RELATIONSHIPS BETWEEN TEMPERATURE AND EMISSION MEASURE IN SOLAR FLARES DETERMINED FROM HIGHLY IONIZED IRON SPECTRA AND FROM BROADBAND X-RAY DETECTORS

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ABSTRACT

We compare the electron temperature and emission measure of flares at the time of maximum soft X-ray intensity derived using two different techniques: (1) from the ratio of a dielectronic Fe xxv line to the resonance line of Fe xxv, combined with the absolute intensity of the Fe xxv line, and (2) from the ratio of the 0.5–4.0 Å and 1–8 Å broadband X-ray fluxes, combined with the absolute flux in one of the broadband spectral regions. The high-resolution Fe spectra are obtained with the Bragg Crystal Spectrometer experiment flown on the Japanese Yohkoh spacecraft. The broadband fluxes are obtained from Geostationary Operational Environmental Satellites (GOES). A data set of 540 X-ray magnitude C2 or brighter flares, observed by both spacecraft, is used for the analysis. Both techniques assume an isothermal plasma. The broadband temperatures are substantially lower than the Fe xxv temperatures. We find that the maximum temperature of flares brighter than M5 exceeds 2 × 10^7 K and that the maximum temperature of flares fainter than C4 is substantially lower than 2 × 10^7 K. We find that the Fe xxv emission measure is linearly proportional to the GOES flux in the 0.5–4.0 Å detector.

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

1. INTRODUCTION

Solar flares are characterized by the release of large amounts of energy, much of which appears as radiation dispersed over most of the electromagnetic spectrum. The radiation in many parts of the spectrum is characterized by bursts which often are irregular in behavior. In the soft X-ray (SXR) region, however, the radiative flare output varies smoothly in time with a characteristic behavior that is similar for most flares. Schematically, the SXR intensity versus time can be characterized by a phase of monotonically increasing intensity (rise phase), a maximum phase, and a phase of declining intensity (decay phase), where the rise phase and often the decay phase can be approximated by exponentials (e.g., Feldman, Doschek, & McKenzie 1984; Feldman et al. 1994). The maximum intensities and the e-folding times of the rise and decay phases vary considerably from flare to flare. In impulsive flares the e-folding time during the rise phase can be somewhat less than 10 s, while in gradual flares it can be hundreds of seconds (Feldman et al. 1984, 1994).

One of the important parameters of the SXR flare is the electron temperature. Two methods for deriving the SXR temperature are commonly used: (1) spectral line ratios such as the ratio of a dielectronic satellite line to the resonance line of a He-like ion, obtained from Bragg Crystal Spectrometer data, (2) broadband (in wavelength) ratios obtained from proportional counters or ion chambers, e.g., the ratio of fluxes in the 0.5–4 Å and 1–8 Å wavelength bands measured by Geostationary Operational Environmental Satellites (GOES), or broadband ratios obtained from images produced by SXR telescopes, e.g., the ratio of fluxes in the 4–8 Å and 6–8 Å wavelength bands measured by the SXR telescope on Yohkoh. The practical use of these methods usually requires the assumption that the SXR plasma is isothermal. However, it is known from the spectral line ratio technique, applied using lines from ions formed over a very broad temperature range, that the plasma integrated over the entire line of sight is in fact multithermal. The multithermal nature of the flare plasma is one of the reasons that different methods for determining temperature frequently give significantly different results. Comprehensive studies on the relationships of temperature and emission measures from soft X-ray measurements were done by Garcia (1988), Garcia & Farnik (1992), and Garcia (1994).

The Bragg Crystal Spectrometer (BCS) experiment on Yohkoh, in conjunction with the GOES 0.5–4 Å and 1–8 Å broadband X-ray detectors now in orbit, gives us the opportunity to apply the first two methods to the same flares and find relationships between these different methods for determining temperature. (Relationships between the first and the third methods will not be discussed in this paper.) If general relationships among the different temperature determinations can be found, then the temperature determined by one method could be used with the relationships to calculate temperatures that would be calculated using the other methods.

The Bragg crystal spectrometer temperature we compare with GOES temperatures is the temperature determined from Fe xxv and Fe xxiv emission lines. (Both of these lines are produced via excitation of a 1s electron beginning with an Fe xxv ion.) This temperature samples the highest thermal temperatures attained by the bulk of the thermal flare plasma (Doschek 1990). It is interesting to compare this temperature with the temperature determined from GOES data, which reflects lower temperature plasma as well as the plasma in which Fe xxv is formed.

Because the flare plasma is multithermal, the temperature determined from spectral lines of a particular ion might be expected to simply reflect the temperature of maximum emitting efficiency of the flare plasma in ionization equilibrium. However, He-like ions, such as those observed by BCS, can exist over a very broad range of temperatures because they have a closed K shell and no electrons in the L shell. As a result, temperatures determined from He-like ions can be sig-
nificantly different at different times during a flare. For example, temperatures determined using Ca xix have been found to vary from about $9 \times 10^6$ K up to about $2 \times 10^7$ K (e.g., Doschek 1990). However, the temperature of maximum emitting efficiency for a Ca xix resonance line is $2.5 \times 10^7$ K. This temperature is greater than most temperatures determined using Ca xix and implies that the emission measure of the SXR flare plasma at temperatures significantly greater than $2 \times 10^7$ K is usually significantly less than the emission measure of lower temperature plasma.

The above result found for Ca xix is even more dramatically illustrated with results from Fe xxv. The maximum emitting efficiency of a Fe xxv resonance line occurs at about $5 \times 10^7$ K, but temperatures determined from spectral lines based on Fe xxv are seldom greater than about $2.5 \times 10^7$ K. This implies that most of the thermal plasma is at a temperature of $2.5 \times 10^7$ K or less, although a small emission measure extending to much higher temperatures can exist (Lin et al. 1981). The point is that the Fe xxv temperatures are special in the sense that they represent the hottest portion of the thermal flare plasma. We therefore expect that the Fe xxv temperatures for SXR flare plasmas will be systematically higher than the temperatures obtained by almost any other means. If we can find a general relationship between temperatures determined using Fe xxv and those determined using GOES data, then we can estimate the highest temperature reached by the bulk of the thermal plasma for any flare observed by GOES.

The Bragg spectrometer temperature of the SXR plasma, as measured by intensity ratios of spectral lines of highly ionized ions such as Fe xxv, reaches its highest value slightly before or during flare maximum (Feldman, Doschek, & Kreplin 1980; Doschek, Feldman, & Kreplin 1980; Sterling, Doschek, & Pike 1994a). The maximum temperature of very hot thermal flares is in excess of $2.3 \times 10^7$ K, whereas the maximum temperature of colder flares can be only $1.0 \times 10^7$ K and perhaps even lower (Denton & Feldman 1984).

A temperature measurement, coupled with the measured SXR flux in a spectral line, or in a broadband wavelength region, can be used to determine a volume emission measure, $EM = \frac{\pi \Delta V}{n_e}$, where $n_e$ is the electron density and $\Delta V$ is the emitting volume. Thus, determining relationships among measured temperatures also leads directly to relationships among emission measures derived using the different techniques. One of the goals of this paper is to determine relationships between GOES temperatures and emission measures and the same quantities determined from the Yohkoh BCS experiment.

Thus far, only one analysis of the relationship among the electron temperature as determined from Bragg Crystal Spectrometer line ratios, the X-ray class as determined from broadband fluxes, and the emission measure of flares has been published (Denton & Feldman 1984), although recent work has been completed by Sterling et al. (1994b). The Denton and Feldman work, which was based on a limited number of flares, indicated that there is a relationship between temperatures and flare classes or emission measures. They showed that, on the average, hot flares belong to high X-ray classes, i.e., have large emission measures, while cold flares typically belong to lower X-ray classes (lower emission measures). In the process of comparing GOES results with BCS data, we have confirmed and refined this relationship. We compare BCS Fe xxv temperatures and emission measures with similar quantities from GOES. In addition, we show the relationship of the BCS quantities to the GOES X-ray class, because this latter quantity is frequently used to describe flare X-ray intensity. We have also devised a method for determining the maximum SXR brightness that a flare may reach, as measured by the GOES detectors, based on a Bragg spectrometer temperature measured near the time of flare onset. This relationship may prove useful for space weather forecasting.

2. THE EXPERIMENT

The Japanese satellite Yohkoh (Ogawara et al. 1991) was launched on 1991 August 30 while the Sun was still very active and has observed hundreds of flares during the first 30 months of operation. The Yohkoh instruments consist of a soft X-ray telescope, a hard X-ray telescope, a wide-band X-ray to gamma-ray spectrometer package, and the Bragg Crystal Spectrometer package. Actual observations started in 1991 October, when the activity of solar cycle 22 was still very high. At present, 3 years into the mission, the satellite and its instruments are continuing to function well.

The BCS is described in detail by Culhane et al. (1991). Briefly, four bent Ge crystals diffract radiation in four narrow wavelength ranges. The BCS consists of two structures, each with a single detector and high voltage unit, and with two wavelength channels per structure and detector. Uncollimated solar X-rays are incident on each crystal, and the reflected radiation passes through one of two windows (channels) of a single sealed proportional counter with one-dimensional position encoding. The position encoding is achieved by a wedge-and-wedge readout. Because the germanium crystals are bent, the Bragg diffraction condition is satisfied for different wavelengths at different locations along the crystal length, so that the detector simultaneously records a complete spectrum covering a small wavelength region. Photon counts are accumulated into either 128 or 256 wavelength bins. There are systems for rejecting background counts and for sensing X-ray count rate increases to enable data readout modes to be changed if desired.

The four wavelength channels cover intervals about the Lyα lines of Fe xxvi (1.78 Å) and the resonance lines (transition $1s^23p_0-1s2p^1P_1$, or line $w$ in the notation of Gabriel 1972) of the helium-like ions Fe xxv, Ca xix, and S xv (wavelengths 1.85 Å, 3.18 Å, and 5.04 Å, respectively). In the usual flare mode, a complete four-channel spectrum is recorded once every 3 s. In this paper we concentrate on measurements obtained in the Fe xxv channel. The Fe xxv channel on the Yohkoh BCS spectrometer is about 10 times more sensitive than any of the correspondingly similar high-resolution spectrometers flown on previous solar flare missions. Thus, high-resolution spectra in the Fe xxv wavelength range are now available from much fainter flares than were available from the previously flown spectrometers.

3. DATA REDUCTION

The present study includes all the flares which were observed by BCS between 1991 October and 1994 February and which satisfy the following conditions:

1. Their X-ray class is equal to or larger than C2.0 ($2 \times 10^{-6}$ W m$^{-2}$), as recorded by the 1–8 Å X-ray detector on the GOES satellite.

2. Complete observations are available for the rise phase, the maximum phase, and the beginning of the decay phase.
3. The radiation appears to be emitted by a single flare, i.e., the GOES X-ray light curve is uncomplicated and exhibits a monotonic rise and decay. Occasionally there are cases in which multiple simultaneous flares produce a GOES X-ray curve with a simple rise and fall. However, such cases can easily be discovered by reference to the list of Hz flares published in the Solar Geophysical Data Bulletin.

Flares listed in the National Oceanographic and Atmospheric Administration (NOAA) event listings obtained from the Space Environment Laboratory were compared with the BCS observations. All events appearing in both lists and satisfying the three requirements listed above are included in the study. The total number of events is 540. Because of the large number of events, we have decided to compare the temperature and emission measure between BCS and GOES for only one time for each flare. We have selected the time of maximum X-ray brightness as observed in the Fe XXV resonance line for this comparison. A spectrum in the Fe XXV channel, obtained during Fe XXV flare maximum, was extracted for each flare. The spectra were averaged over 9.25, or 36 s, depending on the flare brightness. Higher temperature emissions typically peak earlier in solar flares. Thus, since the Fe XXV spectrometer samples hotter plasmas than the GOES 1–8 Å detector, the time of flare maximum derived from the Fe XXV channel is somewhat earlier than the time of maximum 1–8 Å GOES flux.

3.1. The Fe XXV Electron Temperature and Emission Measure

The Fe XXV electron temperature is determined using the method proposed by Gabriel (1972) and Vainstein & Safanova (1978). They showed that the intensity of a line formed by a dielectric recombination process has a different temperature dependency than a line formed by a collisional excitation process. In particular, the intensity ratio of the dielectronic Fe XXV line 1s²2p²P_{3/2} - 1s2p²²D_{5/2} (j) to the Fe XXV resonance line 1s²1S_{0} - 1s2p²²P_{1} (w) is a sensitive temperature indicator of the SXR plasma. Examples of the significantly different appearance of flare spectra at wavelengths near the Fe XXV resonance line at different Fe XXV electron temperatures are shown in Figure 1. The j/w ratio is quite temperature sensitive for T_e < 2.0 x 10^7 K, but less sensitive at temperatures larger than 2.0 x 10^7 K. We have applied this line ratio method to BCS Fe XXV spectra for determining the temperature of the hot component of the SXR flare plasma. The j/w temperature relationship is shown in Figure 3 of Doschek, Feldman, & Cowan (1981).

We have elected to measure the Fe XXIV/Fe XXV intensity ratio using hard copy plots of the spectra. This procedure requires corrections to the measured intensity ratio due to blending from Fe XXIV satellite lines arising from principal quantum numbers of 3 and larger. The 1.850 Å emission feature in Figure 1 is a blend of the Fe XXV resonance line and associated satellites. The ratio between the Fe XXV resonance line and the sum of the Fe XXV resonance line and satellites is shown in Figure 2 assuming a typical FWHM of 1.5 mÅ for the Fe XXV line. Figure 2 has been obtained using data given by Bely-Dubau et al. (1982). Temperatures are obtained by measuring the j/w ratio from hard copy plots of the spectra and using Figure 2 to remove the contributions of satellite lines to line w. We estimate that our uncertainty in determining the Fe XXV electron temperature from the plots is about ±1 x 10^6 K.

![Figure 1](image_url) — Examples of flare spectra in the BCS Fe XXV channel. Notice the pronounced changes in the j/w intensity ratio as a function of temperature.
For many events of GOES X-ray class greater than about M5, the Fe xxv detector reached saturation count rates during flare maximum, and therefore a temperature was derived from rise phase spectra, rather than from flare maximum spectra. This temperature is expected to be a lower limit for the flare temperature at maximum SXR brightness.

Assuming ionization equilibrium, the flare emission measure \( n_e^2 \Delta V \) can be derived from the known photon flux in the Fe xxv resonance line and the electron temperature of the emitting region. The flux \( F \) in a resonance line at the Earth in photons \( \text{cm}^{-2} \text{s}^{-1} \) is given by

\[
F = \frac{1}{4 \pi R^2} \int N_e n_e C_{12} dV, \tag{1}
\]

where \( R = 1 \text{ AU} \) (in cm), \( N_e \) is the ground state number density of the ion, \( C_{12} \) is the collisional excitation rate coefficient \( \text{(cm}^3 \text{s}^{-1}) \) of the resonance transition, and \( dV \) is the flare volume over which the emission occurs. For Fe xxv at flare densities, the entire ion population is in the ground state \( N_e \), to a high degree of accuracy. The ground state number density \( N_e \) can be expressed as an identity,

\[
N_e = \frac{N_e}{N_F} \frac{N_F}{N_H} \frac{N_H}{n_e} n_e, \tag{2}
\]

where \( N_e/N_F \) is the fractional ion abundance in ionization equilibrium at the electron temperature \( T_e \) [which we define as \( X(T_e) \)], \( N_H/n_e \) is the hydrogen to electron ratio, a quantity closely equal to 0.8, and \( N_e/N_H \) is the element abundance [which we define as \( A_{eh} \)]. Substitution of equation (2) into equation (1) gives

\[
F = \frac{1}{4 \pi R^2} 0.8 C_{12}(T_e) X(T_e) A_{eh} (n_e^2 \Delta V), \tag{3}
\]

where \( \Delta V \) is the average volume of plasma at temperature \( T_e \). The atomic data in the above cited references, the measured flux in the Fe xxv resonance line, and equation (3) can be used to obtain emission measures.

We have adopted an average coronal Fe abundance in solar flares relative to H of \( 6.47 \times 10^{-5} \), which is twice the photospheric value (Feldman 1992). We use the values of \( X(T_e) \) from Arnaud & Rothenflug (1985), since they are the most recent calculations which include He i and Li i ions of S, Ca, and Fe. Values of \( C_{12} \) are obtained from Bely-Dubau et al. (1982).

3.2. Electron Temperatures and Emission Measures from GOES Data

The GOES electron temperatures and emission measures are determined using the equations and procedures given by Thomas, Starr, & Cranell (1985) and Garcia (1994). Their papers discuss the assumptions used to derive a broadband temperature from the intensity ratio of two X-ray emission wavelength bands, and the emission measure from this temperature and the flux in one of the wavelength bands. Thomas et al. (1985) refer to the broadband temperature as an effective color temperature. It represents an average temperature, assuming an isothermal plasma, that reflects those plasma regions that contribute substantial emission to the two GOES wavelength bands, 0.5–4 Å and 1–8 Å. Thomas et al. (1985) give analytical expressions for the color temperature and emission measure as functions of the (0.5–4.0 Å)/(1–8 Å) intensity ratio and the flux in the 1–8 Å wavelength band.

4. RESULTS

4.1. The Number Distribution of Fe xxv Temperature at Flare Maximum

The number distribution of Bragg spectrometer Fe xxv temperatures has never been studied before for a sample of flares as large as ours. Figure 3 shows the number distribution in Fe xxv temperature for our sample. Different shadings in the histogram divide the flare list into four categories of GOES X-ray classes. The majority of these flares have maximum temperatures in the \( 1.4 \times 10^7 - 1.8 \times 10^7 \) K range. As the GOES X-ray class increases from \( \geq C2 \) to \( \geq C5 \), to M1.2, and to \( \geq M3 \), the average maximum temperature shifts toward higher values. At temperatures \( \geq 1.9 \times 10^7 \) K, the number of flares rapidly declines, and only a small fraction (\( \approx 2\% \)) of C2 or brighter flares achieve temperatures exceeding \( 2.2 \times 10^7 \) K. As mentioned in § 1, this rough limit to the maximum Fe xxv temperature achieved in the SXR flare is not a result of the method of measurement and has been known from previous observations (Doschek 1990). Although the number of flares in the study having temperatures less than \( 1.4 \times 10^7 \) K is small, it...
is safe to assume that this is partly due to the lower limit of the C2 GOES X-ray class that we have imposed on our sample of events. If increasingly fainter flares could be investigated, the average maximum temperature would likely continue to decline.

4.2. X-Ray Class as a Function of Fe xxv Temperature

Figure 4 shows a plot of the GOES X-ray class as a function of the Fe xxv temperature (at maximum Fe xxv flux) for our flare sample. Flares having X-ray class M4 or greater saturate the BCS detectors near maximum brightness. In order to distinguish them from the nonsaturated events, they are indicated as filled circles in all the figures displaying data. We have included the M4 and brighter flares in the analysis because they provided lower limits on the flux of the Fe xxv resonance line, electron temperature, and emission measure values. Note the lack of flares in the upper left and lower right zones of the figure. It appears that for a flare to reach a particular X-ray class its maximum temperature must exceed some minimum value; for example, we observe no flares brighter than class C9 with maximum temperatures below $1.4 \times 10^7$ K. Conversely, once a certain temperature is achieved, the resulting X-ray brightness will always exceed some minimum value; thus, there are no flares fainter than class C5 with temperatures above $2.1 \times 10^7$ K. Part of the reason for this is that the X-ray class is a function of both the temperature and emission measure of the flare. For a constant emission measure, the X-ray class increases with temperature. However, this is not the complete explanation. For example, it is possible to have an X-class flare at a temperature of $1.4 \times 10^7$ K if the emission measure is large enough. And similarly, it is possible to have a $2.2 \times 10^7$ K low C-class flare, if the emission measure is small enough. Yet such events, if they occur at all, are found to be extremely rare. Any viable flare theory must be able to reproduce, or at least accommodate, this very clear observational result.

As shown in the next section, the large range of X-ray class at a given temperature, e.g., $1.8 \times 10^7$ K, is a reflection of the range of flare emission measure at a given temperature.

4.3. Emission Measure as a Function of Both Electron Temperature and X-Ray GOES Class

Since the broadband X-ray flare class is a function of both the flare emission measure and the temperature, more physical relationships can be obtained by comparing (a) the Fe xxv temperature and the emission measure derived from the Fe xxv flux, and (b) the Fe xxv emission measure and the X-ray flare class.

The Fe xxv emission measure as a function of Fe xxv electron temperature at flare maximum is shown in Figure 5. The general relationship, although somewhat less pronounced, between the X-ray magnitude and Fe xxv temperature is similar to the relationship that exists between the Fe xxv emission measure and electron temperature.

The flare class, as determined by GOES, as a function of the Fe xxv emission measure is shown in Figure 6. In the upper right section of the figure, the scatter is fairly large. As already indicated, this scatter is due to detector saturation for M4 and brighter flares. The saturated count rate is a gross underestimate of the flux in the Fe xxv resonance line. Moreover, the Fe xxv temperature assigned to the flare is only a lower limit. The spread of points along the x-axis ($\pm \Delta EM$) for most flare classes is smaller than a factor of 2 [($EM \pm \Delta EM)/EM \leq 2$]. The scatter is due in part to the $\pm 1 \times 10^6$ K uncertainties in the Fe xxv electron temperature determinations.

GOES also measures the 0.5–4 Å flux. Values obtained by the 0.5–4 Å detector flare maximum were extracted for the events in this study. In accordance with the GOES convention for the 1–8 Å X-ray detector, magnitudes of $\gamma_1$, $\chi_1$, and $\chi_1$ were assigned to fluxes of $1 \times 10^{-7}$, $1 \times 10^{-6}$, and $1 \times 10^{-5}$ W m$^{-2}$, respectively. A plot of X-ray magnitudes extracted from the 0.5–4 Å detector as a function of emission measure is shown in Figure 7. The straight line on the plot is a least-

![Figure 4](image-url)

**Fig. 4—GOES X-ray class as a function of the maximum Fe xxv temperature for Yohkoh flares. Filled circles in this figure and the following figures represent spectra that are saturated near flare maximum.**
squares fit to the data, showing that the flux in the $0.5-4$ Å wavelength band is linearly proportional (on a log-log scale) to the emission measure, i.e.,

$$\log [\text{flux} (0.5 - 4 \, \text{Å})] = 1.054 \times \log (\text{EM}) - 56.75 .$$ (4)

The slope of the fit is essentially unity. The difference from unity is not significant; including or excluding a few flares can easily alter the slope by 10%.

A plot of the $0.5-4$ Å X-ray class as a function of Fe xxv electron temperature is shown in Figure 8. In general, the results shown in Figures 5 and 8 are similar. In both cases, flares having maximum emission measure and X-ray class for a particular temperature increase by an order of magnitude between $1.3 \times 10^7$ and $1.9 \times 10^7$ K. Similarly, the minimum emission measure and X-ray class of flares for a particular temperature increase by an order of magnitude between $1.8 \times 10^7$ and $2.2 \times 10^7$ K, i.e., temperature changes of $\sim 50\%$ result in order of magnitude changes in emission measure or X-ray class behavior.

Figure 6 is useful for quickly estimating a range of probable Fe xxv emission measures from the GOES X-ray flare class. For example, an M2 flare has a probable Fe xxv emission measure in the range from about $1.5 \times 10^{48}$ to about $6 \times 10^{48}$ cm$^{-3}$. An X-ray classification system based on the $0.5-4$ Å flux

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**Fig. 5.** Fe xxv emission measure as a function of Fe xxv electron temperature at maximum soft X-ray flux

**Fig. 6.** Flare class as determined by GOES 1-8 Å flux as a function of the Fe xxv emission measure

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Fig. 7.—X-ray magnitudes from the GOES 0.5–4 Å flux as a function of Fe x xv emission measure. Magnitudes of \( \gamma_1 \), \( \mu_1 \), and \( \chi_1 \) were assigned to fluxes of \( 1 \times 10^{-7} \), \( 1 \times 10^{-6} \), and \( 1 \times 10^{-5} \) W m\(^{-2} \), respectively. The straight line is a least-squares fit to all the flares with X-ray magnitudes less than \( \gamma_1 \).

Fig. 8.—X-ray class determined from the 0.5–4 Å GOES flux as a function of Fe x xv electron temperature. Because of the relatively lower efficiency of the GOES 0.5–4 Å detector, magnitudes of \( \gamma_1 \), \( \mu_1 \), and \( \chi_1 \) were assigned to fluxes of \( 1 \times 10^{-7} \), \( 1 \times 10^{-6} \), and \( 1 \times 10^{-5} \) W m\(^{-2} \), respectively.

4.4. A Comparison Between Temperatures and Emission Measures Derived by the j/w Method and the GOES Method

Figure 9 shows (crosses) the temperatures at flare maximum obtained from the Fe x xv spectra plotted against the GOES 0.5–4 Å/1–8 Å flux ratio. The dotted line represents the temperature that is obtained from the GOES ratio as calculated by Garcia (1994) and is based on the Mewe, Gronenschild, & van den Oord (1985) spectral model. The solid line represents the temperature that is obtained from the GOES ratio by the Thomas et al. (1985) method, described in § 3.2. The Thomas et al. (1985) GOES temperatures are a factor of 1.5–1.7 times lower than the Fe x xv temperatures, while the Garcia (1994) temperatures are intermediate between the two. As discussed in § 1, the Fe x xv temperature is expected to be higher than the temperature obtained from any other method involving X-ray line and continuum from a thermal plasma. For example, for brighter flares, e.g., flares brighter than about M2, the same dielectronic line method applied to Ca xix that is applied to Fe x xv typically gives temperatures that are \( 3-5 \times 10^6 \) K lower than the Fe x xv temperatures (Doschek et al. 1990). The GOES temperature is determined partly from the 1–8 Å flux, which contains strong emission lines from ions such as Si xiv, Si xiii, and S xiv, which are formed at much lower temperatures than Fe x xv. Figure 9 provides the relationship from which an Fe x xv or a GOES temperature can be estimated, given a temperature from the other data set.

The GOES emission measure as a function of the GOES temperature is shown in Figure 10. Use of this figure with Figures 5 and 9 provides the relationship between the Fe x xv and GOES emission measures. The GOES emission measures tend to be higher than the Fe x xv emission measures. This must be a result of the different averaging procedures in deriv-
ing temperatures and emission measures. The difference in emission measure is highly variable, but is on average about an order of magnitude. The well-defined lower limit to the GOES emission measure in Figure 10 is a result of the data selection process, i.e., no flares below C2 are considered. As the temperature drops below $1 \times 10^7$ K for C2 flares, the emission measure must monotonically increase in order to obtain the same 1–8 Å flux value that defines a C2 flare.

5. DISCUSSION AND CONCLUSIONS

In this analysis of 540 Fe xxv spectra, relationships emerge among Fe xxv electron temperature and emission measure and GOES temperature and emission measure (X-ray class). These relationships can be used to further explore the properties of flares and the nature of the energy source that drives them. Below we list the main results from our study.

1. In most flares the peak Fe xxv temperature, as measured by the j/w line ratio, is $\leq 1.9 \times 10^7$ K. Only a very small number of flares, $\approx 2\%$, have a maximum temperature $\geq 2.2 \times 10^7$ K.

2. The trend of average electron temperature as a function of X-ray class that was seen for C2 and brighter flares is expected to continue for the fainter flares. Thus, most likely, the average electron temperature of B and A class flares will
continue to decrease. These first two conclusions extend the results obtained from previous missions and summarized by Doschek (1990). Doschek (1990) reported that for "reasonably large flares" (meaning bright flares), the Fe xxv temperature ranged from about 1.8 \times 10^7 K to 2.7 \times 10^7 K. No significant information was available for C flares and low M flares. The results summarized by Doschek (1990) approximately encompass the black area in Figure 3. Thus, the Yohkoh results have greatly extended our knowledge of the Fe xxv temperature distribution of solar flares as a function of X-ray class.

3. Flares which reach very high Fe xxv temperatures have relatively high X-ray magnitudes (emission measures), while flares having low maximum Fe xxv temperatures have relatively low X-ray magnitudes (emission measures). Although the temperature dependency of the X-ray flux can account for part of this behavior, most of the behavior reflects an intrinsic property of solar flares. One conclusion from this observational result is that intense flares are not simply collections of smaller events, somehow triggered simultaneously. In this case, there would be no temperature difference between intense and weak flares.

4. The Fe xxv emission measures and the X-ray magnitudes determined from the 1–8 Å GOES detector are not proportional to each other. However, Fe xxv emission measures are nearly proportional to the X-ray magnitudes determined from the 0.5–4 Å GOES detector (see Fig. 7). Since the 0.5–4 Å GOES detector is a good representative of the Fe xxv emission measure, perhaps fluxes measured by it rather than those measured by the 1–8 Å detector should be used to define the X-ray classes of flares.

5. The color temperature obtained from the GOES detectors is typically a factor of about 1.6 less than the Fe xxv temperature at maximum Fe xxv emission. The GOES emission measure is about an order of magnitude larger than the Fe xxv emission measure. For theoretical modeling of the hottest portions of the thermal flare plasma, the Fe xxv results are preferable to the GOES results.

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