PLASMA PARAMETERS AND STRUCTURES OF THE X4 FLARE OF 19 MAY 1984 AS OBSERVED BY SMM-XRP

J.T. SCHMELZ[1], J.L.R. SABA[2], and K.T. STRONG[2]

[1]Applied Research Corporation under subcontract to Lockheed PARL

[2]Lockheed Palo Alto Research Laboratory

ABSTRACT

The eruption of a large flare on the east limb of the Sun was observed by the X-Ray Polychromator (XRP) on board the Solar Maximum Mission (SMM) on 19 May 1984. The XRP Flat Crystal Spectrometer (FCS) made polychromatic soft X-ray images during the preflare, flare and postflare phases. The XRP Bent Crystal Spectrometer (BCS) provided information on the temperature and dynamics of the hot ($T_e > 8 \times 10^6$K) coronal plasma from spectra integrated spatially over the whole region.

INTRODUCTION

The XRP instrument observed a major flare from NOAA Active Region (AR) 4492, a complex region on the east limb of the solar disk, which peaked at 2156 UT on 19 May 1984. The flare was classified as X4, with an energy flux of $4 \times 10^{-4} Wm^{-2}$ in the GOES soft X-ray channel. GOES, the Geostationary Operational Environmental Satellite, has a full disk X-ray monitor with a soft X-ray channel (1-8 Å) and a harder channel (0.5-4 Å). The FCS imaged the flare in several soft X-ray lines which are sensitive to different plasma temperatures; ratios of the line fluxes can be used to determine various properties of the plasma. The BCS produced light curves and spectra in Ca XIX and Fe XXV integrated over the entire active region; these provide information on the temperature and dynamics of the high temperature ($T_e > 8 \times 10^6$K) coronal plasma. The flare was observed by other SMM instruments, the Very Large Array, Big Bear Solar Observatory, and Kitt Peak National Observatory; these data will be presented elsewhere.

OBSERVATIONS

XRP consists of two independent but complementary soft X-ray instruments (see Acton et al. 1980): 1) The FCS has six flat Bragg crystals which are mounted such that the detection system can be centered on the resonance lines of prominent H-like and He-like ions in the 1.5 to 20.0 Å part of the electromagnetic spectrum. These resonance lines – O VIII, Ne IX, Mg XI, Si XIII, S XV, and Fe XXV – are sensitive to different plasma temperatures and ratios of the line fluxes can be used to determine the electron temperature (T_e), volume emission measure (EM), and (unit filling factor) density ($n_e f$) of the plasma. The FCS, collimated to 14″ FWHM, can build images by rastering over a portion of a $7' \times 7'$ area with a minimum pixel spacing of 5″, or scan a series of spectral lines at one or more spatial locations. 2) The BCS has eight bent Bragg crystals with position-sensitive detectors. It is collimated to 6′ FWHM and is sensitive to the high-temperature ($T_e > 8 \times 10^6$ K) component of the flare plasma; it provides information on T_e, EM, and the dynamics through light curves and spectra in lines of Ca XIX (peak response at 35×10^6 K) near 3.18 Å and Fe XXV (peak response 70×10^6 K) at 1.91 Å. T_e can be determined as a function of time from the ratio of the dielectronic satellite line flux to the collisionally excited resonance line flux for each ion (k/w in Ca XIX and j/w in Fe XXV in the notation of Gabriel 1972). EM can then be determined using the ion emissivity curves.

The FCS made polychromatic soft X-ray images during the preflare, flare and postflare phases. Contour plots of images taken in the O VIII line at the three phases are shown in Figure 1. The thin lines are photospheric contours from a coaligned white light sensor showing the location of three sunspots and the east limb of the solar disk. Each image was accumulated during a 7′ square raster with 10″ steps which took 30 min to complete.

PREFLARE: During the preflare raster, the entire coronal structure of AR 4492 was imaged in the three softest FCS channels – O VIII (peak response at 3×10^6 K), Ne IX (3.5×10^6 K), and Mg XI (6×10^6 K). During the raster, the full disk intensity seen by GOES was steady at a relatively high C2 ($2 \times 10^{-6} Wm^{-2}$) level.

X4 FLARE: The FCS rastered over the core of the emission at approximately the peak of the X4 flare. Significant counts were detected in all six soft X-ray lines including the three higher energy channels – Si XIII (with peak response at 9.5×10^6 K), S XV (16×10^6 K), and Fe XXV (50×10^6 K), the hottest FCS line. All of the soft X-ray emission displayed is optically thin. The core of the flare seems to be directly over the first sunspot, possibly due to projection effects.

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POSTFLARE: The last set of FCS rasters shows the region cooling and settling into its preflare state. Emission is seen in only the three coolest X-ray channels – O VIII, Ne IX, and Mg XI.

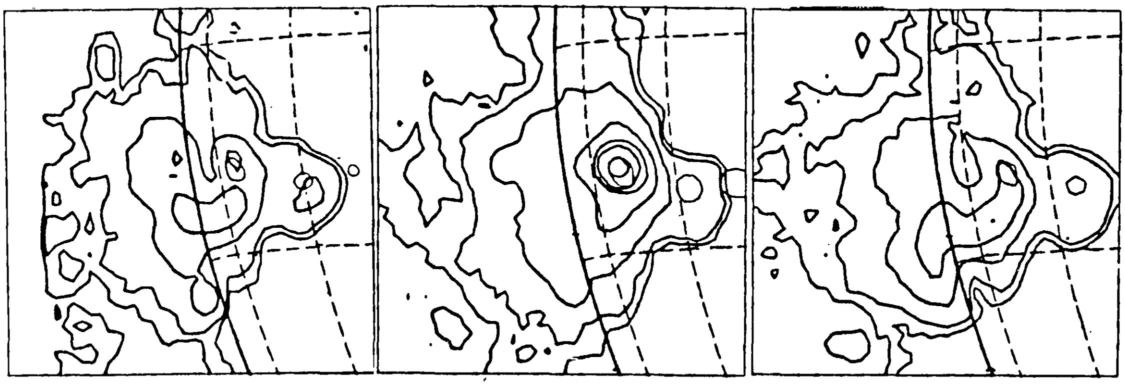

Fig. 1. FCS Soft X-ray maps in O VIII for the preflare, flare, and postflare orbits. Contour levels are 6, 10, 25, 50, 500, 1000, and 2500 counts/s for each image. The thin lines depict the sun spots observed by the coarse, co-aligned white light sensor.

Figure 2 shows sample BCS spectra for the X4 flare in both Ca XIX and Fe XXV (with the temperature sensitive lines labeled) for the hot plasma early in the flare and the cooler plasma later in the flare. The obvious increases in the k/w ratio in Ca XIX and the j/w ratio in Fe XXV correspond to decreasing temperature as the flare proceeds. These line ratios can be converted to temperatures using the atomic physics calculations of Bely-Dubau et al. (1982 and references therein); the emission measure can then be determined using the emissivity curves for each ion.

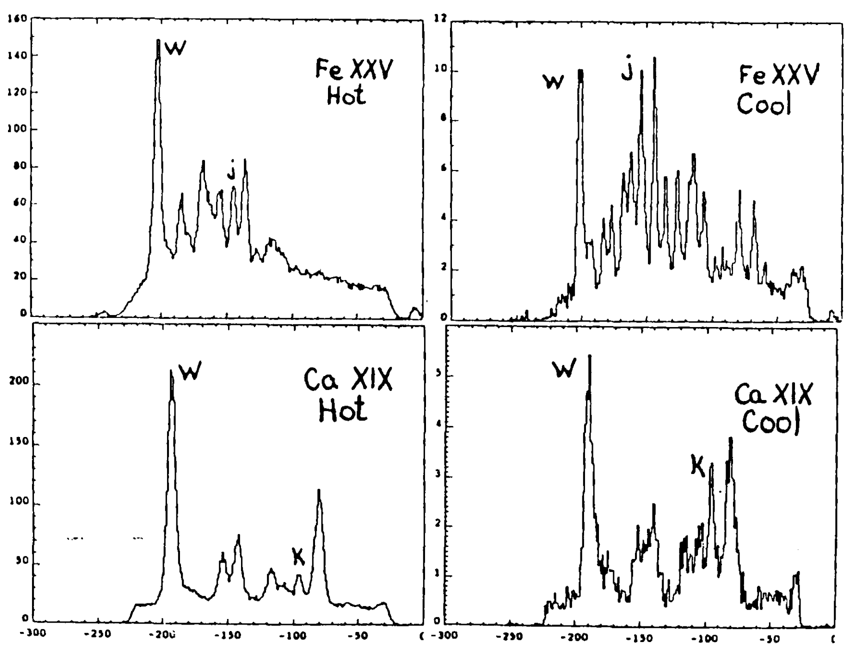

Fig. 2. BCS spectra for Ca XIX and Fe XXV with the temperature sensitive lines labelled.

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RESULTS AND DISCUSSION

A. FCS

The series of FCS maps taken over a six hour period records the effect of this flare on the corona. Even the preflare active region showed a substantial amount of coronal plasma at altitudes of at least 1.85 x 10^5km. The X-ray loops in the high corona showed major changes in the postflare phase. A differential emission measure study (Sylwester et al. 1980) of the soft X-ray line fluxes was used to determine the plasma parameters during the three phases. The preflare active region had $T_e = 4 \times 10^6$K, EM = 1.5 x $10^{47} cm^{-3}$, and $n_e f = 10^{10} cm^{-3}$. In its preflare state, AR 4492 can be characterized as having roughly an isothermal plasma like most quiescent active regions; in such cases, it is typically assumed that a volume filling factor between 1.0 and 0.1 can be applied. During the flare, the emission measure of the flare kernel peaked at several temperatures and the density increased by at least a factor of 10. The plasma parameters derived for the flare were determined after a "pedestal correction" (needed for photon fluorescence effects during large, energetic events) was applied to the detector counts. The resulting temperatures are 10 x 10^6K and 17 x 10^6K, with volume emission measures of 2.7 x 10^{48} and 5.7 x $10^{48} cm^{-3}$, respectively. There is some evidence for a hotter flare component with an order of magnitude lower emission measure. The postflare active region had T_e = 4 x 10^6K, EM = 1.5 x $10^{47} cm^{-3}$, and $n_e f = 10^{10} cm^{-3}$, nearly identical to preflare values.

The return of the active region structure and plasma parameters to approximately their preflare values several hours after the flare indicates that this large flare had little permanent effect on the lower corona. Further evidence for this is given by the continued production of large flares by AR 4492 as it crossed the solar disk. The magnetic structure remained complex; the Hα images show that the flare left a large dark filament undisturbed and the flare is believed to be confined (Schmahl et al. 1988). However, disturbance of the high coronal plasma is seen in the the FCS images where plasma heated up and moved out of the field of view. These images also show some evidence of a shock wave. If this shock was moving along the coronal loop confined by the magnetic field its velocity was approximately 350 km/s; if it broke through the magnetic field and traveled out radially through the high corona its velocity was approximately 250 km/s.

The thermal energy of the flare can be estimated from the formula: $E_{th} = 3 n_e k T_e V$ where V = 9 x $10^{20} cm^2$ x 2 x $10^9 cm$ = 2 x $10^{30} cm^3$ and n_e = 10 x $10^{10} cm^{-3}$ and T_e = 8 x 10^6K. The resulting energy is approximately E_{th} = 4 x 10^{32} ergs, where the greatest uncertainty comes from the volume estimation.

B. BCS

Information on the hotter temperature component of the plasma is available from the BCS spectra. T_e and EM as a function of time are shown in Figure 3. Note the differences in the Fe XXV and Ca XIX results: the electron temperatures determined by the Fe XXV ratio are higher and the emission measures lower than those determined by the Ca XIX ratio. If the lines were produced by an isothermal plasma with "normal" solar abundances, the curves would coincide. This standard method of analysis cannot be applied straight forwardly to a plasma with a temperature distribution or anomalous (or changing) elemental abundances. The inconsistent results for the two ions prompted further investigation into the details of the plasma evolution during this flare.

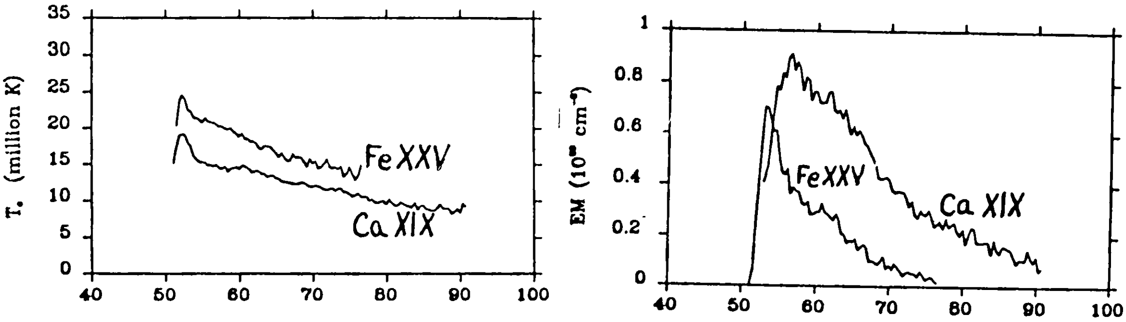

Fig. 3. BCS temperature and emission measure as a function of time after 2100 UT (min).

A simple method was devised to determine the amount of "superhot" plasma present in a flare from simultaneous observations of Ca XIX and Fe XXV spectra: 1) A plasma electron temperature and emission measure are determined using the Ca XIX k and w lines. 2) The photon flux *expected* in the Fe XXV w line from this plasma is calculated. 3) From the Ca XIX temperature and the Fe XXV w line flux expected from the Ca XIX emission measure, the *expected* Fe XXV j line flux is determined. 4) The *expected* Fe XXV w (and j) line fluxes are subtracted from the *observed* Fe XXV w (and j) line fluxes. 5) The remainders come from a component whose temperature and emission measure can be determined from the ratio of the w and j flux residuals calculated in 4).

From this method, the temperature determined for the peak of the X4 flare is 33 $\times 10^6$ K, high enough to be considered "superhot;" the emission measure is 1.5 $\times 10^{48} cm^{-3}$, about an order of magnitude lower than that of the cooler component determined from Ca XIX.

CONCLUSIONS

An X4 flare erupted from AR 4492 on 19 May 1984, peaking at 2156 UT. The flare was observed by XRP soft X-ray instruments on SMM. The FCS imaged the preflare, flare, and postflare phases of the event in various resonance lines which are sensitive to different plasma temperatures. Results from a differential emission measure study indicate the preflare active region had T_e = 4 × 10^6K and $n_e f$ = $10^{10} cm^{-3}$. During the flare, the emission measure of the flare kernel peaked at two temperatures, 10×10^6K and 17×10^6K, with some evidence for an even hotter component with an order of magnitude lower emission measure; the average density increased by at least a factor of 10.

The active region structure and plasma parameters returned to approximately their preflare values several hours after the flare. This indicates that this large flare had little permanent effect on the lower corona. This interpretation is supported by the lack of structural changes seen in ground-based data and the continued production of large flares by the region as it transited the disk. However, the FCS images show a disturbance of the high coronal plasma and some evidence of a shock wave. The thermal energy produced by the flare is approximately E_{th} = 4 x 10^{32} ergs, where the greatest uncertainty comes from the volume estimation.

The BCS results seem to confirm the evidence of the superhot component of the flare plasma seen in the FCS differential emission measure study. The temperature determined for the peak of the X4 flare is 33 $\times 10^6$ K; the emission measure is 1.5 $\times 10^{48} cm^{-3}$, about an order of magnitude lower than the component determined from Ca XIX (which agrees with the FCS results of temperature and emission measure for the hot component). If this method of determining the temperature of a superhot component of large flare is confirmed, it will be possible to examine the BCS data for all the large flares observed during the SMM lifetime over the past solar cycle. Such a survey should show how wide-spread the superhot thermal plasma is and if it varies as a function of the solar cycle.

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REFERENCES

Acton, L.W., et al., Solar Phys. 65, 53, 1980.
Bely-Dubau, F., et al., Mon. Not. R. Astr. Soc. 201, 1135, 1982.
Gabriel, A.H., et al., Mon. Not. R. Astr. Soc. 160, 99, 1972.
Schmahl, E.J., et al., Ap.J., in prep., 1988.
Sylwester, J., Schrijver, H., and Mewe, R., Solar Phys. 67, 285, 1980.