MULTIWAVELENGTH ANALYSIS OF A WELL OBSERVED FLARE FROM SMM

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Abstract. We describe and analyse observations of an M1.4 flare which began at 17:00 UT on 12 November, 1980. Ground based $H\alpha$ and magnetogram data have been combined with EUV, soft and hard X-ray observations made with instruments on-board the Solar Maximum Mission (SMM) satellite. The preflare phase was marked by a gradual brightening of the flare site in $O\nu$ and the disappearance of an $H\alpha$ filament. Filament ejecta were seen in $O\nu$ moving southward at a speed of about 60 km s$^{-1}$, before the impulsive phase. The flare loop footpoints brightened in $H\alpha$ and the Ca xix resonance line broadened dramatically 2 min before the impulsive phase. Non-thermal hard X-ray emission was detected from the loop footpoints during the impulsive phase while during the same period blue-shifts corresponding to upflows of 200–250 km s$^{-1}$ were seen in Ca xix. Evidence was found for energy deposition in both the chromosphere and corona at a number of stages during the flare. We consider two widely studied mechanisms for the production of the high temperature soft X-ray flare plasma in the corona, i.e. chromospheric evaporation, and a model in which the heating and transfer of material occurs between flux tubes during reconnection.

1. Introduction

Solar flares radiate over a large range of wavelengths from $\gamma$-rays to radio waves (e.g. Švestka, 1981). This is indicative of the large range of physical conditions which exist throughout the flaring plasma. To properly understand the complex processes that constitute a flare, we must analyse data for the same flare from as large a subset of this wavelength range as possible. The advent of the Solar Maximum Mission (SMM), P-78 and HINOTORI satellites have greatly improved our ability to do this. We have combined ground based $H\alpha$ and magnetogram observations with EUV, soft X-ray, and hard X-ray data from SMM for a disk flare which occurred on November 12, 1980. First appearing in $H\alpha$ around 16:59 UT, it lasted for less than 20 min, and was classified as X-ray class M1.4 in the NOAA solar survey listings. It occurred near disk centre at S14 W11 in Hale active region 17255 (Boulder number 2779), which, during it's lifetime, was particularly rich in flares. The flare was most probably a consequence of the

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emergence of new magnetic flux to the south of the trailing sunspot group in the region (Figure 1a). This flare involved three interconnected bright regions. The flare site was connected by large overlying loops to other sites in the active region, which also flared regularly.

2. Magnetograms and Hα Observations

The best spatially resolved data on this flare are ground based Hα photographs, which achieved up to 1" resolution. We have used these, along with magnetograms to place some constraints on the magnetic topology of the flare.

A series of daily magnetograms covering the period about November 12 was obtained from Kitt Peak National Observatory, and the image for November 12 (Figure 1a) was taken at 17:06 UT, covering the thermal phase and aftermath of the flare. It shows that the active region was separated down the centre into two large areas of opposite polarity, negative (black) to the west, and positive to the east. A second region of negative polarity (pointed out in Figure 1a) could be seen in the south–east. From a study of magnetograms for the previous two days we conclude that this represented recently emerged flux. The flare was probably a consequence of this flux emergence and it occurred along the neutral line.

With an area of 2.5 square degrees in Hα, this flare qualified as Hα class 1B. A sequence of off-band Hα photographs, covering the period 16:56–17:16 UT (with 15 s temporal resolution) was provided by the U.S. Air Weather Service Solar Optical Observing Network (SOON), some examples of which are shown in Figure 1b. The most significant features are lettered to aid identification in the text. The relation between the magnetogram and the Hα kernels is shown in Figure 2a.

An Hα photograph at line centre for 16:56 UT shows that a twisted filament lay along the neutral line, between D and E where faint ribbons later appeared. This filament disappeared shortly afterwards, a fact which is generally interpreted to mean that large scale reorganisation of the magnetic field had begun. The light curve (Figure 7e) of the upper transition region Ov line (1371.29 A) peaked twice during the preflare phase, at 16:58 UT and 16:59 UT, with the brightest emission from the regions of the filament ends. This Ov brightening was already in progress at the start of observations at 16:55 UT, which suggests that the filament disruption might have begun before 16:55 UT.

The first Hα brightenings seen were at regions A, B, and C at 16:59:31 UT (Figure 1b), with C the most intense and probably the earliest. This suggests loop connections between C, which was in a region of negative polarity and A, which had

Fig. 1. (a) A magnetogram of active region 2779 taken during the flare. The flare site is indicated by an arrow. The arrow also indicates where new flux emerged in the region. The white frame shows the location of the Hα frames shown in (b). (b) A series of off-band (+0.5 Å) Hα photographs taken during the flare by the U.S. Air Weather Service Solar Optical Observing Network. The most important features are lettered to aid identification in the text.

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positive polarity, and perhaps also between C and those parts of B which had positive polarity (B appears to have straddled the neutral line). A faint ribbon D was also observed to the west of the neutral line. The patches A, B, and C continued to brighten and grow during the next two minutes. A wide diffuse tail appeared to the south of C. This was probably material ejected from the disrupted filament. At 17:01 UT a second ribbon E had appeared. Evenly spaced point-like brightenings occurred along its length. There were similar point-like brightenings along D. It seems therefore that low lying arcades of loops connected E to D. There was a gap of ≈3000 km between D and E. (Features D and E have been referred to as ribbons because of their shape. There is, however, no strong evidence to suggest that they developed like the ribbons in conventional two-ribbon flares).

As the flare progressed the bright patches continued expanding. In particular, A extended further south, and point C which had extended in the north–south direction
already, filled out in an easterly direction. The temporal coincidence of these expansions suggests that a loop or arcade of loops connected the southern end of \( A \) to the eastern edge of \( C \). The footpoints of this brightened from north to south during the period 17 : 01 to 17 : 04 UT and this pattern was observed also in the soft X-ray observations of the XRP and by the UVSP. The H\( \alpha \) emission peaked near 17 : 04 UT. A dark rift between \( B \) and the ribbon \( E \) was now sharply defined, and a new brightening occurred at point \( G \). From then on the intensity decreased throughout. By 17 : 11 UT the flare had shrunk again to three bright patches, slightly displaced from the original kernels.

At 17 : 01 : 31 UT two bright features separated from the diffuse tail and began moving southward with speeds of \( \sim 300 \) km s\(^{-1} \) (Rust et al., 1985). Their points of origin are labelled S in Figure 1b. These were probably ejecta moving along open field lines to the south. Alternatively, they might represent disturbances travelling along large loops which curve around to the west. At 17 : 03 UT a region (labelled W in Figure 1b) 2.5' to the west of point S was seen beginning to brighten, and continued to brighten for \( \sim 10 \) min. The HXIS data showed a disturbance propagating along the loop SW (see Section 4.2).

We shall see later from the HXIS data that there was a loop or arcade connecting S to point A also.

Although we believe that the complete morphology is extremely complex the most important loops were those connecting \( A \) to C, and \( B \) to \( C \). The distance between \( A \) and the centre of \( C \) was \( \approx 2.7 \times 10^9 \) cm, and between \( B \) and \( C \) was \( \approx 2.4 \times 10^9 \) cm. Assuming semi-circular loops shapes with diameters AC and BC we find loop lengths of \( L_{AC} \approx 4.2 \times 10^9 \) cm, and \( L_{BC} \approx 3.6 \times 10^9 \) cm. The diameters of the bright points \( A \) and \( B \) at their initial brightening at 17 : 01 : 13 UT were approximately \( 2.5 \times 10^8 \) cm, which implies that the loop cross-sections at their bases were \( \approx 5 \times 10^{16} \) cm\(^2 \). This is also close to the areas of the bright point remnants at the end of the flare. If we assume constant uniform cross-sections for the loops we find volumes of \( V_{AC} \approx 2.1 \times 10^{26} \) cm\(^3 \) and \( V_{BC} \approx 1.9 \times 10^{26} \) cm\(^3 \). During the flare the initial bright points (\( A \), \( B \), and \( C \)) expanded, probably as more field lines in the arcades were energised, and this expansion roughly trebled the footpoint areas, giving a total volume of \( \approx 1.2 \times 10^{27} \) cm\(^3 \).

### 3. SMM Image Overlay

A large section of *Solar Physics*, Vol. 65, was devoted to a description of SMM and the instruments on board. Of the five instruments on SMM designed to study flaring plasma, four recorded this flare. These were the Hard X-Ray Burst Spectrometer (HXRBS), the Hard X-Ray Imaging Spectrometer (HXIS), the X-Ray Polychromator (XRP) which comprises two instruments the Bent Crystal Spectrometer (BCS) and the Flat Crystal Spectrometer (FCS) observing in soft X-rays, and the Ultra-Violet Spectrometer and Polarimeter (UVSP). Of these only HXIS, FCS, and UVSP were capable of imaging the flare. HXIS has a fixed array of detectors comprising an inner fine field of view with pixel size 8'' \( \times \) 8'' embedded in a large coarse field of view with pixel sizes of 32'' \( \times \) 32'' (Van Beek et al., 1980). Both UVSP and FCS have more...
flexible rastering capabilities with variable raster sizes and positions within their full field of view, and variable step sizes. For this particular flare, during the impulsive and thermal phases both UVSP and FCS were performing $2' \times 2'$ rasters with pixel sizes of $10''$ and $15''$, respectively. The positions of these rasters relative to the HXIS fine field of view are shown in Figure 2a. The Bent Crystal Spectrometer (BCS) has a $6' \times 6'$ field of view which covered all the other frames. The HXRBS is not collimated (Orwig et al., 1980) but no other flare was in progress during this event to confuse the analysis.

Before presenting the data in detail we present an overview of the principal characteristics.

Throughout the flare the FCS and UVSP images, produced by lower temperature ions ($<10^7 \text{ K}$), show separated regions of strong emission, which might have been the footpoints of a loop or arcade of loops. The higher temperature emission ($T > 10^7 \text{ K}$) came from a source lying between these footpoints. The HXIS images are more complex. They show two footpoints during the impulsive phase, but during the thermal phase there was a single extended source between these footpoints. The relative positions of the different images and the positions of features in these images relative to points in the Hα frame are shown in Figure 2. (Note the spatial resolution of the SMM instruments is $>8''$).

To within the spatial resolution of the instruments the O v, O viii, Ne ix, Mg xi, HXIS (bands 1, 2, 5, and 6) and Hα footpoints showed the same separation. The simplest interpretation is that the different emissions originated from nearly the same height in the legs of coronal loops which had footpoints at A, B, and C. The Fe xxv and S xv emissions originated from between these footpoints, as did the Fe xxii emission during the soft X-ray maximum and decay phases, and the HXIS emission during the decay phase. These later emissions identify the coronal sections of the loops.

4. Hard X-Ray Observations

The HXRBS provides uncollimated high time resolution observations of hard X-ray bursts over a range of energies from 29–508 keV. The HXIS complements this dataset with finely resolved images of the X-ray emission in the range 3–30 keV.

4.1. HXRBS Observations

The hard X-ray emission integrated over the energy range 29–508 keV is plotted in Figure 3b. It shows that an initial increase in intensity to twice the background level occurred at 17 : 00 UT, lasting for a minute, and was followed by a steep rise, in a series of sharp spikes to a peak at 17 : 02 : 16 UT. The count rate then dropped back to its preflare value shortly after 17 : 05 UT. Note that the Hα peak occurred shortly before 17 : 04 UT. This delay between Hα and hard X-ray peaks is consistent with previous flare observations (eg. Švestka, 1981). During the impulsive phase the profile showed significant variations over times of order 1–2 s. A weak microwave burst was observed during the impulsive phase.
Fig. 3. (a) X-ray emission recorded by the HXIS in the range 22–30 keV during the flare. (b) Hard X-ray emission recorded by the HXRBS over the energy range 29–508 keV as a function of time. Most of this emission was recorded in the two lowest energy channels (29–57 keV).

Within its energy range, the HXRBS uses 15 different energy channels, and so provides spectral information for the hard X-ray bursts. Most of the emission was recorded by the two lowest energy channels. If the observed spectra are fitted with a power law the spectral index rose from 6, at 17:01 UT at the start of the initial plateau, to 7.5 by 17:02:20 UT at the peak of the impulsive phase. It dropped then to 6.5 before rising to 7.2 at the second peak at 17:03:30 UT. It then fell back to ~6.7 for the remaining minute of the bursts. The hard X-ray spectra were relatively soft.

4.2. HXIS

The Hard X-Ray Imaging Spectrometer provides spatial information of the X-ray emission in 6 energy ranges covering 3.5–30 keV. At this point it is useful to divide the hard X-ray light curves (Figure 3) into their distinct phases and relate them to the equivalent HXIS spatial features. We should bear in mind of course that because of its lower energy range, HXIS will give a greater response to the thermal component than
does HXRBS. Figure 3b divides into 5 stages, the pre-impulsive phase (up to 17:00 UT), the 1 min steady burst beginning at 17:00 UT, the sharp rise of the impulsive phase over the next minute (17:01–17:02 UT), the peak about 17:02 UT, and finally the decay phase.

Figures 4 and 5 show the HXIS images in 3.5–5.8 keV and 16–30 keV channels respectively, for these periods. Some preflare activity was visible in the 3.5–8 keV channels (Figure 4a) for several minutes before the onset of the impulsive phase at 17:00 UT.

3.5–8.0 keV

![Images showing X-ray channel transitions over time](image)

Fig. 4. Images in the soft X-ray channels (3.5–8 keV) of the HXIS throughout the flare. The feature to the right (west) in frame (a) represents the final stages in the decay of a previous flare. The contour levels are 40, 80, 160, 320, 640, 1200, and 2400 counts per pixel.

By 16:58 UT the ratio of counts in the lower energy channels was consistent with a thermal source at \((11 \pm 1) \times 10^6\) K, but with a significant high energy extension to 16 keV at the point labelled C in the Hα photographs.

The 3.5–8 keV light curve (Figure 7a) began to rise at 16:59:40 UT. This brightening occurred at C and was seen during the next 100 seconds propagating toward the eastern Hα bright point A, with a speed of approximately 200 km s\(^{-1}\).
During the first minute (17:00–17:01 UT) of the impulsive phase, the HXRBS light curve remained steady at twice the background level. This ‘plateau-like’ feature was not seen in the total 22–30 keV HXIS light curves (Figure 3a) probably because of lower sensitivity.

Between 17:01 UT and 17:02 UT both C and A brightened dramatically (Figures 4c, d, and 5a). At this time a disturbance could also be seen moving to the South. This coincided with a southward moving feature seen in Hα and Ov, which was interpreted as ejecta resulting from a filament eruption. Rust et al. (1975) have described similar Hα, EUV, and soft X-ray brightenings associated with a flare filament eruption. At the time of the hard X-ray peak at 17:02 UT, two separated bright points were still visible in the 16–30 keV image (Figure 5b), although the region between them had brightened considerably. The bright point A and the loop top were then of comparable intensity in the softer X-ray channels (Figure 4d).

The hard X-ray light curve reached a second peak at about 17:03 UT and then dropped over the next 2 min to its preflare value. Figure 5c covers the interval around this second peak, and it shows that the loop tops have brightened. By 17:05 UT, diffuse emission from the central pixels imaging the loop tops dominated what weak emission persisted. The strongest hard X-ray emission throughout the event came from the footpoint regions.

Fig. 5. Hard X-ray images (16–30 keV) from the HXIS. The contour levels are 2, 4, 8, and 16 counts per pixel.

The light curve for the HXIS pixel imaging point A shows two peaks. The first (at 17:02:30 UT) was well correlated with the peak in a pixel 40" directly to the south. This pixel was the site of the two isolated brightenings (S in Figure 1b) seen in Hα at
17:01:13 UT which developed into the moving features travelling toward W. This connection helps us to establish further the magnetic field structure. However this region, S, did not receive a large proportion of the total flare energy.

The region S, to the south, was also connected by a very large loop to a point, W, 2.5° to the west which was imaged outside the fine field of view. The 3.5–8 keV pixel intensities for these points showed two peaks, at 17:05 and 17:15 UT at S, and at 17:09 and 17:24 UT at W. We previously noted a brightening at W, seen in Hα beginning at 17:10 UT.

5. XRP Soft X-Ray Observations

The X-Ray Polychromator has two instruments, the Bent Crystal Spectrometer (BCS), which provides good spectral and temporal coverage of soft X-ray emission in the range 1.7–3.3 Å, and the Flat Crystal Spectrometer (FCS), which can image the flare or perform high spectral resolution scans in 7 wavelength regions covering 1.7–3.2 Å. These instruments are described in detail by Acton et al. (1980).

5.1. FCS

Before and throughout the flare, FCS was operating in rastering mode at the crystal drive home position. This means that the observations were made near the peak of the resonance lines of the H- and He-like ions, FeXXV (50 × 10^6 K), SXXV (16 × 10^6 K), SiXIII (9.5 × 10^6 K), MgXI (6 × 10^6 K), NeIX (3.5 × 10^6 K), and O VIII (3 × 10^6 K). The temperatures in brackets indicate the peaks of the theoretical contribution functions for these lines. The actual temperatures of formation will be weighted by the thermal structure of the emitting regions. Thus we have sets of 6 rasters simultaneously imaging different temperature ranges in the coronal gas. Initially these rasters covered 4° × 4° of the full 7° × 7° field of view and were centered 17" W and 37" N of the flare site. At 16:57:39 UT, the first of three sets of 3° × 3° (15° steps) rasters was begun 45" W of the flare site. A series of 2° × 2° (15") rasters was then performed about the MgXI brightest pixel of the previous 3° × 3° raster. These began at 17:01:10 UT and continued at this position for the remainder of the flare with a repeat time of 70 s. Note that the flaring region of the rasters was imaged roughly 45 s after the start of each raster. A selection of the images is illustrated in the contour plots of Figure 6.

The summed counts for 17:01:10 to 17:15:00 UT are plotted for five of the channels in Figure 7d. (The FeXXV light curve recorded by FCS is similar to that of the BCS, Figure 7b). These plots, together with the BCS FeXXV (Figure 7b) and CaXIX (Figure 7c) show that within the temporal resolution, the lines peaked in order of decreasing temperature of formation (i.e. FeXXV earliest and O VIII latest), as is usually observed.

These curves and contours highlight the multi-thermal nature of the coronal plasma. For reasonable flare coronal densities (≈ 5 × 10^{10} cm^{-3}), the ionization and recombination timescales for these ions are short (<20 s – Mewe and Schrijver, 1980).
Fig. 6. Contour maps generated from a selection of FCS images in soft X-ray He-like and H-like resonance lines which sample a range of coronal temperatures from $3.5 \times 10^6$ K (Ne IX) to $5 \times 10^7$ K (Fe XXV). The times listed are the raster start times. The flaring pixels were monitored ~45 s later.

Therefore the timescales associated with Figure 7 can be regarded as the timescales for change of the differential emission measure.

The images in the lower temperature lines give the impression of two footpoint regions, while the Fe XXV and S XV emission appeared from a source (or sources) centred between these footpoints. As the thermal phase progressed the high temperature lines faded and the ‘footpoints’ in the lower temperature lines moved closer together. There was also a noticeable southward shift, seen in the Fe XXV rasters between 17:02:20 and 17:03:30 UT. This coincided with similar southward shifts seen in
Hα, by HXIS, and as we shall see later by UVSP (Fe XXI), and might be the same ‘coronal explosion’ phenomenon identified by de Jager and Boeele (1984).

These footpoints were separated by 34″ (≈ 2.5 × 10⁹ cm) initially. From the overlay diagram (Figure 2), we can see that the southern footpoint corresponds to the expanded patch C in the Hα images, while to within the spatial resolution available the northern footpoint was in the same position as the northern HXIS footpoint, and Hα kernel A.

The central appearance of the Fe XXV and S XV emission at the start of the soft X-ray flare (Figure 6) points to some in situ heating of the loop tops. If these high temperatures were due to material heated and evaporated from the footpoints we would expect to have seen some bright footpoint emission in Fe XXV and S XV, since before evaporation, the hot material would be dense and so have a higher emission measure. We return to this point in greater detail later (see Section 7.2).

5.2. BCS

The curved crystals of the Bent Crystal Spectrometer allow it to observe continuously 8 wavelength bands in the range 1.765–3.226 Å, with a time resolution as short as 0.128 s. Included in this range are the resonance, forbidden and intercombination lines along with dielectronic satellites in Ca XIX (3.165–3.226 Å) and Fe XXV (1.843–1.896 Å). The instrument has a 6′ × 6′ FWHM collimator, and is described in detail by Acton et al. (1980).

Figures 7b, c show the light curves for the complete Fe XXV and Ca XIX channels. From 17:00 UT they rose to 600 cts s⁻¹ for Ca XIX and 160 cts s⁻¹ for Fe XXV over a period of roughly 4 min. The Fe XXV curve was similar to its FCS counterpart as regards timing. Ca XIX emission peaked after Fe XXV but before S XV. The decay in Fe XXV took 5–6 min. The Ca XIX count rate dropped steadily for about 6 min to twice the preflare level and took another 10 min to fall the rest of the way.

During the rise phase Ca XIX showed broadening and a blue-shifted component. The blueshifted component was first observed at 17:01:30 ± 30 UT with a velocity of 240 km s⁻¹. We note that these velocities are of the same order as the ion sound speed in a 10⁷ K plasma.

The averaged electron and effective ion temperatures of the source plasma can be derived by fitting synthetic theoretical spectra to the observed spectra (Antonucci et al., 1982; Bely-Dubau et al., 1982). The electron temperature of the Ca XIX source is plotted in Figure 7f. It had an averaged temperature of 9.2 × 10⁶ K at 16:56 UT. It is difficult to measure lower values of $T_e$ because by then the lower emissivity leads to small count rates in the lines. Rising through 1.1 × 10⁷ at 17:00 UT, it peaked by 17:04 UT at 1.64 × 10⁷ K and then dropped to 10⁷ at 17:08 UT where it levelled off. (The temperatures derived from the Fe XXV spectra were typically ~ 20 × 10⁶ K though because of poor statistics the error bars on these measurements were large.) The error bars are difficult to determine because of the nature of the analysis. Those shown for $T_e$ indicate statistical error due to count numbers only. The accuracy of the fitting and systematic errors in the fitting program’s atomic data may increase this substantially.

The effective ion temperature derived from the resonance line width, showed a
Fig. 7. Soft X-ray and EUV light curves for the flare. The axis scales are linear with the highest and lowest values for each curve marked for reference. Units are counts s\(^{-1}\) except in (f) where the Ca XIX temperatures are shown in K. (a) Light curve for the 3.5–8 keV X-rays recorded by HXIS. (b) Light curve for all the bins in channel 4 (Fe XXV resonance line and satellites) of the BCS. (c) Light curves for channel 1 (Ca XIX resonance line and satellites) of the BCS. (d) Light curves for five channels of the FCS integrated over the full rasters. (e) The count-rates in O V and Fe XXI summed over the full UVSP raster. (f) The electron temperature (solid curve) and effective ion temperature (dotted curve) as a function of time, derived from an analysis of the Ca XIX spectra. The error bars represent only the effects of ±1σ variation of the counts used in deriving the line ratios on the temperature estimates.
considerable increase above $T_e$ (Figure 7f) around the impulsive phase where it rose to $36 \times 10^6$ K (corresponding to a FWHM of 2.1 mÅ). This began at least 1 min before any rise in hard X-ray intensity. If this is interpreted as microturbulent broadening, the turbulent velocities inferred from the Ca xix resonance line widths were largest in the preflare phase between 16:59 and 17:01 UT when they averaged $120 \text{ km s}^{-1}$, dropping to insignificant values at soft X-ray maximum.

The blue shifts seen in Ca xix can be interpreted as evidence for chromospheric evaporation early in the flare. At 16:55 UT the Ca xix emission measure was $4 \times 10^{48} \text{ cm}^{-3}$. By 17:01:30 ± 30 UT, when the blue-shifted component was first detected, the emission measure had risen to $6 \times 10^{48} \text{ cm}^{-3}$. No significant blue-shifted component was detected after 17:05 UT. The emission measure peaked around 17:06 UT at $1.4 \times 10^{49} \text{ cm}^{-3}$.

If we assume that the flare-associated Ca xix source occupied the volume of $10^{27} \text{ cm}^{-3}$ which we determined from the H α photographs, then this rise in emission measure represented a rise in the flare coronal density from $\leq 5 \times 10^{10} \text{ cm}^{-3}$ at 17:00 UT to $12 \times 10^{10} \text{ cm}^{-3}$ at 17:07 UT.

At 17:09 UT some non-thermal structure was again apparent in the resonance line, lasting for some minutes. Timing considerations suggest that this was produced by activity in the long loop, SW, stretching to the west. Blue-shifted components representing upflows of $\sim 150 \text{ km s}^{-1}$ appear to have been present.

6. UVSP Observations

The Ultra-Violet Spectrometer and Polarimeter is perhaps the most flexible of all the SMM instruments, being capable of many different observing modes. It has been described by Woodgate et al. (1980).

For this orbit of the satellite, UVSP was operating with a slit set which recorded simultaneous and co-spatial emission from Fe xxi (1354.1 Å) and O v (1371.3 Å). The Fe xxi ion is formed at about $10^7$ K, and the O v at $2 \times 10^5$ K in the transition region. Thus, the observing mode allows for direct comparison of transition region and coronal emission.

Rasters of size $2' \times 2'$ were made every 12 s until the line intensity began to rise significantly. Then the rasters were alternated with spectral scans across the Fe xxi and O v lines, which were taken at the position of maximum Fe xxi emission. This was located at footpoint C until 17:03 UT, and then moved to the pixel imaging the loop tops. These scans were done to allow an accurate determination of the true Fe xxi intensity. Because Fe xxi (1354.1 Å) is partially blended with a narrow C i line at 1354.29 Å, it was necessary to offset the wavelength position 0.15 Å to the blue during the rasters. The scans allow us to integrate across the Fe xxi and O v lines and correct the intensity for this offset. They also show the contribution of the time-dependent continuum to the lines. The rasters each took 15 s and the scans 30 s. The raster pixels each subtended $10'' \times 10''$ at the spacecraft, and the exit slit widths were 0.3 Å for both
detectors. The flare mode (i.e. alternate rasters and scans) was initiated at 17:00:06 UT.

Our first requirement is to clarify the true level of Fe XXI and O V emission. The line scans spanned 3 Å in both channels in 0.1 Å steps and were designed to cover 5 different lines, Fe XXI (1354.1 Å), O V (1371.29 Å), C I (1354.19 Å, 1355.84 Å), and O I (1355.6 Å). In the early stages the low temperature O V, O I, and C I lines dominated. A weak Fe XXI contribution was visible which was some 2–3 times the continuum contribution. At later times we saw Fe XXI dominant, and all the transition region lines greatly diminished. Then the continuum contributed less than 4% to the measured intensity in the Fe XXI channel.

Observations made with the NRL instrument on Skylab show the presence of two potential blends (at 1371.05 Å and 1371.37 Å) with the O V line at 1371.29 Å in the spectrum of the 1973, June 15 flare (Feldman et al., 1977). These lines are discussed further by Jordan (1985). The behaviour of the lines is similar to that of lines of H₂ and CO excited by resonance fluorescence with strong transition region lines, i.e. they are strongest during the impulsive phase. Therefore we caution that the O V emission during the impulsive phase may have a blended resonance fluorescence component.

Fig. 8. Images of the flare at transition region (O V) and coronal (Fe XXI) temperatures recorded by the UVSP. The O V contour levels are 300, 600, 900, 1200, 1400, and 1600 counts s⁻¹, and the Fe XXI levels are 200, 600, 1000, 1300, 1600, 1900, 2200, 2500, and 2800 counts s⁻¹.
A selection of the rasters have been contoured and are displayed in Figure 8. The summed counts for the two detectors are plotted as a function of time in Figure 7e. The O\textsc{v} emission began to increase before HXRBS showed any rise in count rate. The O\textsc{v} rasters showed the same broad tail extending to the south–east that was seen to develop in H\alpha. This distinctive feature was useful in adjusting the UVSP/H\alpha overlay in Figure 2. The site of this preimpulsive phase O\textsc{v} emission is illustrated in Figure 8 at 16:59:26 UT. It came from a long broad structure most intense to the south in the ‘tail’ between C and S (see Figure 1b), with a weaker footpoint in the pixel covering the northern end of the filament. The southern brightening moved steadily southward at a speed of $\sim 100$ km s\(^{-1}\), and was spatially coincident with the southward propagating disturbance seen by HXIS. This suggests that the preflares O\textsc{v} emission was associated with the disruption of the filament. The peak of this filament associated O\textsc{v} emission occurred between 16:58 and 16:59 UT.

At 17:00 UT the loop footpoints began to brighten in O\textsc{v}. By 17:02:05 UT two strong footpoints had appeared, in the same positions as the H\alpha footpoints A/B and C (which have already been identified with the HXIS footpoints). Note that the UVSP field-of-view did not include all of footpoint A/B. At 17:02 UT the emission measure in O\textsc{v} was $6 \times 10^{47}$ cm\(^{-3}\). By 17:05:52 UT however the O\textsc{v} intensity had greatly diminished. From spectral scans in Fe\textsc{xxi} at footpoint C we know that Fe\textsc{xxi} also brightened at 17:00 UT (this was probably also true of the other footpoints, but we have no line scans to verify it). This strengthened during the next minute, but soon was dominated by emission from the pixels between the footpoints. It peaked at this position about 17:05 UT, when its emission measure was $5 \times 10^{48}$ cm\(^{-3}\).

Both O\textsc{v} and Fe\textsc{xxi} line widths have been measured from the line scans. The O\textsc{v} line was symmetrical with an approximately constant 0.17 Å FWHM, over the period 17:00–17:06 UT. This corresponded to a Doppler temperature of $1.2 \times 10^6$ K, or assuming a temperature of formation for O\textsc{v} of $2 \times 10^5$ K, to turbulent velocities of 35 km s\(^{-1}\). During the period 17:00:06–17:03:07 UT the Fe\textsc{xxi} profile was asymmetrical towards the blue. This could be partially accounted for by the low temperature line at 1353.55 Å (Cohen et al., 1977; Jordan, 1984) but some upward motion is indicated. The spectral scans did not extend far enough to record the blue-shifted component (240 km s\(^{-1}\)) seen in the Ca\textsc{xix} emission.

Later scans (17:03:52–17:07:08 UT) which were taken at the peak in Fe\textsc{xxi} emission were symmetrical, consistent with an ion temperature of $12 \times 10^6$ K.

7. Discussion

7.1. Observational summary

We can summarize the most important observational points as follows:

(1) The flare occurred along the neutral line in a complex magnetic region. It was probably a consequence of the emergence of new magnetic flux just to the south of the neutral line.
(2) The flare was in progress for several minutes before the start of the hard X-ray bursts. A filament disappearance marked the flare onset. The disruption of the filament was accompanied by enhanced emission in O v ($T \approx 10^5$). The earliest brightening was seen in O v along the filament $>4$ min before the hard X-ray bursts. Filament ejecta were first seen moving to the south in H$\alpha$, O v, and the HXIS soft X-ray channel about 2 min before the hard X-ray burst.

(3) H$\alpha$ bright kernels began appearing a couple of minutes later. At about the same time, and before the start of the hard X-ray burst, significant non-thermal broadening ($v_{\text{turb}} \approx 100 \text{ km s}^{-1}$) was observed in Ca xix lines.

(4) The hard X-ray count-rate first rose significantly at 17:00 UT and remained at this level for $\sim 1$ min before rising sharply. The hard X-ray energy spectrum was always soft.

(5) The comparison of high-temperature X-ray images with lower temperature UV and H$\alpha$ images and with a magnetogram indicates a complex morphology of flaring loops connecting the bright H$\alpha$ regions.

(6) The spatial and temporal coincidence of the hard X-ray, H$\alpha$, and O v brightenings during the impulsive phase indicate significant energy deposition at the footpoints of the loop.

(7) Soft X-ray images from FCS show that the emission in the highest temperature line (Fe xxv at $T \approx 20 \times 10^6$ K) was brightest at the tops of the loops in the early flare phases and at the time of the peak of the hard X-ray burst. This suggests some in situ heating at the loop top. On the contrary, the emission in lower temperature lines (e.g. Ne ix and Mg xi at $T \approx 4-6 \times 10^6$ K) was spatially coincident with the H$\alpha$ bright regions and loop footpoints throughout the flare evolution.

(8) Fe xxii emission (at $T \approx 10 \times 10^6$ K) seen by the UVSP, peaked several minutes after the maximum of the hard X-ray burst. The location of these emissions in the region between the footpoints, and the time delay of maximum emission, may be taken as evidence of filling of coronal loops by evaporated chromospheric material.

(9) Upflows were detected in the high temperature plasmas (Ca xix emission) during the impulsive phase. The derived velocities ($v_{\text{up}} \approx 200-300$ km s$^{-1}$) were always subsonic.

(10) The main flaring site was magnetically connected to regions at distant as a few arc min. X-ray observations from HXIS show evidence of disturbances propagating with velocities of $\sim 1000$ km s$^{-1}$ along these magnetic connections (Rust et al., 1985).

The magnetogram evidence and the early disappearance of the H$\alpha$ filament are consistent with newly emerged flux having triggered the flare. This could happen in three different ways (e.g. Spicer, 1977) depending on whether the emerging flux acts merely to perturb an overlying sheared magnetic configuration which is already in a state of marginal stability, whether the flux itself becomes unstable as it rises, or whether the energy release occurs through reconnection between the old and newly emerged flux.

In the first two models – which we shall refer to as the ‘unstable arch’ models – the emerging flux may perturb an already sheared and marginally stable magnetic configuration or it may become unstable itself as it rises. MHD macro-instabilities (e.g. the
tearing modes) are excited with an associated release of energy. If the temperature at the energy release site(s) were sufficiently high, thermal hard X-ray emission would result. Conduction fronts and particle beams would be generated at the energy release site(s), and these would then transport energy to the footpoints of the loops. This excites hard X-ray, EUV, and Hα emission and heats chromospheric material to coronal temperatures, which then rises to fill the loops. The soft X-ray flare is therefore, a product of chromospheric evaporation (Antiochos and Sturrock, 1978; Antonucci et al., 1984).

The third model is known in the literature as the 'emerging flux' model (Heyvaerts et al., 1977). In this case the emerging flux pushes up against the existing flux, forming neutral sheets between them. Reconnection occurs at these interfaces, and again the energy release can generate conduction fronts and particle beams. In this case, however, the emerging flux tubes may be cooler and denser than the overlying ones with which they reconnect. During the reconnection process this cool dense material is heated to above 10⁷ K and this produces the soft X-ray flare. The accelerated particles can travel down the legs of the lower density pre-existing flux tubes and so produce non-thermal thick target hard X-ray emission.

Important aspects of these models which our observations can address are the stages and sites of the energy release, the source of the soft X-ray plasma and the relationship between the soft and hard X-ray flares. We shall now discuss these issues within the framework of the flare models outlined above.

7.2. ENERGY RELEASE STAGES AND SITES

There were three identifiable energy release phases during this flare:

The first was associated with the filament disruption and brightening in OⅦ, and occurred over a wide area, beginning at 16:56 UT.

The second was indicated by the large non-thermal broadening of the CaⅩⅨ resonance line seen as early as 16:59 UT. This was accompanied by a slight rise in intensity recorded by the BCS CaⅩⅨ channel and also by a slight rise seen in the HXIS soft X-ray channels (3.5–8 keV). The HXIS images showed this source to be situated at or above the southern footpoint region C.

The third stage was indicated by the hard X-ray emission starting at 17:00 UT. The HXIS 16–30 keV channels place these hard X-ray sources at or above the loop footpoints A/B and C. The main reconnection region was probably above footpoint C since this area was brightest in Hα and hard X-rays. The second peak of the hard X-ray light curve was associated with sources at the expanded footpoint C, and G, indicating a change in the site of the energy deposition.

The coincidence in OⅦ, Hα and hard X-ray brightenings at the loop footpoints during the impulsive phase shows that energy deposition occurred in the chromosphere. There is evidence from radio and Hα observations of two-ribbon flares (Marsh and Hurford, 1980; Kundu et al., 1982) that energy release can also occur in small (≈2") hot kernels at the tops of loops. Is there any evidence of loop top heating in this flare which is not a two-ribbon flare?
To locate the hotter (> 10⁷ K) regions of the flare, we must look at the FCS Fe XXV images and the HXIS images. We might expect these to appear similar but this is not the case. The 3.5–8 keV HXIS images show bright footpoints with weaker (by a factor of 2) emission from the loop tops. The Fe XXV images, however, show bright loop tops with very little footpoint emission. The observed ratio of loop top to footpoint intensities in Fe XXV during the impulsive phase (at 17:02 UT) was roughly 5.

Comparing the emission measures derived from the FCS (Fe XXV) and HXIS pixels imaging the loop top and footpoints at this time, under the crude assumption that the Fe XXV emission originates from an isothermal source at ~20 × 10⁶ K we find that there is more footpoint emission in the HXIS images than could be explained by thermal emission from the Fe XXV emitting plasma. Between 17:02 UT and 17:03 UT, footpoint C is between 3–10 times brighter than we would expect, whereas the intensities in the loop top pixels are roughly consistent. Given these inconsistencies the differences between the HXIS and Fe XXV emissions can only be explained as the result of a significant non-thermal continuum contribution to the footpoint emission recorded by HXIS.

Thus, from the earliest FCS Fe XXV image at 17:02 UT, i.e. the time of the hard X-ray peak, the most intense Fe XXV emission came from the loop tops. The Fe XXV peaked at 17:04 UT and later decayed, with the most intense region always remaining between the H α and softer X-ray (e.g. Ne IX) footpoints. At first sight this may be taken as evidence of some in situ heating at the loop tops. Alternatively, we could interpret the Fe XXV region at the loops tops as hot material accumulated there from upflows starting as early as 17:00 UT and driven by energy deposition at the loop footpoints. With an observed upflow of 250 km s⁻¹ (from Ca XIX) and a loop half-length of L ~ 2 × 10⁹ cm, the time to transfer matter from the loop footpoints to the top would be τ ~ 80 s, consistent with this interpretation. However, since the evaporation region would be much denser and (in the absence of some coronal heating) at the same temperature as the evaporated material, we would expect to see brighter Fe XXV emission from the footpoints than from the loop tops. This is difficult to believe because substantial non-thermal energy occurred only from 17:01 UT (as shown by the HXRS) and the total amount of hot material seen at the loop top at 17:02 UT should be seen evaporating from the chromosphere at times earlier than 17:01 UT. Under these circumstances why do we not see significant footpoint emission in Fe XXV at 17:02 UT when the hard X-ray burst is at its peak and the non-thermal energy deposition is a maximum?

Thus the most consistent interpretation of the impulsive phase observations points to heating in both the chromospheric and coronal plasma.

7.3. The high-temperature soft X-ray flare

The ‘emerging flux’ and ‘unstable arch’ models can differ significantly in their production of the high-temperature (< 10⁷ K) soft X-ray flare. We recall that the BCS spectra show the presence of a blue-shifted component of the Ca XIX resonance line for which the most obvious explanation is upward moving material. This component is present as an asymmetry in the line in addition to any symmetric broadening in excess of the thermal
(and instrumental) width. The flux in the far blue wing rises more rapidly, peaks earlier, and decays more rapidly than that in the line core. The symmetric broadening behaves in a similar manner to the blue wing. Both peak before the electron temperature, as measured from Ca xix intensities (Figure 7f).

Antonucci et al. (1982) have proposed that the emission seen as the blue wing asymmetry is from 'evaporated' material which rises to fill the pre-existing loops thus accounting for all the subsequent high temperature soft X-ray flux.

In the unstable arch models where some preheating of the flare loops can be assumed to have occurred, the preflare Ca xix emission measure of $4 \times 10^{48} \text{ cm}^{-3}$ and the loops' volume of $10^{27} \text{ cm}^{3}$ (see Section 2) give a density of $5 \times 10^{10} \text{ cm}^{-3}$. At this time (i.e. before 17:00 UT) the averaged source temperature was $10^7 \text{ K}$ (Figure 7f). By 17:06 UT the emission measure had risen to $1.4 \times 10^{49} \text{ cm}^{-3}$, corresponding to a density of $1.2 \times 10^{11} \text{ cm}^{-3}$.

The relative timing of the rise and fall of the Ca xix resonance line blue wing and line core are consistent with this picture of evaporation. Also, with the inferred velocities, footpoints areas, loop lengths and evaporation duration, the up-flows can comfortably provide the required mass in the corona. Peres et al. (1985) have further established the viability of this model by using a hydrodynamic loop modelling program to calculate the FCS and BCS light curves for this flare, which are in reasonable agreement with the observations.

The evaporation process could also be responsible for the high temperature soft X-ray emission in the 'emerging flux' model. However, there is another mechanism which might also be important or even dominant. Consider a small dense loop emerging near region C and pushing up against a larger, lower density pre-existing loop. Reconnection begins, bringing some new dense material which is being rapidly heated onto the pre-existing field lines. The lower density of the pre-existing loop then allows the accelerated electrons with energies below 30 keV to traverse the loop producing hard X-ray emission from footpoint A/B. The material that is allowed by reconnection to move into the pre-existing loop will be in a dynamic state and because of its high pressure will expand into the loop. Although conduction fronts and beams travelling down to the chromosphere may cause additional ablation of material this no longer needs to be the main source of the additional material. The blue wing emission would then be emitted by the material rising to fill the larger low density loop. The line core emission would come from both the small hot emerging loop, and from material accumulating in the larger loop.

Both models are consistent with our observations. It is difficult to see how one could choose between them except by substantially increasing the spatial resolution in the EUV and soft X-ray images. The density, temperature and velocity distributions of the up-flowing material could in principle be investigated using the FCS in its crystal scanning mode, and this would help to refine these models.
8. Conclusions

The flare on November 12, 1980 at 17:00 UT was probably a consequence of the emergence of new magnetic flux. Prior to the flare, an Hα filament was observed lying along the neutral line between the loop footpoints observed in the subsequent flare. This area gradually brightened in Ov before the impulsive phase. The filament was already erupting 2 min before the flash phase and filament associated ejecta was imaged in Hα, EUV, and soft X-rays. About this time also the Ca xix resonance line began to broaden dramatically. Thus the flare was in progress for several minutes before the start of the hard X-ray bursts. During the impulsive phase the 3.5–20 keV X-ray images were dominated by bright footpoint emission. The only interpretation of these images which is consistent with the Fe xxv rasters is that the bulk of this footpoint emission was non-thermal continuum. Subsonic upflows of 200–250 km s⁻¹ were detected during the period of hard X-ray emission. The high temperature soft X-ray emission peaked after the hard X-ray bursts ceased, by which time up-flows were no longer detected.

We have shown that heating was required not only in the chromosphere, but also in the corona, and that energy release occurred at a number of stages during the preflare, flash and impulsive phases. The hard and soft X-ray emission was discussed within the context of the ‘unstable arch’ (Spicer, 1977) and ‘emerging flux’ (Heyvaerts et al., 1977) models. Both models are sufficiently flexible to accommodate these observations although the existence of non-thermal hard X-ray emission from two footpoint regions is more easily achieved in the ‘emerging flux’ model, in which accelerated electrons could be injected into the lower density pre-existing loops.

The high-temperature (> 10⁷ K) soft X-ray flare can be explained in terms of chromospheric evaporation in either model. An alternative in the ‘emerging flux’ model is that, during the reconnection process, material in the small dense emerging loop is heated to temperatures of 10⁷ K and higher. Some of this hot material is injected and expands into the lower-density pre-existing loop, thus accounting for the blue-shifted Ca xix emission. These observations cannot discriminate between the two mechanisms. This will only become possible with better spatially and temporally resolved EUV and X-ray images.

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