HIGH-RESOLUTION SOLAR FLARE X-RAY SPECTRA

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ABSTRACT

High spectral resolution solar flare spectra have been recorded by four Bragg crystal spectrometers flown by the Naval Research Laboratory on a spacecraft launched 1979 February 24 by the Air Force. The wavelength ranges discussed in this Letter are 1.82–1.97 Å, 2.98–3.07 Å, and 3.14–3.24 Å. Electron temperatures ranging between $12 \times 10^6$ K and $30 \times 10^6$ K are derived from dielectric satellite to resonance line ratios for an X9 flare that occurred on 1979 March 25. Non-thermal motions varying between about 70 and 160 km s$^{-1}$ are derived from line profiles. Equilibrium conditions in the plasma are investigated using lithium-like satellite lines excited by electron impact excitation. Emission measures of about $5 \times 10^{50}$ cm$^{-2}$ are determined for the times of maximum X-ray flux.

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

I. INTRODUCTION

The Naval Research Laboratory has four uncollimated Bragg X-ray crystal spectrometers (SOLFLEX = solar flare X-rays) on the backup Orbiting Solar Observatory (OSO 7) spacecraft launched on 1979 February 24 by the Air Force under the Space Test Program. The instruments record spectra in four narrow-wavelength bands: 1.82–1.97 Å, 2.98–3.07 Å, 3.14–3.24 Å, and 8.26–8.53 Å. These bands henceforth refer to spectrometers I, II, III, and IV, respectively. Spectrometer I observes the well-known iron-line feature produced by Fe xxv and inner-shell transitions in lower ionization stages of iron. Spectrometer II observes La Ca xx, or hydrogen-like calcium, and associated Ca xix satellite lines. Spectrometer III observes primarily lines of Ca xix and associated Ca xvii satellite lines, and spectrometer IV observes primarily 2$I$–$4l$ transitions in Fe xxiv and Fe xxviii and also the $\alpha$ Mg xii line. In this Letter we report preliminary results for flare observations with spectrometers I–III.

II. THE SPECTROMETERS

The crystals for spectrometers I–III are flat Ge crystals ($2d = 4$ Å). The crystals are stepped in Bragg angle in increments of approximately 20° by a stepping motor coupled to a harmonic drive. The crystals can be stepped at four speeds: 2 steps per s, 4 steps per s, 8 steps per s, and 16 steps per s. There are 450 steps in a complete wavelength scan.

The detectors for the spectrometers are argon- and xenon-filled proportional counters with Be windows. The entrance aperture of the crystals is covered with aluminized mylar to eliminate excessive heating of the crystals. The crystals were prepared and mounted by Dr. Richard Deslatte and his group at the National Bureau of Standards (NBS). The rocking curve widths of the crystals are all quite narrow, $\sim 33^\circ$ for spectrometers II and III and $14^\circ$ for spectrometer I. The rocking curve profiles and integrated reflectivities were determined by the NBS group, and the detector efficiencies were measured at NRL. The spectrometers are completely calibrated. A much more detailed description of the instrument is in preparation.

III. RESULTS

We consider spectra recorded by spectrometers I, II, and III of a class X9 flare (1B optical) observed on 1979 March 25 at N10, W77 near 18 UT. Spectrometer IV was saturated by high counting rates for this particular event. Figure 1 shows three spectra of iron. Spectrum (a) was recorded during the time of increasing X-ray flux, spectrum (b) was recorded near the time of X-ray maximum, and spectrum (c) was recorded during the decay phase of the flare. The ordinate scale is counts per $1/32$ s, the data readout rate ($N$). For this event the scan speed was eight steps per second, and a $1 \sigma$ deviation in counting is $(2N)^{1/2}$. The spectra appear similar in many respects, showing that all the strong features are real and not statistical fluctuations. Examples of the calcium spectra recorded by spectrometers II and III are shown in Figure 2.

The iron spectra cover a larger wavelength range than those previously reported by Grineva et al. (1973). Although not shown in Figure 1, our spectra extend to the $\alpha$ feature, while the Grineva et al. (1973) spectra do not extend far beyond 1.87 Å. Recently, recorded iron spectra from the Princeton Large Torus (PLT) tokamak plasma are comparable in spectral resolution to our data (see Bitter et al. 1979; Hill et al. 1979). No solar calcium spectra of the quality of our data have previously been obtained. The identifications of the strongest transitions responsible for the observed emission lines in Figures 1 and 2 are well known (see Gabriel 1972; Bhalla, Gabriel, and Presnyakov 1975; Bely-Dubau, Gabriel, and Volonté 1979a; Hill et al. 1978; Garcia and Mack 1965; Ermolaev, Jones, and Phillips 1972).
Fig. 1.—Flare spectra of iron-line emission near 1.86 Å. Note that the ordinate scale is different for each spectrum, e.g., full-scale for spectrum (a) is $1.2 \times 10^3$ counts/0.0313 s. The wavelength scale is only approximate.

Fig. 2.—Flare spectra of calcium-line emission near 3 Å. Most of the emission of the (z,j) blend is due to line z.
There is no absolute wavelength calibration on SOLFLEX. However, the wavelengths of lines of helium-like ions are known from theoretical calculations such as those by Ermolaev, Jones, and Phillips (1972). The same is true for lines of hydrogen-like ions for which very accurate wavelengths exist (e.g., Garcia and Mack 1965). The resonance, inter-system, and forbidden lines of Ca xix and Fe xxv, and the Ka iron feature, are easily identifiable in the spectra, which allows a wavelength scale to be established. The lines of Fe xxv, Fe xxiv, Ca xix, and Ca xviii are labeled in Figures 1 and 2 using the notation devised by Gabriel (1972). Detailed classifications of the Fe xxiv, Fe xxii, Fe xxi, Fe xx, and Ca xvii lines are not given in this Letter, but will be considered in a subsequent paper. The La Ca xx line was only intense enough to obtain good counting statistics near times of maximum X-ray intensity of the flare (~1810 UT). The line is double because the two fine-structure components are completely resolved, i.e., $1^2S_{1/2}-2^2P_{1/2}$ and $1^2S_{1/2}-2^2P_{1/2}$. The line marked $J$ is the Ca xx satellite line, $1^2S^2_{1/2}-2^2P_{3/2}$ analogous to line $j$ of the lithium-like ions. This tentative identification is based on wavelengths kindly supplied to the authors by Mandelshtam and his colleagues at the P. N. Lebedev Physical Institute in Moscow (Safronova, Urnov, and Vainstein 1978).

**IV. DISCUSSION**

The spectra in Figures 1 and 2 provide information on the electron temperature and departure from ionization equilibrium of the flare plasma (from line intensity ratios), and on nonthermal mass motions (from the line profiles). Because of the brevity required for a Letter, we assume that the reader is familiar with the theory necessary for the diagnostic analysis of the spectra in Figures 1 and 2. The theory is described in detail in the papers mentioned above by Gabriel and co-workers. An independent and parallel theoretical development has also been done by Safronova, Urnov, and Vainstein (1978) and others at the P. N. Lebedev Physical Institute. They have extended the calculations to include helium-like satellite lines of hydrogen-like ions, and calculations are available to us for interpretation of our Ca xx spectra (Safronova, Urnov, and Vainstein 1978).

The lines $k$ and $j$ are produced almost entirely by dielectronic recombination for both calcium and iron, and therefore the ratio $(k/j)/w$ gives a determination of the electron temperature $T_e$ that is independent of ionization equilibrium. For calcium, $j$ is blended with $z$, but $k$ is resolved. For iron, $j$ is well resolved in the spectra. Values of $T_e$ determined in this way using Bhalla, Gabriel, and Presnyakov (1975) are given in Table 1 for representative spectra obtained over the rise time, the time of maximum X-ray flux, and the decay phase of the flare. The temperatures for iron may be lowered by about 14% due to recent improvements in the theory (Bely-Dubau, Gabriel, and Volonté 1979).
Temperatures were also derived from the Ca $\text{xx}$ spectra using the line $J$ and the theory in Safronova, Urnov, and Vainstein (1978). The temperatures are significantly higher than for Fe $\text{xxv}$ and Ca $\text{xix}$.

Emission measures were calculated from the counting rates, the instrumental calibration, and the standard theoretical treatment for excitation of coronal resonance lines (see Table 1). The relative abundances of calcium and iron given by Ross and Aller (1976) were used to obtain these results.

The other strong Fe $\text{xxiv}$ satellite lines marked in Figure 1, including those arising from $n = 3$ levels (Bely-Dubau, Gabriel, and Volonté 1979a), are also produced mainly by dielectronic recombination. Their intensities relative to $w$ are in fair agreement with expectations based on the $j/w$ ratio. However, the predicted intensity for the blend of lines $a$ and $r$ for Ca $\text{xviii}$ is about a factor of 1.82 small. Also, the ratio $y/w$ for both Ca $\text{xix}$ and Fe $\text{xxv}$ is larger than predicted by Gabriel (1972). Gabriel's values for $x/w$, $y/w$, and $z/w$ are $0.35$, $0.25$, and $0.41$, for Fe $\text{xxv}$, and $0.26$, $0.25$, and $0.51$ for Ca $\text{xix}$, respectively. Our values are $0.34$, $0.42$, and $0.46$ for Fe $\text{xxv}$, and $0.24$, $0.29$, and about $0.4$ for Ca $\text{xix}$.

The most surprising and perhaps questionable result in Table 1 is that $T_z < T_e$, i.e., the flare plasma is continuously ionizing, even during the decay phase of the flare. We feel that this conclusion is probably not correct. Furthermore, it appears that a multithermal analysis will not completely solve the problem. The difficulty may lie in some of the theoretical atomic parameters. An analysis of several more flares may help clarify this issue.

One of the most interesting aspects of the spectra in Figures 1 and 2 is the line profiles. Although the spectrometers are uncollimated, flares are frequently small (as determined from Skylab data), much less in angular dimension than the crystal rocking curve widths. The expected thermal widths of the iron and calcium lines are considerably larger than the rocking curve widths and the expected average source sizes. Thus the profiles give the intrinsic line widths. However, a small source size contribution to the line widths may exist for the iron spectra. Inspection of Figure 1 shows that during the rise phase of the flare the lines are substantially broader than at X-ray maximum, and that they are narrowest during the decay phase. The profiles of the lines appear to be Gaussian. If Gaussian profiles are assumed, the nonthermal motions $\xi$ can be derived from the line widths by deconvolving the thermal Doppler width, which is known from the temperatures given in Table 1 ($T_e$ is assumed equal to the ion temperature). Values of $\xi$ are given in Table 1, and are about the same for all the lines measured at similar time periods. $\xi$ is an upper limit for the iron spectra, but not for the calcium spectra.

Inspection of Table 1 shows that $\xi$ appears to be larger during the X-ray rise time than at maximum and during the decay phase. The effect is clearest for the calcium data. It remains to be seen if this result is true for all flares.

There are two results given above that are surprising or that need clarification: the apparent transient ionizing condition of the flare plasma even during the decay phase, which we regard as questionable, and the high temperature inferred for Ca $\text{xx}$ from the satellite line $J$. These issues should be resolved by analysis of the spectra of a large number of flares, and by combining the SOLFLEX data with data from Solrad 11 and data from other spectrometers flown by the Aerospace Corporation on the backup OSO 7 spacecraft.

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