5 flare, no other Hz flare was reported in Solar Geophysical Data at the time of the June 5 event, and no other bright Hz source is evident in the NAOJ solar images.

5. By comparing Hz images of the June 5 flare with Hz and XUV images of the September 7 flare observed from Skylab, it was possible to determine a probable length for the loops emitting Fe xxv and Ca xix in the June 5 flare. This length is about 2.5.
6. From a mass conservation argument, we find that chromospheric evaporation can be responsible for the soft X-ray emission only if some of the ablating plasma is not confined to closed flux tubes and does not contribute to the emission from the stationary component. A mathematically equivalent scenario is that all the blueshifted plasma is confined to closed flux tubes, but that some of it cools on a time scale much shorter than other time scales associated with the event. However, in this case it remains to be explained how some loops can cool quickly while others remain hot for hours, producing the long-duration flare.

7. Since the blueshifted component was observed for at least 28 minutes (limited only by spacecraft night), we can conclude that this component is not produced by an erupting filament as has been suggested by some workers for other flares (e.g., Batchelor 1986).

8. An important more general result is that the blueshifted plasma seen in X-ray spectra is not always “impulsive” in nature. The blueshifted plasma can exist over very long time periods, such as observed for the June 5 event; time periods that are longer than the total lifetimes of very impulsive flares. The blueshifted plasma is more accurately characterized as a flare rise phase phenomenon, rather than an impulsive phenomenon, regardless of the length of the rise time.

This work was partly supported by a NASA grant from the Solar Physics Branch of the Space Physics Division. We thank T. Watanabe for kindly sending us Hα data for the June 5 flare.

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