OBSERVATION OF NONTHERMAL ENERGY DISTRIBUTIONS DURING THE IMPULSIVE PHASE OF SOLAR FLARES

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ABSTRACT

The Fe xxv resonance line and dielectronic satellite intensities have been measured as functions of time for several flares recorded by the Naval Research Laboratory crystal spectrometer (SOLFLEX) flown on the US Air Force P78-1 spacecraft. The intensity ratios of the Fe xxv resonance line, the Fe xxiv n = 2 satellite line j, and the Fe xxiv n = 3 satellite line d13 indicate that nonthermal electron energy distributions occur during the impulsive phase of the flares. For the electron energies at which the j and d13 satellites are formed (4.7 and 5.8 keV, respectively), the electron energy distributions during the impulsive phase of the flares are observed to have a bump or to be nearly flat. For all of the flares that were studied, hard X-ray bursts occurred near the time of the nonthermal distributions observed in the SOLFLEX data.

Subject headings: atomic processes — radiation mechanisms — Sun: flares — Sun: X-rays — X-rays: spectra

I. INTRODUCTION

Nonthermal electron energy distributions can occur in plasmas when energy is deposited into the tail of the distribution at a rate that is sufficiently high to overcome the equilibration processes. Nonthermal distributions are most likely to occur in low-density plasmas where collisional relaxation is slow and in plasmas confined by strong magnetic fields that inhibit the dissipation processes.

Since the electron impact excitation rate coefficients for many X-ray spectral lines formed in flare plasmas tend to increase with electron energy, even a relatively small number of hot electrons can have a major effect on spectral line intensities. If two spectral lines are excited by different portions of the electron energy distribution, then the line ratios are sensitive to the shape of the distribution, and such line ratios can be used as a diagnostic for nonthermal distributions.

Gabriel and Phillips (1979) suggested that the presence of nonthermal distributions can be determined using the ratios of the helium-like Fe xxv resonance line designated w, the Fe xxiv n = 2 satellite line j (Gabriel 1972), and the Fe xxiv n = 3 satellite line d13 (Bely-Dubau, Gabriel, and Volonté 1979a):

Line w:
Fe xxv 1s2 1S0 - 1s2p 1P1 ,
λ = 1.85046 Å

Line j:
Fe xxiv 1s2p2 p3/2 - 1s2p2 2D3/2 ,
λ = 1.86598 Å

Line d13:
Fe xxiv 1s23p 2P3/2 - 1s23p 1P1 2D3/2 ,
λ = 1.85349 Å
where the wavelengths are from Seely and Feldman (1985). The resonance line w is excited by electrons with energies that exceed the threshold energy 6.700 keV. The Fe xxiv doubly excited levels are populated by dielectronic recombination from the Fe xxv ground state:

Line j:
Fe xxv 1s2 1S0 + e ↔ Fe xxiv 1s2p2 2D3/2 ,
ε = 4.694 keV

Line d13:
Fe xxv 1s2 1S0 + e ↔ Fe xxiv 1s2p3p(1P) 2D3/2 ,
e = 5.815 keV

where ε is the difference in energy between the Fe xxv doubly excited level and the Fe xxv ground state. The reverse process is autoionization.

Since dielectronic recombination is a two-body process, only electrons with energies within an autoionization width of the excitation energy ε can recombine. As shown in Figure 1, the satellite lines sample discrete points on the electron energy distribution, and the resonance line is excited by electrons with energies exceeding the threshold energy. The line ratios are sensitive to the shape of the energy distribution. For example, Gabriel and Phillips (1979) suggested that an abundance of electrons in the high-energy tail of the distribution results in an enhancement of the resonance line relative to the satellite lines.

Apicella et al. (1983) and Bartiromo, Bombarda, and Gianella (1985) used the satellite to resonance line ratio d13/w and the independently measured electron temperature to infer nonthermal electrons in tokamak plasmas, but they did not observe the j satellite. Lee et al. (1985) measured the j/w ratio (but not the d13/w ratio) and also inferred nonthermal electrons in tokamak plasmas.

To date, nonthermal energy distributions have not been detected in the soft X-ray spectral data from solar flares. In this paper we show that the relative intensities of the Fe xxv and Fe xxiv X-ray spectral lines are consistent with nonthermal energy distributions during the impulsive phase of the flares. Hard X-ray bursts were also observed by instruments on the P78-1, Solar Maximum Mission (SMM), and Hinotori spacecraft, and in all cases the hard X-ray bursts occurred near the time of the nonthermal distributions in the SOLFLEX spectral data. This observation is important for the understanding of the sequence of events that results in the heating of the flare plasma.

This work represents the first full implementation of the technique of Gabriel and Phillips (1979). We calculate the line ratios for a model nonthermal distribution, measure all three...
Fig. 1.—Maxwellian distribution for a temperature of $20 \times 10^6$ K showing the excitation energies for the Fe xxiv satellite lines $j$ and $d13$ and the threshold energy for the Fe xxv resonance line $w$.

The intensity ratio of two satellite lines is

$$I_j/I_m = \frac{(A_{ji}/A_{jm})}{(W_{jm} + \sum A_{jk})} .$$

This expression depends on the excitation cross section, the energy distribution, and the atomic constants. Again we assumed that the wavelengths of the two lines are approximately equal.

The Fe xxv excitation cross section has been calculated by Sampson, Goett, and Clark (1983) and is shown in Figure 2. The cross section at threshold is $\sigma_0 = 3.8 \times 10^{-22}$ cm$^2$, increases to $4.8 \times 10^{-22}$ cm$^2$ at twice the threshold energy, and decreases to $2.6 \times 10^{-22}$ cm$^2$ at 10 times the threshold energy. The cross section calculated by Sampson, Goett, and Clark (1983) does not include resonances and relativistic effects that tend to increase the cross section for energies well above
threshold (Bartiromo, Bombarda, and Giannella 1985). We shall set \( \sigma_m/\sigma_0 \) in equation (8) equal to the threshold value \( \sigma_0 \). This is in good agreement with the calculations of Pradhan (1985). The satellite to resonance line ratio can now be written

\[
I_{jm}/I_{nm} = (A_{jm}/\sigma_0/\langle v \rangle)(W_{jm} + \sum A_{jk}),
\]

where

\[
\langle v \rangle = \int_0^\infty vF(e)de.
\]

Calculated values are available for all of the atomic constants in the expressions for the line ratios given by equations (6) and (10). The transition energies, radiative decay rates, and autoionization rates for the Fe xxiv \( n = 2 \) and \( n = 3 \) satellite lines have been calculated using the University College London computer package by Bely-Dubau, Gabriel, and Volonté (1979a, b) and using the Z-expansion method by Vainshtein and Safronova (1978, 1980). The calculated wavelengths and line intensities for the Fe xxiv \( n = 2 \) satellites are in good agreement with the observations in solar flares (Seely, Feldman, and Safronova 1986). The atomic data for the Fe xxiv satellite lines are listed in Table 1.

### III. MODEL DISTRIBUTION

Our intention is to compare the experimental line ratios with the theoretical expressions and to study the departure of the electron energy distribution from a Maxwellian. One should keep in mind that the comparison is done only for lines formed at 4.7 keV and higher energies, and it is possible that the bulk of the electrons have much lower energy. Therefore, the conclusions we draw from the comparison are valid only for the high-energy electrons.

In order to compare the experimental and theoretical line ratios, we shall assume a model electron energy distribution. Since we have three experimental line intensities and two independent line ratios, the model distribution can depend on two parameters. The model distribution we have chosen is

\[
F(e) = e/n!2/e^{-eT}/(n/2 + 1)(nT)^{n/2 + 1},
\]

where \( T \) is the gamma function and \( n \) and \( T \) are parameters. The distribution is normalized to unity, and the electron energy density is

\[
N_e \int_0^\infty eF(e)de = N_e(n/2 + 1)kT.
\]

This model distribution has been used in the analysis of nonthermal distributions in laboratory plasmas (Hares et al. 1979). For \( n = 1 \), the model distribution reduces to the Maxwellian distribution given by equation (2), and \( T \) is the electron temperature. In the case of a non-Maxwellian distribution \( (n > 1) \), we shall refer to the parameter \( \tau = nT \) as the pseudotemperature. The pseudotemperature reduces to the Maxwellian temperature for \( n = 1 \). The model distribution is shown in Figure 3 for several values of \( n \). As \( n \) increases, the peak of the distribution shifts to higher energy.

The model distribution parameter \( n \) that is determined from the data is a measure of the departure from a Maxwellian

### TABLE 1

| ATOMIC RATES \( (10^{13} \text{ s}^{-1}) \) FOR THE Fe XXIV SATELLITE TRANSITIONS |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| TRANSITION | RADIATIVE DECAY | AUTOIONIZATION |
| Vainshtein | Bely-Dubau | Vainshtein | Bely-Dubau |
| \( j \) | 21.4\* | 21.02\* | 16.0\* | 14.4\* |
| \( d13 \) | 44.9\* | 42.68\* | 2.90\* | 3.20\* |

\* Vainshtein and Safronova 1978.
\* Vainshtein and Safronova 1980.
\* Bely-Dubau, Gabriel, and Volonté 1979a.

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distribution. We shall show that the energy distribution of the high-energy electrons departs from a Maxwellian distribution during the impulsive phase of several solar flares. The actual electron energy distribution in the flare plasma does not necessarily have the assumed shape given by equation (12), but the analysis indicates that the actual distribution is non-Maxwellian.

For odd values of \( n \), the integral for \( \langle \nu \rangle \) given by equation (11) has a simple analytical solution (Gradshteyn and Ryzhik 1980). Expressions (6) and (10) for the line ratios can be written

\[
I_{2}/I_1 = \left( g_2 A_2 W_2/g_1 A_1 W_1 \right) (\varepsilon_2/\varepsilon_1)^{n/2-1/2} \nonumber \\
\times \exp \left( (W_1 + A_1 - W_2 - A_2) \right),
\]

\[
I_{2}/I_\nu = a \varepsilon_\nu W_2 A_2/kT B_\nu (\varepsilon_2/\varepsilon_\nu)^{n/2-1/2} \nonumber \\
\times \exp \left( (\varepsilon_\nu - \varepsilon_2)/kT (W_2 + A_2) \right),
\]

where

\[
\begin{align*}
  a &= 3h^3/8\pi m_e \varepsilon_\nu^2, \\
  B_1 &= 1 + b, \\
  B_\nu &= 1 + \frac{1}{2}(n + 1) b B_{n-2}, \\
  b &= kT/\varepsilon_\nu.
\end{align*}
\]

Using the atomic data listed in Table 1, the line ratios for iron are numerically equal to

\[
I_{j}/I_{d13} = 3.77(0.807)^{n/2}e^{1.12/T},
\]

\[
I_{j}/I_\nu = (0.649/B_\nu T)^{-0.12} (0.701)^{n/2}e^{2.01/T},
\]

\[
I_{d13}/I_\nu = (0.172/B_\nu T (0.868)^{n/2}e^{0.886/T},
\]

where the parameter \( T \) is in units of keV.

The iron line ratios are shown in Figure 4. We see that for a Maxwellian distribution \( (n = 1) \) and for the high temperatures \( (>1.5 \times 10^7 \text{ K}) \) that are typical of solar flares, the ratio \( I_{j}/I_{d13} \) is a rather weak function of temperature. This is because there is not a great difference between the excitation energies of the \( j \) and \( d13 \) satellites (see Fig. 1). The satellite to resonance line ratios \( I_{j}/I_\nu \) and \( I_{d13}/I_\nu \) decrease more rapidly with increasing temperature owing to the enhanced excitation of the resonance line \( \nu \) by the energetic electrons. For nonthermal distributions \( (n > 1) \), the line ratios shown in Figure 4 decrease dramatically for increasing values of the parameters \( n \) and \( T \), owing to the enhanced excitation of the highly excited lines by the energetic electrons. The dependence of the line ratios on \( n \) and \( T \) is the basis for the observation of nonthermal distributions.

The dependence of the line ratios on the pseudotemperature \( \tau = nT \) is somewhat more subtle. Shown in Figure 5 are the line ratios as functions of \( n \) and for two values of \( \tau \). The line ratios increase for increasing values of \( n \) and for fixed values of \( \tau \) (and decreasing \( T \)). The effect of decreasing \( T \) is more important than the effect of increasing \( n \), and the overall result is that the highly excited lines are diminished. For the same reason, the line ratios increase when \( \tau \) is reduced. Thus, for a fixed value of the energy density of the electron distribution (fixed \( \tau \)), the satellite to resonance line ratio increases with the departure from a Maxwellian distribution (increasing \( n \)), and this is the most apparent signature of nonthermal distributions in the X-ray data.

Late in the decay phase of the flares, the electron energy distribution is expected to be Maxwellian. The temperatures that are derived from the three line ratios using \( n = 1 \) should agree. As discussed below, the temperatures agree if the measured intensity \( I_{d13} \) is multiplied by the factor 0.7. The uncertainties in the calculated wavelengths and relative intensities of these satellites were recognized by Gabriel and Phillips (1979), and the need for a semiempirical correction factor was anticipated.
IV. DATA REDUCTION

The SOLFLEX crystal spectrometer recorded X-ray data from a large number of flares beginning in 1979 March. Transitions in Fe xxv-xx were identified by Feldman, Doschek, and Kreplin (1980) and by Doschek, Feldman, and Cowan (1981), and the wavelengths of transitions in Fe xxv-xvm were precisely measured by Seely, Feldman, and Safronova (1986). In these spectra, which were reflected from the (220) plane of the Ge crystal, the Fe xxiv n = 2 satellite transitions were clearly resolved, but the n = 3 satellites were partially blended with the Fe xxv resonance line (see Fig. 6). Several of the n = 3 satellites were resolved in the higher resolution spectra reflected from the Ge (131) crystal plane (Seely and Feldman 1985).

As shown in Figure 6, the n = 3 satellites in the (131) spectrum appear to be rather intense early in the flare, but the count rate is very low. On the other hand, the count rate is high in the (220) spectrum, but the n = 3 satellites are partially blended with the Fe xxv resonance line. As shown below, it is possible to fit a synthetic spectrum to the (220) n = 3 feature that is based on the theoretical wavelengths and relative intensities of the n = 3 satellites.

The (220) spectra were selected for analysis based on the following criteria. We looked for flares for which a complete set of data was recorded from the onset of the impulsive phase through the end of the decay phase. In order to avoid the Doppler shifts caused by the bulk motion of the flare plasma (Feldman et al. 1980), we were interested only in flares that occurred on the solar limb. The increase in altitude of the limb flares appears to shift the entire spectrum in wavelength (Seely

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**Fig. 4.** Fe line ratios as functions of the model distribution parameter $T$ and for the indicated values of $n$.

**Fig. 5.** Fe line ratios as functions of the model distribution parameter $n$ and for $nT = 100 \times 10^6$ K (solid curves) and $nT = 150 \times 10^6$ K (dashed curves).
and Feldman 1984), and this effect can be easily accounted for in the data reduction. The three flares that were selected for analysis are listed in Table 2.

The relative intensities of the resonance and satellite lines were determined by numerically fitting profiles to the spectral features. Shown in Figure 7 are the Fe xxiv j satellite and the Fe xxv 1s² 1S₂-1s2s 3S₁ transition that is designated z. Two Gaussian profiles were fitted to the data using the least-squares technique. The wavelengths, line widths, and intensities of the two profiles were independently varied, and the resulting profiles fit the data quite well.

As shown in Figure 8, the n = 3 satellites appear as a feature on the long-wavelength wing of the resonance line. The satellite transitions with n > 3 are totally blended with the resonance line. The relative intensities of the resonance line and the satellite feature were determined by generating a synthetic satellite spectrum that was based on the calculated wavelengths and intensities of Bely-Dubau, Gabriel, and Volonté (1979a, b) and Bely-Dubau et al. (1982). Since the excitation energies of the n = 3 satellites are approximately equal, the relative intensities of the n = 3 satellites are insensitive to the electron temperature and to departures from a Maxwellian distribution. All of the strong n = 3 and n = 4 satellite transitions were individually included in the synthetic spectrum, and the satellites with n = 5–11 were lumped into seven lines with wavelengths and relative intensities given by Bely-Dubau, Gabriel, and Volonté (1979b). The best fit to the data was found by the least-squares technique. The six parameters that were varied were the wavelength of the resonance line, the wavelength shift between the resonance line and the synthetic spectrum, the width of the resonance line, the width of the satellite lines that compose the synthetic spectrum, the width of the satellite lines that compose the synthetic spectrum, the intensity of the resonance line, and the intensity of the synthetic spectrum. Typical fits to the data are shown in Figure 8.

### Table 2

<table>
<thead>
<tr>
<th>Date</th>
<th>Solar Latitude and Longitude</th>
<th>Onset Time (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981 Aug 3</td>
<td>N10, E89</td>
<td>20h18m</td>
</tr>
<tr>
<td>1980 Nov 13</td>
<td>N08, W90</td>
<td>9h43m</td>
</tr>
<tr>
<td>1979 Mar 25</td>
<td>N08, W71</td>
<td>18h03m</td>
</tr>
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</table>
Fig. 7 — Fe xxiv satellite \( j \) and Fe xxv transition \( z \) from the 1981 August 3 flare. (a) Spectrum was recorded during the nonthermal phase; (b) spectrum was recorded during the thermal phase. Solid curves are least-squares fits to the data.

Fig. 8 — Fe xxv resonance line feature from the 1981 August 3 flare. (a) Spectrum was recorded during the nonthermal phase; (b) spectrum was recorded during the thermal phase. Solid curves are least-squares fits to the data of the Fe xxv resonance line \( w \) and the Fe xxiv satellite lines.
V. RESULTS

The measured count rates for the 1981 August 3 flare are shown in Figure 9a. The line ratios \( j/w \) and \( d13/w \) are relatively high early in the flare and diminish during the peak emission phase. This is the signature of the nonthermal distribution early in the flare and the relaxation to a Maxwellian distribution during the peak emission phase. Late in the flare, the resonance line decreases more rapidly than the satellite lines, and this results from the decreasing Maxwellian temperature.

Early in the flares, the values of the parameters \( n \) and \( T \) of the nonthermal distributions were measured from the line ratios as shown in Figure 10. The point at which the line-ratio curves cross in the \((T, n)\)-diagram determines the unique values of the parameters \( T \) and \( n \) at a particular time in the flare. At the time 20 h 19 s 59 s near the onset of the 1981 August 3 flare, the curves cross at \( T = 6.5 \times 10^6 \) K and \( n = 18 \).

Fig. 9. (a) The parameters \( n \) and \( nT \) of the electron distribution from the 1981 August 3 flare. Open squares are the values of \( n \). Filled squares are the values of \( nT \) for a Maxwellian distribution during the impulsive phase to be consistent with a Maxwellian distribution, the \( d13 \) intensity would have to be at least a factor of 2 smaller than the presently measured values. This is much greater than the estimated uncertainties in the line ratios, and the distribution during the impulsive phase is clearly nonthermal. The need for the semiempirical correction factor of 0.7 is probably due to random errors in the measurement of the intensity of the \( d13 \) line, which is weak and is partially blended with the resonance line. The estimated uncertainties in the measurement of the intensities of \( j \) and \( w \) are 10%. In order for the line ratios observed during the impulsive phase to be consistent with a Maxwellian distribution, the \( d13 \) intensity would have to be at least a factor of 2 smaller than the presently measured values. This is much greater than the estimated uncertainties in the line ratios, and the distribution during the impulsive phase is clearly nonthermal. The need for the semiempirical correction factor of 0.7 is probably due to inaccuracies in the theoretical wavelengths and intensities of the satellites. For example, the satellite intensities are proportional to the autoionization rates. The ratios of the autoionization rates for the \( d13 \) and \( j \) satellites calculated by Bely-Dubau, Gabriel, and Volonté (1979a) and by Vainshtein and Safronova (1978, 1980) are 0.222 and 0.181, respectively (see Table 1). These two ratios differ by a factor of 0.82, which is comparable to the semiempirical correction factor 0.7.

The results for the flares of 1980 November 13 and 1979 March 25 are shown in Figures 11 and 12. For both flares, the distributions are nonthermal \((n > 15)\) for a period of several minutes at onset and then relax abruptly to a Maxwellian during the following peak emission phase and the decay phase. The pseudotemperature \( \tau = nT \) during the nonthermal period is \( 120 \times 10^6 \) K.

VI. HARD X-RAY BURSTS

For the 1981 August 3 flare, hard X-ray bursts were observed by instruments on the P78-1, SMM, and Hinotori spacecraft. The event observed by the high-energy monitor...
Fig. 10.—Determination of the model distribution parameters $n$ and $T$ at $20^h19^m59^s$ just after the onset of the 1981 August 3 flare.

For the 1980 November 13 flare, a hard X-ray event was observed by SMM but not by MONEX or Hinotori. As shown in Figure 15, the hard X-ray event began about $18^h03^m$, while the nonthermal distributions in the SOLFLEX data were observed at $18^h04^m$ (see Fig. 12). Thus, for the 1980 November 13 flare, the gradual onset of the hard X-ray burst occurred just prior to the nonthermal distributions in the soft X-ray data.

VII. DISCUSSION

In the previous sections it was shown that the electron energy distributions during the impulsive phase of the flares are nonthermal. It is possible that these nonthermal distributions are the result of the local heating of a fraction of the electrons. In this case, the hot electrons result in a bump in the tail of the distribution. For electron energies just below the position of the bump in the distribution, a dip in the distribution may occur where the slope of the distribution is positive.

As discussed in § I, the $j$ and $d13$ satellite lines are formed by dielectronic recombination that takes place at discrete electron energies (4.7 and 5.8 keV, respectively). The intensity of the satellite line is proportional to the electron energy distribution.
Fig. 11.—The parameters $n$ and $nT$ of the electron distribution from the 1980 November 13 flare. Open squares are the values of $n$. Filled squares are the values of $nT$ for the nonthermal distribution, and filled circles are the values of $T$ for a Maxwellian distribution ($n = 1$). The dashed line is the temperature derived under the incorrect assumption of a Maxwellian distribution at onset. The hard X-ray burst (HXRB) observed by SMM is also indicated.

Fig. 12.—The parameters $n$ and $nT$ of the electron distribution from the 1979 March 25 flare. Open squares are the values of $n$. Filled squares are the values of $nT$ for the nonthermal distribution, and filled circles are the values of $T$ for a Maxwellian distribution ($n = 1$). The dashed line is the temperature derived under the incorrect assumption of a Maxwellian distribution at onset.
at the discrete energy. Using equation (6) and the atomic data of Vainshtein and Safronova (1978, 1980) listed in Table 1,

$$F(4.7 \text{ keV})/F(5.8 \text{ keV}) = 0.265 I_j/I_{d13}.$$  

(23)

Using equation (23), the slope of the distribution between the energies 4.7 and 5.8 keV can be determined from the observed satellite intensities $I_j$ and $I_{d13}$. As discussed above, the observation of a positive slope $F(4.7 \text{ keV}) < F(5.8 \text{ keV})$ represents the observation of a dip in the distribution that is associated with a hot-electron bump in the tail of the distribution.

For the 1981 August 3 flare, $F(4.7 \text{ keV})/F(5.8 \text{ keV})$ averaged 0.9 during the impulsive phase and 1.9 during the following peak emission and decay phases. The ratio $F(4.7 \text{ keV})/F(5.8 \text{ keV})$ during the impulsive phase of the 1980 November 13 and 1979 March 25 flares averaged 1.2 and 0.9, respectively, and then increased to at least 1.6 during the following peak emission and decay phases. In general, the slope of the distribution between 4.7 and 5.8 keV is slightly positive or nearly flat during the impulsive phase and is strongly negative for later times.

The observed Fe line ratios cannot be explained as due to a differential emission measure from a multithermal plasma. The effect of a differential emission measure is to cause line ratios to reflect different temperatures rather than the same temperature. Lines from ions formed at high temperatures give temperatures that are higher than lines formed at low temperatures. For example, the temperatures determined from Ca xix and Ca xviii lines can be several million degrees lower than temperatures determined from Fe xxv and Fe xxiv lines. Since the $d_{13}$ line is formed from more energetic electrons than the $j$ line, it is expected that the $d_{13}/j$ temperature should be equal to or higher than the $j/w$ temperature in a multithermal plasma. Doschek and Feldman (1987) found this to be the case. From their work, it is difficult to obtain a difference in temperature between $d_{13}/w$ and $j/w$ that corresponds to a $d_{13}/j$ intensity difference (from isothermal values) of more than a factor of 1.3. Under realistic assumptions, the factor is much less. Since the $d_{13}/w$ temperature is higher than the $j/w$ temperature, the $d_{13}$ line is decreased in intensity relative to the $j$ line. However, this is opposite to what is observed during the impulsive phase. The $d_{13}$ line is actually enhanced relative to

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Fig. 13.—Hard X-rays from the 1981 August 3 flare recorded by the MONEX instrument on the P78-1 spacecraft. Presented are the data for the three channels with threshold energies of 20.3, 28.2, and 38.5 keV.
Fig. 14 — The hard X-ray burst from the 1981 August 3 flare that was recorded by (a) SMM and (b) Hinotori.

Fig. 15 — The hard X-ray burst from the 1980 November 13 flare that was recorded by SMM.
Fig. 16.—Hard X-rays from the 1979 March 25 flare recorded by the MONEX instrument on the P78-1 spacecraft.
the $j$ line, and therefore a multithermal plasma cannot reproduce the present observational results.

The reason for the close similarity in temperature between the $j/w$ and $d13/w$ ratios in the thermal case is that, for a Maxwellian distribution, the contribution functions for $j$ and $d13$ are quite similar in shape. Thus the temperature dependence of the ratio $j/d13$ is small in a thermal plasma. A further consequence of this result is that the observed enhancement of $d13$ cannot be reproduced by an energy distribution that can be represented as a sum of Maxwellian distributions with typical flare temperatures. For example, an electron distribution that consists of two Maxwellian distributions, representative of two different temperatures, cannot reproduce the observations.

VIII. CONCLUSIONS

We have studied the electron energy distribution over the range 4–10 keV for several limb flares. The relative intensities of the Fe xxv resonance line and the Fe xxiv satellite lines were measured. Using a technique originally suggested by Gabriel and Phillips (1979), we looked for evidence of nonthermal electron distributions. The spectral line ratios during the first few minutes of recorded data indicate the presence of nonthermal distributions.

The nonthermal distributions persist for several minutes at the onset of the flares and then relax abruptly to Maxwellian distributions. For all of the flares that were studied, hard X-ray bursts were observed to occur near the time of the nonthermal distributions.

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