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High-temperature plasma in solar flares

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The thermal soft X-ray flare plasma is at temperatures ranging from a few million degrees up to about 40×10^6 K. In this paper I discuss some current problems in our understanding of the physical conditions in this plasma, particularly the ionization balance and the possible detection of non-thermal electrons. I discuss X-ray spectroscopic diagnostics that might help in resolving some of the issues, and I also discuss the possibility of addressing these problems with the bent crystal spectrometer experiment to be flown on *Solar-A*.

1. Introduction

The X-ray spectrum from about 1 to 25 Å† of solar flares has been investigated extensively using Bragg crystal spectrometer data obtained from the *DoD P78-1* mission, the *Solar Maximum Mission* (*SMM*), and the Japanese *Hinotori* spacecraft. The spectrum is characterized by strong line emission from solar abundant highly ionized elements and by a continuum due to bremsstrahlung, free-bound and two-photon emission. Much can be learned about physical conditions in the thermal coronal flare plasma by applying spectroscopic plasma diagnostic techniques to the interpretation of these spectra. In addition to the usual parameters that can be derived, such as electron temperature and density, the emission measure distribution, element abundances, and plasma dynamics, the X-ray spectrum offers the unique opportunity to determine possible departures from ionization equilibrium, the possible presence of non-maxwellian electron distributions, and the accuracy of certain atomic physics parameters.

The focus of this paper is on the detection of non-thermal electron distributions and on the ionization balance in flares. The recent advances in laboratory measurements of atomic physics parameters for highly ionized ions make such a discussion timely.

There are other recent developments that I do not consider in this paper. One concerns solar element abundances in flares. I refer the reader to papers by Widing & Feldman (1989) and Feldman & Widing (1990). Another topic is the X-ray ultraviolet (XUV) (170–600 Å) flare spectrum of $\mathrm{Fe}^{\mathrm{XVII}}$, and I refer the reader to Doschek *et al.* (1991). Finally, I do not discuss the interesting area of plasma dynamics of the soft X-ray flare, because I have reviewed some of the most recent work for the International *Solar-A* Science Meeting in Tokyo (Doschek 1991).

† 1 Å = 10^{-10} m = 10^{-1} nm.

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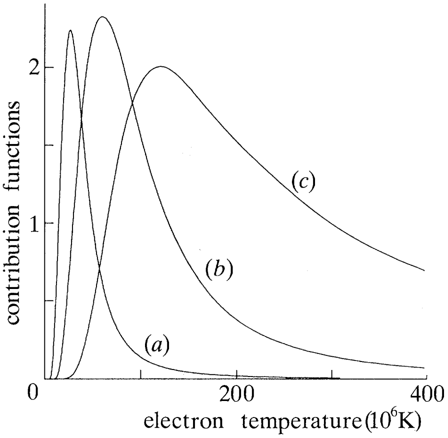

Figure 1. Contribution functions for the spectral lines: (*a*) Ca^{XIX} (3.177 Å); (*b*) Fe^{XXV} (1.85 Å); (*c*) Fe^{XXVI} (1.78 Å).

2. The temperature and ionization balance in solar flares

I now discuss some problems concerning the highest temperatures reached in the thermal soft X-ray flare, and the ionization balance in these high temperature regions. The pertinent data useful for our purposes are primarily the high-resolution spectra of He-like (Fe^{XXV}) and H-like (Fe^{XXVI}) iron, and the associated satellite lines of these ions. The strong X-ray resonance lines of these ions fall at 1.850 Å and 1.78 Å respectively.

First I consider results obtained from the Fe^{XXV} spectra. Iron is the heaviest element that produces intense spectral lines in solar flare spectra (nickel lines are weak). A range of ionization stages of iron is found in solar flare spectra, from Fe^{XVIII} up to Fe^{XXVI} in the hottest flares. The He-like and H-like ionization stages of any element exist over a very broad temperature range. The fractional abundance of Fe^{XXV} compared with the total iron abundance is greater than about 70% between 20 and 55×10^6 K (Arnaud & Rothenflug 1985). The Fe^{XXV} contribution function, which is the product of the fractional ion abundance and the excitation rate coefficient for the spectral line considered, peaks at about 60×10^6 K for the resonance transition at 1.85 Å. Spectral line intensities are proportional to their corresponding contribution functions. At 100×10^6 K the contribution function is still over 50% of its peak value, and the Fe^{XXV} ion abundance is still greater than 30%. The point is that Fe^{XXV} can be emitted over a large temperature range, which extends to very high temperatures. The iron-line contribution functions are shown in figure 1, along with the contribution function for the well-observed He-like Ca^{XIX} resonance line at 3.177 Å.

Therefore, the fact that the temperature of solar flares, as inferred from the intensity ratio of a dielectronic line of Fe^{XXIV} to the resonance line of Fe^{XXV} (see, for example, Doschek *et al*. 1979) is usually around 25×10^6 K or less, implies that there is generally an upper bound to the temperature of the bulk of the soft X-ray emitting flare plasma (Doschek & Feldman 1987). As discussed in Doschek (1990), this upper bound appears to be the same, regardless of other flare parameters, such as X-ray flux rise-time and size of emitting region. This result is surprising in light of numerical simulation results, and indicates that some important physics is missing in the numerical work.

However, in most flares there is no unique temperature; there is rather a distribution of temperatures (Doschek *et al*. 1990). Thus there could be some very hot plasma at temperatures significantly greater than 25×10^6 K, but in ionization equilibrium this plasma must have a much smaller emission measure than the bulk of the plasma. The use, as a temperature diagnostic, of a line of $\mathrm{Fe^{XXIV}}$ produced by dielectronic capture onto $\mathrm{Fe^{XXV}}$, somewhat biases the temperatures to regions cooler than the region where the bulk of the $\mathrm{Fe^{XXV}}$ ion is produced. Nevertheless, this effect alone cannot explain why temperatures significantly greater than 25×10^6 K are not found from analysis of $\mathrm{Fe^{XXV}}$ spectra.

The above discussion has focused on results from $\mathrm{Fe^{XXV}}$ and associated satellite line spectra, and the super-hot component, which is present in some solar flares and was discovered by Lin *et al*. (1981), has been ignored. Tanaka (1986) and Akita (1984) have shown that the super-hot component reveals its presence in Bragg spectrometer data by comparing the $\mathrm{Fe^{XXVI}}$ spectrum with the $\mathrm{Fe^{XXV}}$ spectrum. The $\mathrm{Fe^{XXVI}}$ spectrum is sensitive to the super-hot component because $\mathrm{Fe^{XXVI}}$ is present with significant abundance only at temperatures much higher than 20×10^6 K (see figure 1). When a super-hot component is present, its temperature is about 40×10^6 K, as determined from the $\mathrm{Fe^{XXVI}}$ resonance lines and nearby dielectronically produced $\mathrm{Fe^{XXV}}$ satellite lines, and temperatures determined from the $\mathrm{Fe^{XXVI}}$ spectra are quite different from the temperatures determined from the $\mathrm{Fe^{XXV}}$ spectra discussed above. When the super-hot component is not present, the $\mathrm{Fe^{XXV}}$ and $\mathrm{Fe^{XXVI}}$ temperatures are about the same.

Tanaka (1986) and Akita (1984) went a step further and calculated the ion abundance ratio $\mathrm{Fe^{XXVI}/Fe^{XXV}}$ from the intensity ratio of the $\mathrm{Fe^{XXVI}}$ and $\mathrm{Fe^{XXV}}$ resonance lines. Their result is not significantly dependent on instrumental sensitivity because both $\mathrm{Fe^{XXV}}$ and $\mathrm{Fe^{XXVI}}$ spectra were recorded by the *Hinotori* low-resolution spectrometer. They also calculated the ion abundance ratio from the intensity ratio of the forbidden line of $\mathrm{Fe^{XXV}}$ (line z in the notation of Gabriel (1972)) and the $\mathrm{Fe^{XXV}}$ resonance line. The forbidden line has a contribution due to radiative recombination from $\mathrm{Fe^{XXVI}}$, as well as from innershell ionization of $\mathrm{Fe^{XXIV}}$. Although there are some approximations inherent in their methods, they found that the $\mathrm{Fe^{XXVI}/Fe^{XXV}}$ (H-like/He-like) abundance ratio was larger than expected assuming ionization equilibrium by factors of 5–10. This may explain the large emission measures Tanaka (1986) found for the super-hot component, which were calculated assuming ionization equilibrium.

In contrast to the overabundance of $\mathrm{Fe^{XXVI}}$ relative to $\mathrm{Fe^{XXV}}$, it has been known since the first high-resolution X-ray spectra of $\mathrm{Fe^{XXV}}$ and $\mathrm{Ca^{XIX}}$ were obtained (Doschek *et al*. 1979) that the abundance ratios of $\mathrm{Fe^{XXIV}/Fe^{XXV}}$ and $\mathrm{Ca^{XVIII}/Ca^{XIX}}$ are larger than expected from ionization equilibrium calculations such as summarized by Arnaud & Rothenflug (1985). These results are obtained by first obtaining temperatures in the manner mentioned above. Then the abundance ratios $\mathrm{Fe^{XXIV}/Fe^{XXV}}$ and $\mathrm{Ca^{XVIII}/Ca^{XIX}}$ are obtained from other line ratios involving only lines produced by electron impact excitation (see, for example, Doschek *et al*. 1979). Most workers have concluded that the Li-like/He-like abundance discrepancies are due to inaccuracies in the ionization equilibrium calculations, because the magnitude of the discrepancies is within the errors of the calculations. In particular, the ionization rate coefficient seems to be the most probable source of error.

The error in the Li-like/He-like abundance ratio is in the direction expected assuming the ionization rate to be the source of the discrepancy, since the Lotz formulation of the ionization rate coefficient (used by most authors) only agrees well with low atomic number (Z) ions because of the effects of excitation followed by autoionization, which increases the total measured ionization rates (Crandall 1981). However, autoionization is not included in the Lotz formulation, and therefore we expect the Lotz expression to be an overestimate for high Z ions such as $\mathrm{Fe^{XXIV}}$, because radiative stabilization reduces the importance of autoionization for these heavier ions.

Other recent work on the ionization balance has been carried out by Doschek *et al.* (1990). The authors investigated the behaviour of the resonance line intensity ratio $\mathrm{Ca^{XIX}/Fe^{XXV}}$ with temperature and found that the data did not agree fully with the Arnaud & Rothenflug (1985) predictions, but were in somewhat better agreement with other calculations that took account of the increased Li-like/He-like abundance ratios.

We thus see that the H-like/He-like abundance ratios for iron and the Li-like/He-like abundance ratios for iron and calcium do not agree with ionization equilibrium calculations. However, the Li-like/He-like results are in the opposite sense of the H-like/He-like results. Therefore, neither reducing nor increasing the ionization rate coefficients can solve all of the problems. In particular, reducing the ionization rate coefficient to fix the Li-like/He-like abundance problem will worsen the H-like/He-like abundance discrepancy.

One source of possible error neglected in the above discussion is the accuracy of atomic excitation rate coefficients. We have been assuming that if there is an error in atomic physics all the error lies in the ionization balance rather than in the spectral line excitation rates. Recently, it has become possible to measure at least relative excitation cross sections for moderately high Z He-like ions in the laboratory using the electron ion beam trap (EBIT) at Lawrence Livermore National Laboratory. Excitation in the EBIT is produced by a highly directional monoenergetic electron beam, and therefore it is possible to measure polarization of spectral lines as well as relative cross sections. Relative excitation cross sections for $\mathrm{Fe^{XXV}}$ have been measured by Brown *et al.* (1989) and polarization has been measured for He-like scandium by Henderson *et al.* (1990). In both cases we found that calculated values agreed reasonably well with measured values. From these results, it appears that errors in the excitation rate coefficients cannot be responsible for the ion abundance discrepancies. This work also strengthens the use of the $\mathrm{Fe^{XXV}}$ and $\mathrm{Ca^{XIX}}$ forbidden line (z) and quadrupole line as indicators of the H-like/He-like ion abundance ratios.

Because the ion abundance discrepancies cannot easily be removed by a simple adjustment of atomic physics data, it is reasonable to ask whether the measured ion abundances are real and therefore reflect physics in the flare plasma that has not yet been considered in our discussion. There are two obvious possibilities: (a) the plasma is not in ionization equilibrium; and (b) some other process, such as a departure from a maxwellian velocity distribution, is affecting the ion abundance ratios. A combination of these effects is also possible. Such processes have recently been considered by Kato & Masai (1991) in an attempt to explain Tanaka's (1986) *Hinotori* results. Earlier, these ideas have been considered by Koshelev & Kononov (1982) and Gabriel & Phillips (1979), among others.

It is not a simple matter to postulate a departure from ionization equilibrium in the soft X-ray flare plasma, because at the known electron densities and temperatures of flares ionization equilibrium is reached within a minute or less. Thus, some means must be found to maintain a departure from equilibrium over the much longer timescales, which correspond to the lifetimes of at least the impulsive phases of flares. Koshelev & Kononov (1982) have suggested that the flare plasma is composed of many random 'elementary bursts', each of which lasts on timescales comparable with the ionization equilibrium time.

The most recent work on non-equilibrium processes has been carried out by Kato & Masai (1991). These authors combine a non-ionization equilibrium model with a non-thermal (suprathermal) electron model, and find agreement between theory and observation for several key physical parameters. The Kato & Masai (1991) model postulates the existence of a source of non-thermal electrons superimposed on a maxwellian velocity distribution. In addition, their results depend on the breakdown of ionization equilibrium for H-like and totally stripped iron. In contrast, I attempt here to explain the observations with a simpler model. I also postulate the existence of non-thermal electrons above a critical energy of the order of 10 keV. However, the assumption of ionization equilibrium is retained.

Of course we know that there are high-energy electrons in flares that obey power law or mathematically similar energy distributions, but their low energy cut-off is unknown because of masking by the thermal spectrum. It is possible that low energy (*ca.* 10 keV) non-thermal electrons are continuously produced during at least the rise phase of a flare, and if observable would have a light curve that more resembles the rise phase soft X-ray thermal light curve rather than the highly impulsive hard X-ray bursts. Some evidence for such non-thermal electrons has already been reported by Seely *et al.* (1987).

The presence of non-thermal electrons at energies greater than the threshold energy for ionization of $\mathrm{Fe^{XXV}}$ (8.8 keV) would increase the ionization rate coefficient for ionization from He-like to H-like iron. However, at typical flare temperatures these electrons might have a far lesser effect on the ionization rate coefficient for lower degrees of ionization because of the much greater pool of electrons that are able to ionize lower ionization stages. The ionization potentials of Li-like and lower ionization stages of iron are 2 keV or less. Thus, at least qualitatively there is a mechanism for increasing the $\mathrm{Fe^{XXVI}/Fe^{XXV}}$ abundance ratio without also significantly decreasing the $\mathrm{Fe^{XXIV}/Fe^{XXV}}$ abundance ratio.

If non-thermal electrons are present, however, they will influence the temperature diagnostics for iron that have been used to interpret all of the spectra up to now, in the manner described by Gabriel & Phillips (1979). For the sake of argument, assume that the postulated non-thermal electrons have energies of about 10 keV and greater. The presence of these electrons would increase the resonance line intensity because any electron with an energy greater than the threshold energy for the excitation of the $\mathrm{Fe^{XXV}}$ line, 6.7 keV, can excite the $\mathrm{Fe^{XXV}}$ line upper level. However, in contrast, the dielectronic line of $\mathrm{Fe^{XXIV}}$, used to obtain a temperature by comparing its intensity with the intensity of the $\mathrm{Fe^{XXV}}$ resonance line, will not be affected at all by the non-thermal electrons, because it is produced only be electrons with an energy of about 4.7 keV. The ratio of the two lines will be influenced such that temperatures derived under the assumption of a maxwellian velocity distribution will be too high.

Interestingly, the ratio of the two lines that are used to derive the $\mathrm{Fe^{XXIV}/Fe^{XXV}}$ ion abundance ratio would not be influenced significantly by the non-thermal electrons, and therefore in this model they would in principle be a better temperature indicator than the dielectronic to resonance line ratio. A lower actual temperature than measured would also reduce the $\mathrm{Fe^{XXIV}/Fe^{XXV}}$ abundance ratio discrepancy.

We can pursue the idea of a non-thermal tail on the maxwellian distribution

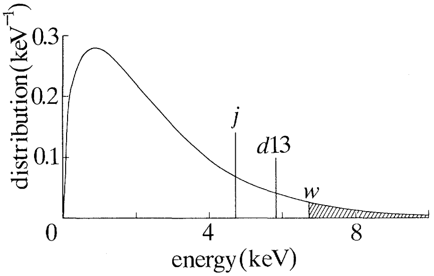

Figure 2. A maxwellian distribution for a temperature of 20×10^6 K. Electrons in the cross-hatched area can excite line *w*. Lines *d*13 and *j* can only be excited by electrons at the energies indicated.

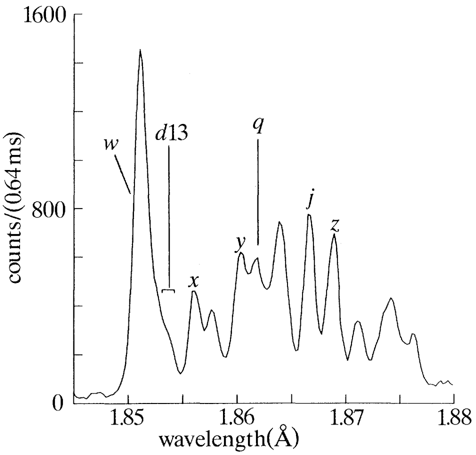

Figure 3. A typical solar flare iron-line spectrum. The wavelength scale is approximate. *w*, *x*, *y*, *z* ($\mathrm{Fe^{XXV}}$); *d*13, *q*, *j* ($\mathrm{Fe^{XXIV}}$).

further by investigating somewhat more quantitatively the effects of such electrons on the electron temperature diagnostics. For the sake of brevity, we now introduce the commonly used names suggested by Gabriel (1972) for the spectral lines of interest. The resonance line of $\mathrm{Fe^{XXV}}$ is line *w*, the temperature diagnostic dielectronic line of $\mathrm{Fe^{XXIV}}$ is line *j*, and the innershell excited line of $\mathrm{Fe^{XXIV}}$ used to obtain the $\mathrm{Fe^{XXIV}/Fe^{XXV}}$ abundance ratio is called *q*. The detailed spectroscopic transitions are given in many places (see, for example, Doschek & Feldman 1987). In addition to these lines, there is another dielectronic line called *d*13 that can be used to obtain temperatures. (The line *d*13 is one of a group of blended lines. The blend is unimportant if spectra are analysed by spectral synthesis fitting.)

As an example of the energetics, the electrons that can excite lines *w*, *j* and *d*13 are shown in figure 2 for a representative temperature of 20×10^6 K. The location of the spectral lines is shown for a typical flare spectrum in figure 3.

Since we are assuming that all the non-thermal electrons have energies above the $\mathrm{Fe^{XXV}}$ ionization threshold, lines *j* and *d*13 will not be affected in any way in our model by the presence of these electrons. As suggested by Gabriel & Phillips (1979), the $d13/j$ ratio can therefore be used to obtain a temperature that will not be influenced by the non-thermal electrons. It turns out that the $d13/j$ ratio has an almost linear dependence on temperature. For example, approximate values for the

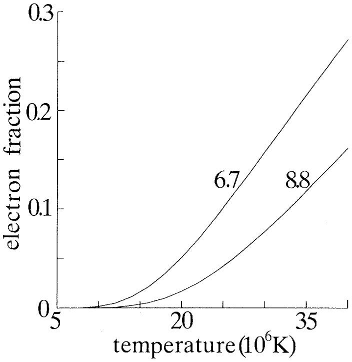

Figure 4. The fraction of electrons in a maxwellian distribution with energies greater than the energies (in keV) indicated.

$d13/j$ ratio are about 0.069, 0.17 and 0.29 at 10×10^6 K, 20×10^6 K and 40×10^6 K respectively.

Typical spectral fits to iron line data such as shown in figure 3 fit the $d13$ and j intensities to 15% or better. In other words, the $d13/j$ temperatures agree with the j/w temperatures to 15% or better. This means that the effect of the non-thermal electrons in our postulated energy distribution must not increase the derived j/w temperature by more than about 15%. Expressed differently, the 'true' electron temperature can be no more than about 15% lower than the apparent temperature derived from j/w. We can therefore reduce our derived j/w temperature by 15% and ask what j/w intensity ratio gives the reduced temperature. The ratio of this j/w ratio to the observed j/w ratio then gives the empirical maximum enhancement factor by which the intensity of line w can be increased by non-thermal electrons. For a 15% temperature decrease, this factor is about 1.5. (The j/w ratio is a very strong function of temperature.)

We can calculate the expected enhancement factor for line w assuming a given energy distribution of non-thermal electrons. For the sake of simplicity, assume that the energy distribution of these electrons is the same as a maxwellian above 8.8 keV, the ionization potential of $\mathrm{Fe}^{\mathrm{XXV}}$. We can therefore easily calculate the intensity enhancement to line w by simply increasing the number of electrons above 8.8 keV by various factors. These factors f for the numbers of electrons then correspond to factors F for the enhancement of line w. The relation between f and F is not linear because of the large number of thermal electrons between the threshold for excitation of line w (6.7 keV) and the ionization threshold for $\mathrm{Fe}^{\mathrm{XXV}}$ (8.8 keV). The fractions of the electron population greater than the 6.7 and 8.8 keV threshold energies assuming a maxwellian distribution are shown in figure 4. Another effect that destroys linearity is the fact that the collision strength for line w is an increasing function of energy (Bely-Dubau *et al.* 1982). The energetics and our postulated non-thermal energy cut-off demand that $F < f$.

The exact relation between f and F under our stated assumptions is shown in figure 5 for values of $f = 2$–5, 10. The higher end of these values is typical of the numbers of non-thermal electrons expected from the analysis of Tanaka (1986) (see his fig. 12, for example). From figure 5 it can be seen that values of $f = 5$ produce $F \approx 2.5$ for a typical temperature of 20×10^6 K. This is not too much higher than allowed by the $d13/j$ ratio. However, if Tanaka's (1986) analysis is altered to take into account that the j/w temperature diagnostic he used must be modified, then factors of f closer to

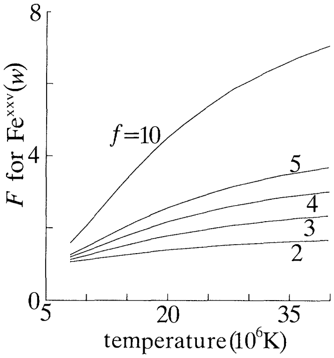

Figure 5. The factor F is the factor by which the excitation rate coefficient for $\mathrm{Fe}^{\mathrm{XXV}}$ line w is increased due to non-thermal electrons, as postulated in the text. The factor f is the factor by which the electron population is increased beyond 8.8 keV, as postulated in the text. The energy 8.8 keV is the threshold for ionization of $\mathrm{Fe}^{\mathrm{XXV}}$.

10 are more appropriate, which will result in factors F that are much larger than allowed by the $d13/j$ ratio. It therefore appears that a non-thermal tail on a maxwellian distribution above 8.8 keV cannot account for the observations.

Further support for this conclusion can be found in the effect of very large values of f on the intensity of line z of $\mathrm{Fe}^{\mathrm{XXV}}$ in figure 3. This line receives a contribution from innershell ionization of $\mathrm{Fe}^{\mathrm{XXIV}}$, and this process can only be produced by electrons with energies greater than about 8.7 keV. Thus, the innershell ionization rate is increased by the factor f. For $f = 3$, the total contribution of innershell ionization to the intensity of line z is still rather small, but for $f = 10$, the intensity of line z would be doubled, and this would produce a very large disagreement between observation and synthetic spectral fits that is not observed.

How can the model be altered to better fit the observations? If we extend the non-thermal electron energy cut-off down to 6.7 keV, we will worsen the agreement with observations. For example, with our specific non-thermal energy distribution, extending the cut-off to 6.7 keV results in $f = F$. However, if we extend the non-thermal distribution down to the energies of the electrons that produce j and $d13$, then clearly our analysis above needs modifications, and these modifications should be investigated. In fact, Seely *et al.* (1987) suggest that such a non-thermal energy distribution is needed to fit their results. Another possible conclusion is that a more complicated model, involving the breakdown of ionization equilibrium, such as proposed by Kato & Masai (1991), is essential to reproduce all of the physical parameters satisfactorily.

3. The *Solar-A* spectrometers

The *Solar-A* spacecraft will contain four bent crystal spectrometers built by science groups in the United Kingdom and the United States. Two of these spectrometers will observe the $\mathrm{Fe}^{\mathrm{XXV}}$ and $\mathrm{Fe}^{\mathrm{XXVI}}$ spectral regions that we have been discussing. The primary goal of the experiment is to investigate plasma dynamics. However, the sensitivity of the spectrometers will be about 10 times greater than previous experiments, which will allow statistically significant spectra to be obtained with higher time resolution than previously possible. Statistically significant spectra can therefore be obtained at times closer to flare onset. The higher sensitivity of the

Solar-A spectrometers will greatly aid in detecting possible departures from ionization equilibrium near flare onset, and in using the dielectronic to reasonance line ratios to detect possible non-maxwellian electron distributions, such as attempted by Seely *et al.* (1987).

Solar-A will also carry high spatial resolution soft and hard X-ray telescopes. The combination of the telescope images with the spectrometer data will allow for the first time a rather detailed examination of the morphology of the Fe$^{\mathrm{XXV}}$ and Fe$^{\mathrm{XXVI}}$ plasma regions. Hopefully, new insights and new questions will result from the *Solar-A* mission.

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