X-RAY SPECTRA OF SOLAR FLARES OBTAINED WITH A HIGH-RESOLUTION BENT CRYSTAL SPECTROMETER

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ABSTRACT

Preliminary results obtained for three solar flares with the Bent Crystal Spectrometer on the SMM are presented. Resonance and satellite lines of Ca xix and xviii and Fe xxv and xxiv are observed together with the Fe xxvi Lyα line. Plasma properties are deduced from line ratios and evidence is presented for changes of line widths coincident with the occurrence of a hard X-ray impulsive burst. Fe Ka spectra from a disk center and a limb flare agree with the predictions of a fluorescence excitation model. However, a transient Fe Ka burst observed in a third flare may be explained by the collisional ionization of cool iron by energetic electrons.

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

I. INTRODUCTION

The results presented here were obtained with the Bent Crystal Spectrometer (BCS) on the Solar Maximum Mission (Acton et al. 1980). The instrument differs from crystal spectrometers previously used for solar X-ray studies in that eight curved crystals simultaneously diffract and disperse photons into position-sensitive proportional counter detectors. With the exception of the flight of a rocket-borne spectrometer (Catura et al. 1974; Rapley et al. 1977), all previous solar instruments have operated by changing Bragg angle with time to scan in wavelength. The BCS permits eight wavelength ranges to be observed continuously with a time resolution as short as 0.128 s. To date, times in the range 1–11 s have been used. The spectrometers have 6' × 6' (FWHM) collimators, thus allowing one active region to be studied at a time.

In this Letter we report preliminary results from observations of three flares in the wavelength ranges 3.165–3.226 Å (Ca xix and satellites), 1.843–1.896 Å (Fe xxv and satellites), 1.765–1.795 Å (Fe xxvi), and 1.927–1.945 Å (Fe Ka1, Ka2). These events have been selected from more than 200 observed in the period 1980 March–May.

II. OBSERVATIONS

X-ray spectra and light curves from a disk center flare (optical 1B, X-ray M8) on 1980 April 7, are shown in Figure 1. The spacecraft entered sunlight just before the peak of the X-ray event, so that light curves

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Spectra are also presented for two additional flares. Figure 2a shows the Kα spectrum registered during a 350 s period of an M2 class X-ray flare (optical class N) which occurred at the solar limb on 1980 April 30 at 20:21:00 UT (see Gabriel et al. 1981 for a more detailed discussion). The lines are considerably fainter relative to the continuum than was the case for the 1980 April 7 event.

The third flare, observed on 1980 March 29 at 09:18:06 UT, showed an impulsive precursor in the Fe Kα lines. A light curve of the flux in these lines is shown in Figure 3a together with the curve for a simultaneously observed hard X-ray burst (Dennis, Frost, and Orwig 1981). The Fe Kα spectrum obtained during the 20 s burst is shown in Figure 3b.

### III. DISCUSSION

The Ca xix and Fe xxv resonance line light curves show a previously unachieved combination of wavelength and time resolution. Following the earlier discussion of the satellite line intensities (Gabriel, Jordan, and Paget 1969), electron temperatures have been derived from the Ca xix k satellite-to-resonance line ratio using calculations by Bhalla, Gabriel, and Pressnyakova (1975) and F. Bely-Dubau, J. Dubau, P. Faucher, L. Steenman-Clark, and S. Volonte (private communication). For the April 7 flare (Fig. 1a) the temperature decreases from around 16 x 10^6 K at 05:38:00 UT to 12 x 10^6 K near the end of the event. The j satellite-to-resonance line ratio for Fe xxv, (Bely-Dubau et al. 1981), shows temperature decreasing from 22 x 10^6 K to 16 x 10^6 K. Thus the Fe lines are formed in different regions from that of the Ca lines. The line widths are initially very broad but become narrower after the hard X-ray impulsive event. If interpreted as turbulent velocities, the Ca xix resonance line measurements indicate a change from 100 km s^-1 at the peak to 60 km s^-1 (see also Feldman et al. 1980). Higher values (170 km s^-1) have been observed in association with hard X-ray bursts during the rising phases of other Ca xix events (e.g., 1980 March 29). Alternatively, the line broadening may be interpreted as a decrease of ion temperature from 40 x 10^6 K to 20 x 10^6 K. The fact that the Fe xxv and Ca xix light curves peak at different times together with the difference in the electron temperature derived from the Fe and Ca spectra indicate the complex multithermal nature of the plasma. These light curves show short-term structure during the event. An increase in intensity occurs at 05:55:50 UT coincident with a small hard X-ray burst. Although no change in electron temperature was observed, a slight increase in the Ca xix resonance line width was noted. Such increases have been observed in the decay phases of several other events.

The ionization-stage abundance ratio \( \frac{N(Li\ ion)}{N(He\ ion)} \) deduced from the q satellite-to-resonance line ratio changes from 0.2 at the time of maximum intensity to 0.3 at the end of the event for Ca xix and from 0.7 to 1.1 for Fe xxv. Comparison of these ratios with the results of ionization equilibrium calculations by Jordan (1970) or by Jacobs et al. (1977) indicates that transient ionizing conditions prevail throughout the event. Similar results have been obtained by Feldman et al. (1980) who suggest that the effect may be due to inaccuracies in the atomic data or in the ionization equilibrium calculations. A comparison of FCS and BCS observations of the flare at peak intensity with calculated line intensities indicates that the effective emission measure \( \int \frac{J'}{N^2} dV \) is 1.4 x 10^{44} cm^-3 at a temperature of 22 10^6 K. Determination of a 3σ upper limit for the Fe xxv \( n = 2 \) dielectronic satellite line at 1.7917 Å (Fig. 1d) indicates \( T_e > 18 \times 10^6 \) K (Dubau et al. 1980).

Previous solar spectra (Neupert et al. 1969; Doschek et al. 1971) have contained a weak feature which has been identified as Fe Kα radiation from low-ionization stages. The absence of this feature from a limb event spectrum led Doschek et al. (1971) to suggest fluorescence as the excitation mechanism, but models involving both inner shell collisional ionization by nonthermal electrons (Acton 1965; Phillips and Neupert 1973) and fluorescence due to the interaction of quasi-thermal X-rays \( (E > 7.1 \text{ keV}) \) with cool photospheric material (Basko 1979; Bai 1979) have been presented. Fe Kα spectra from the disk center (05:38:00 UT, April 7) and limb (20:20:00 UT, April 30) events are shown in Figure 2. The Kα and Kβ transitions are resolved and show the expected intensity ratio. The general similarity of the Fe Kα line curves with those of the Fe xxv and Ca xix lines (Fig. 1a) have led us to compare the Fe Kα line intensities with the predictions of Bai’s (1979) fluorescence model. A height of 0.02 R\( \odot \) above the limb for the hot flare plasma was deduced for the April 30 event from an FCS observation (see Gabriel et al. 1981). The effective emission measure in this case was 3.5 x 10^{44} cm^-3 at a temperature of 23 10^6 K. Following Bai (1979), we may write

\[
F_{\text{Kα}} = f(\theta, h)I_e, \tag{1}
\]

where \( F_{\text{Kα}} \) (photons cm^-2 s^-1) is the flux of Kα and Kβ photons observed at Earth, \( f(\theta, h) \) is a function of the heliocentric angle, \( \theta \), at which the event occurred and its height above the
power law) suggests that the electrons which produced the required Fe Kα emission by fluorescence. Although a long-enduring hard X-ray burst was observed by the HXRBS instrument above 26 keV during the April 7 event (K. J. Frost, private communication), a preliminary estimate of the spectral slope (−9.4 for a power law) suggests that the electrons which produced the X-rays could not have directly excited the observed Kα emission. Thus we conclude that fluorescence, rather than ionization, by high-energy electrons is the preferred excitation mechanism for these Kα lines.

In contrast, the 1980 March 29 event exhibits different behavior, suggesting an impact ionization origin for the Kα emission, at least during the hard X-ray burst. The light curves in Figure 3a show the remarkable time coincidence between the hard X-ray burst and the early Fe Kα spike. The Fe Kα spectrum obtained during the initial 20 s burst is shown in Figure 3b. The data have been summed in wavelength to improve the signal-to-background ratio. We compare the observed flux in the Kα line with that predicted by the thin-target model of Phillips and Neupert (1973), in which the electrons giving rise to the hard X-ray spectrum excite Kα transitions by K-shell ionization of Fe ions. We correct the model fluxes to the currently favored iron abundance $N(Fe)/N(H)$ of $4 \times 10^{-5}$. For the purpose of this analysis, the hard X-ray spectrum measured by the HXRBs instrument was approximated by a simple power law with an index of $-3.2$ (B. R. Dennis, private communication). This was used to deduce the electron flux and thus obtain a Kα line flux of 490 photons cm$^{-2}$ s$^{-1}$, in acceptable agreement with the observed value of 400 photons cm$^{-2}$ s$^{-1}$. An estimate of the Fe Kα flux produced by X-ray burst fluorescence was a factor 5 lower. Fifteen seconds after the impulsive peak, when the hard X-ray burst intensity had dropped by a factor of 20, the Kα flux began to increase again, and by 09:19:00 UT the line intensities as measured from the spectra had reached more than twice their value at the peak of the impulsive burst. We suggest that the impulsive Fe Kα signal detected during the initial 20 s of the 1980 March 29 event may have been generated by the energetic electrons believed to cause the hard X-ray burst and that the subsequent emission was due to X-ray fluorescence.

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