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High Resolution Solar Flare X-ray Spectra: The Temporal Behavior of Electron Density, Temperature, and Emission Measure for Two Class M Flares

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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High resolution soft x-ray flare spectra recorded by Naval Research Laboratory (NRL) and Aerospace Corporation Bragg crystal spectrometers flown on an orbiting spacecraft (P78-1) are combined and analyzed. The instruments were launched on 1979 February 24 by the U.S. Air Force and the data discussed in this paper cover the wavelength ranges, 1.82-1.97 Å, 3.14-3.24 Å, and 18.4-23.0 Å. The NRL experiment (SOLFLEX) covers the two short wavelength ranges (highly ionized Fe and Ca lines) and the Aerospace experiment (SOLEX) covers

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the 18.4-23.0 Å range, which includes the Ly-α O VIII line and the resonance, intercombination, and forbidden lines of O VII. We analyze the spectra of two flares which occurred on 1980 April 8 and May 9. Temporal coverage is fairly complete for both flares, including the rise and decay phases. Measurements of electron density N_e with rather high time resolution (about 1 minute) have been obtained throughout most of the lifetimes of the two flares. These measurements were obtained from the O VII lines and pertain to flare plasma at temperatures near 2×10^6K. Peak density seems to occur slightly before the times of peak X-ray flux in the resonance lines of Fe XXV, Ca XIX, and O VII, and for both flares the peak density is about 10^{12} cm^{-3}. Electron temperature T_e as a function of time is determined from the Fe and Ca spectra. Peak temperature for both flares is about 18×10^6K. Differential emission measures and volume emission measures are determined for the low (O VII) and high temperature (Fe, Ca) plasma. The number of electrons $N_e\,\Delta V$ and the volume ΔV over which the O VII lines are formed are determined from the O VII volume emission measure $N_e^2\,\Delta V$ and the density N_e. These quantities are determined as a function of time. The relationship of the low and high temperature regions is discussed.

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PREFACE

The Aerospace contribution was supported by the U.S. Air Force Space Division under Contract F04701-80-C-0081. The NRL contribution was supported jointly by ONR and NASA. We thank Drs. J. W. Cook, K. P. Dere, and K. G. Widing for useful discussions.

CONTENTS

FIGURES

I. INTRODUCTION

Recently a number of papers have been written concerning high resolution x-ray flare spectra obtained by Naval Research Laboratory (NRL) and Aerospace Corporation Bragg crystal spectrometers flown on an orbiting spacecraft (P78-1) launched by the U.S. Air Force on 1979 February 24 (e.g., Doschek et al. 1980, Feldman et al. 1980, McKenzie et al. 1980a,b). The NRL spectrometers (SOLFLEX) cover four narrow wavelength regions: 1.82 - 1.97 Å, 2.98 - 3.07 Å, 3.14 - 3.24 Å, and 8.26 - 8.53 Å. In this paper only spectra for the 1.82 - 1.97 Å and 3.14 - 3.24 Å regions will be considered. The shorter wavelength region covers 1s-2p type transitions in iron ions from Fe II - Fe XXV. The longer wavelength region covers 1s-2p type transitions in Ca XVII - Ca XIX. In the flare plasma at electron temperatures $T_e > 10^7$ K, the dominant ions are Fe XVIII - Fe XXV and Ca XVIII - Ca XIX. Discussions of flare spectra are given in Feldman, Doschek and Kreplin (1980), Feldman et al. (1980), Doschek et al. (1980), and Doschek, Feldman and Cowan (1980). Brief descriptions of the NRL spectrometers are given in these papers. The Aerospace Corporation's spectrometers (SOLEX) cover the wavelength region between 3 and 25 Å. In this region for $T_e > 2 \times 10^6$ K, lines of highly ionized O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni are emitted. The instrument is described by Landecker, McKenzie and Rugge (1979) and flare spectra are discussed by McKenzie et al. (1980a,b) and Landecker and McKenzie (1980).

The NRL spectrometers observe only the highest temperature thermal regions of flares ($T_e > 8 \times 10^6$ K), while the Aerospace spectrometers are able to observe regions as cool as 2×10^6 K (O VII lines). Clearly it is desirable to combine data sets from the two experiments in order to extend the temperature range observed. In practice this has proved difficult because the Aerospace spectrometers are collimated in order to study the spatial distribution of plasma in active regions and flares (two fields of view are available: 60" or 20" FWHM). The NRL instruments are sensitive only to flare plasma ($T_e > 10^7$ K) and thus it was unnecessary to provide collimation since many flares are small (<1') (Vorpahl et al. 1975; Kahler, Krieger, and Vaiana 1975; Cheng and Widing 1975) and the probability of two large flares occurring at the same time is not very large. Frequently an interesting flare in the NRL data was not observed by the Aerospace instruments because they were not pointed at the flare. We have nevertheless made an attempt to find events observed by both experiments and have in fact found a few. One event was the 10 June 1979 flare discussed in the papers by McKenzie et al. (1980a,b). This flare was also observed by NRL and was discussed by Doschek et al. (1980). It is a complex event and more than one flare may have been involved. Recently, however, we have found two apparently single events, observed by both experiments, and in this paper we discuss the NRL and Aerospace results for these flares.

II. OBSERVATIONS

Spectra were obtained from flares that occurred on 1980 April 8 and 1980 May 9. The April 8 flare occurred near $03^h\ 07^m$ UT at N12, W10 and was a class M4 event. The May 9 flare occurred near $07^h\ 14^m$ UT at S21, W32 and was a class M7 event. Observations of the April 8 flare began before the onset of the flare. However the rise phase of the flare was rather fast and we do not have many observations for this period. Observations of the May 9 event began slightly before the time of maximum x-ray flux was reached in lines emitted by plasma at $T_e > 10^7$K. As for the April 8 event, the rise phase was very fast and was only observed by the SOLEX spectrometers. Most of the decay phase of both events was observed. The decay phase of the May 9 event was relatively rapid; the Fe XXV flux decreased by a factor of about 30 in 8 minutes.

a) SOLFLEX Spectra

The NRL SOLFLEX spectra consist of repeated scans of the iron and calcium lines (a complete scan was accomplished in 56s). Representative spectra are shown in Figure 1. From these spectra the electron temperature and nonthermal motions in the plasma can be derived from relative line intensities and line profiles. The temperature measurements are independent of the assumption of ionization equilibrium and are based on a theory of line emission following dielectronic recombination developed by Gabriel and Jordan (1972). A description of the techniques can be found in the papers on the SOLFLEX results cited above. The most complete description is given in Doschek, Feldman and Cowan (1980), where the theory originally developed for Ca XIX and Fe XXV is extended to the less ionized iron ions, Fe XXIII and Fe XXIV. Average temperatures of the flare region emitting lines of Fe XXV can be derived from the intensity ratio, j/w (see Figure 1). The average temperatures for the regions emitting lines of Ca XIX can be derived from the ratio k/w. Lines j and k are produced by the Fe XXIV and Ca XVIII transitions, $1s^2 2p\ ^2P_{3/2} - 1s2p^2\ ^2D_{5/2}$ and $1s^2 2p\ ^2P_{1/2} - 1s2p^2\ ^2D_{3/2}$, respectively. Line w is the resonance transition in Fe XXV and Ca XIX, $1s^2\ ^1S_0 - 1s2p\ ^1P_1$. Identifications for the other transitions in Figure 1 are given in Feldman, Doschek and Kreplin (1980) and Doschek, Feldman and Cowan (1980). We use the theory given in Bely-Dubau, Gabriel and Volonté (1979) to derive temperatures from the j/w ratios. For k/w temperatures we use the theory given in Bhalla, Gabriel and Presnyakov (1975). Once temperatures are determined from line ratios, volume emission measures $N_e^2\ \Delta V$, ($\equiv \int_{\Delta V} N_e^2\ dV$) where N_e is the electron density and ΔV is the approximate plasma volume in which the lines are formed, can be derived using relationships given in Doschek et al. (1980) and discussed further in Section

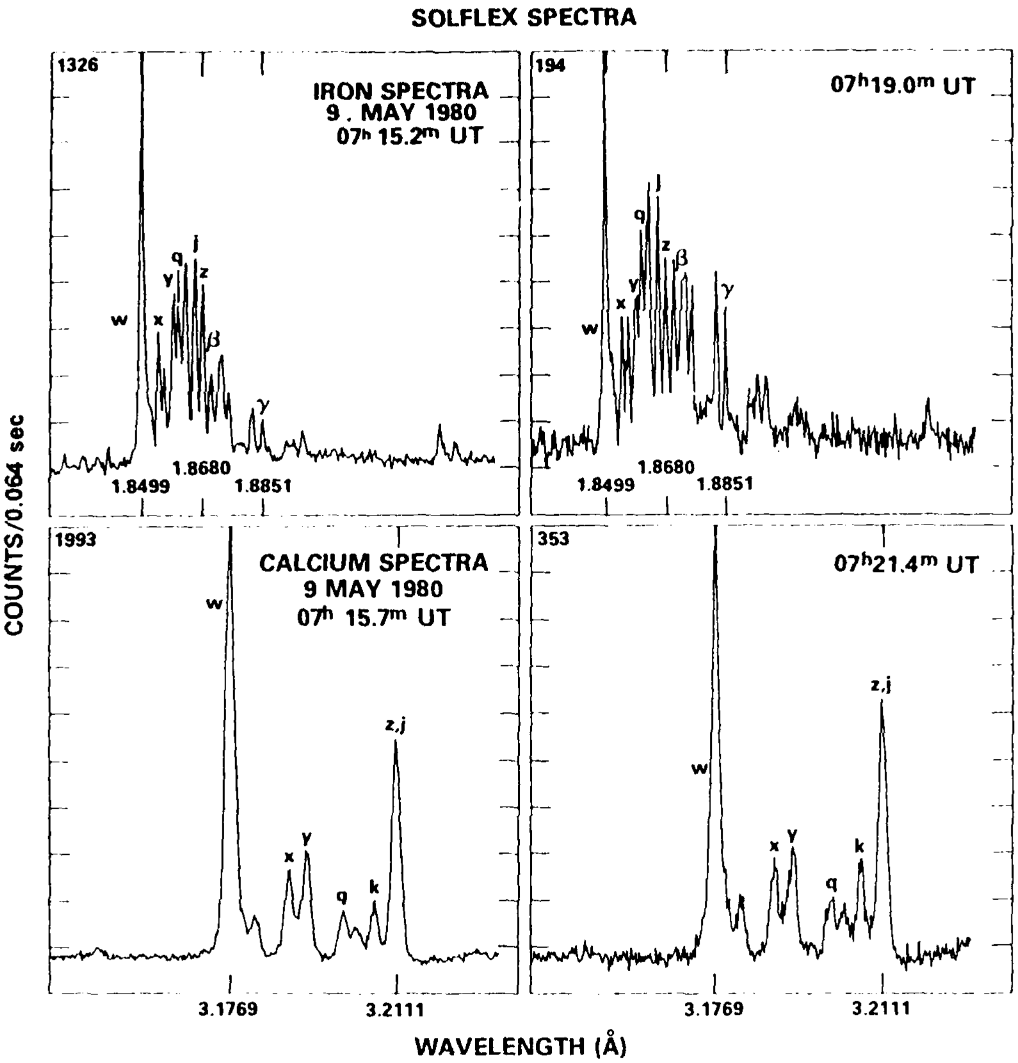

Figure 1 - Sample Fe and Ca SOLFLEX spectra of the 1980 May 9 event. Spectra near peak flux in the resonance line of Fe XXV (line w) are shown, as well as spectra recorded during the decay phase. The notation referring to the emission lines is defined in Feldman, Doschek and Kreplin (1980) and Doschek, Feldman and Cowan (1980). The numbers in the upper left hand corner of each panel are the peak counting rates for each ordinate scale.

III. These depend on ionization equilibrium calculations and element abundances. (Ionization equilibrium or near equilibrium for Fe XXV and lower ions appears to be valid for reasons discussed in Doschek, Feldman and Cowan 1980 and Feldman, Doschek and Kreplin 1980). We used the calculations of Jacobs et al. (1977) for iron and Jacobs et al. (1980) for calcium. The results of Jacobs et al. differ only slightly from the results of Jordan (1970) and Landini and Fossi (1972) for the ions Fe XXIV, Fe XXV and Ca XIX. The element abundances used are from Ross and Aller (1976).

In summary, the NRL SOLFLEX spectra allow the electron temperature and volume emission measure to be determined as a function of time during the flares for the ions, Fe XXIII, Fe XXIV, Fe XXV and Ca XIX. In this paper we will consider only temperatures obtained for Ca XIX and Fe XXV. Temperatures obtained from lines of Fe XXIII and Fe XXIV are similar. Finally, the nonthermal motions obtained from the line profiles for the two events under discussion appear quite similar to the motions derived for many flares. The magnitude and temporal variations of the motions are described in Doschek et al. (1980) and Feldman et al. (1980) and will not be discussed further in this paper.

b) SOLEX Spectra

Although the observable spectral range of the Aerospace SOLEX spectrometers is from 3 to 25 Å, it is possible to scan narrower ranges in order to achieve high time resolution observations of diagnostically important lines. During the time of the April 8 and May 9 flares, the 60" FWHM SOLEX B channel was in a special observing mode in which the wavelength range 18.4 - 23.0 Å was scanned repeatedly. The heliumlike O VII resonance ($1s^2\ ^1S_0$ - $1s2p\ ^1P_1$), intercombination ($1s^2\ ^1S_0$ - $1s2p\ ^3P_1$), and forbidden ($1s^2\ ^1S_0$ -

1s2s $^3S_1$) lines at 21.60, 21.80, and 22.10 Å, respectively, were included in this range as was the O VIII Ly-α line at 18.97 Å. The ratio of the forbidden to intercombination line enables the density N_e to be determined, using the theory developed by Gabriel and Jordan (1972). The volume emission measure $N_e^2\ \Delta V$ can be derived from the resonance line using the same techniques as discussed in Doschek et al. (1980) and in Section III. Since in this case N_e is known, the number of particles $N_e\ \Delta V$ and the volume ΔV, can also be determined. We note that all these results pertain to the region of the flare plasma where O VII is formed. The temperature in ionization equilibrium for maximum emitting efficiency of the O VII lines is about 2×10^6 K (Jacobs et al. 1978). In determining $N_e^2\ \Delta V$, we again use Ross and Aller (1976) abundances.

Recently, new excitation rate coefficients have been calculated for heliumlike ions by Pradhan, Norcross and Hummer (1980). The significant rate coefficient for density determinations is the 1s2s $^3S_1$ - 1s2p ^3P collisional excitation rate, which is a factor of 1.9 higher than the rate given in Table 4-6-1 in Gabriel and Jordan (1972). We used the Gabriel and Jordan (1972) rate coefficient in McKenzie et al. (1980b), and therefore densities derived in that paper should be reduced by a factor of 1.9. Actually, Gabriel and Jordan (1972) alluded to the possible underestimation of this rate in their paper. In this paper we use the new value for 1s2s $^3S_1$ - 1s2p ^3P. Other data are from Gabriel and Jordan (1972). The forbidden to intercombination line ratio R is given as a function of N_e in Figure 2. This calculation was done assuming $T_e = 2 \times 10^6$ K for the O VII formation region. We do not have a dielectronic recombination temperature diagnostic for the O VII lines as for the Ca XIX and Fe XXV lines, because the O VII satellite lines are very weak. However the ratio G of the sum of the intercombination and forbidden

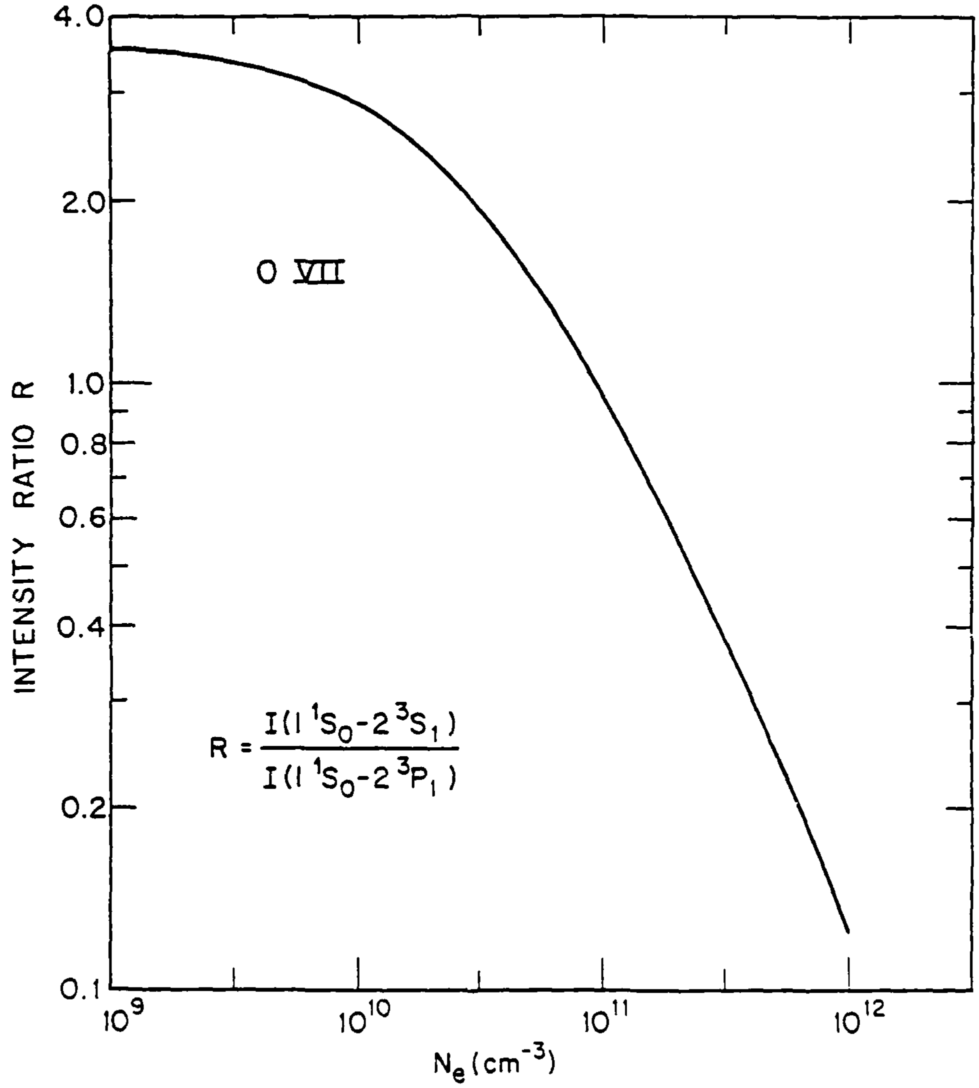

Figure 2 - The intensity ratio R of the forbidden to intercombination line for O VII, as a function of electron density at a temperature of 2×10^6 K.

lines to the resonance line is somewhat temperature sensitive and our results are consistent with $T_e = 2 \times 10^6$ K, which we assume throughout this paper.

Sample O VII spectra are shown in Figure 3 for the May 9 event. Since O VII is formed in the quiet corona and active regions as well as in flares, the spectrum of the background emission within the 60" field of view should be taken into account if possible. In general flares are much smaller than 60" in size (e.g. see Landecker and McKenzie 1980). For the April 8 and May 9 events this is relatively straightforward. For the April 8 flare two spectra of the region are available just prior to the flare. These spectra have been averaged and subtracted from the flare spectra in order to obtain densities and emission measures. For the May 9 event one background spectrum is available, just prior to the flare, and this spectrum has been subtracted to obtain the results discussed in Section III.

In summary, the SOLEX spectra allow N_e and $N_e^2 \Delta V$, and therefore $N_e \Delta V$ and ΔV, to be determined as functions of time for the flare plasma near 2×10^6 K. The electron pressure P ($\equiv N_e T_e$) can then be calculated at 2×10^6 K as a function of time. These results are related to the higher temperature plasma parameters derived from the NRL spectra in the next section.

III. RESULTS

Analysis of the NRL and Aerospace spectra leads to the results shown in Figures 4 and 5. Plotted for both flares are the fluxes in the resonance lines of Fe XXV, Ca XIX, O VIII and O VII, and the electron densities derived from the O VII lines, as functions of time. Also shown are the temperatures derived for the hotter plasma from the line ratios j/w and k/w using iron and calcium lines, respectively.

Consider first the variation with time of the high temperature flare

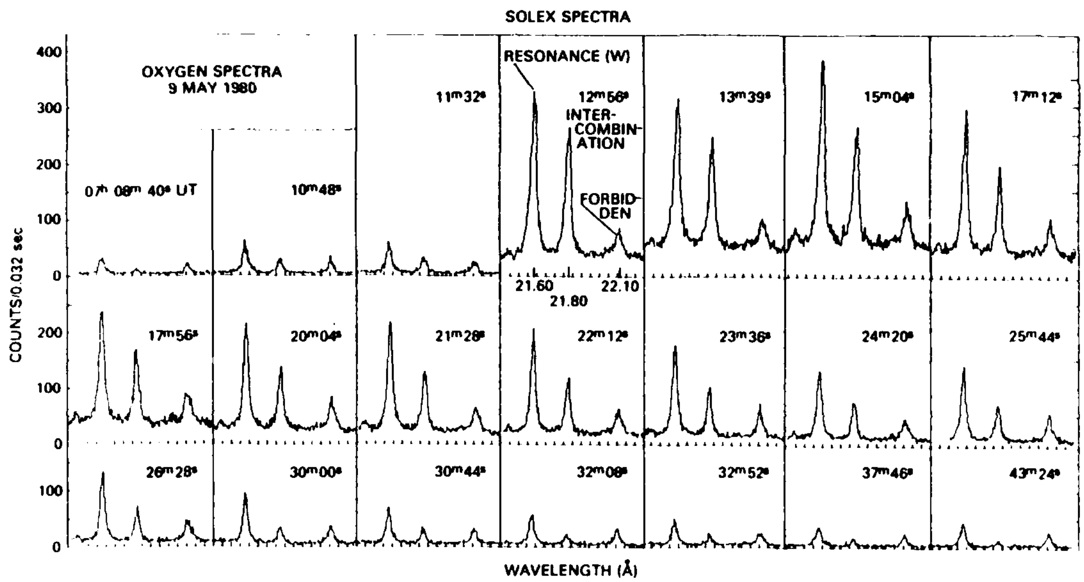

Figure 3 - The O VII SOLEX spectra for the 1980 May 9 flare. The times at which the resonance line (w) was scanned are given in the upper right hand corner of each panel.

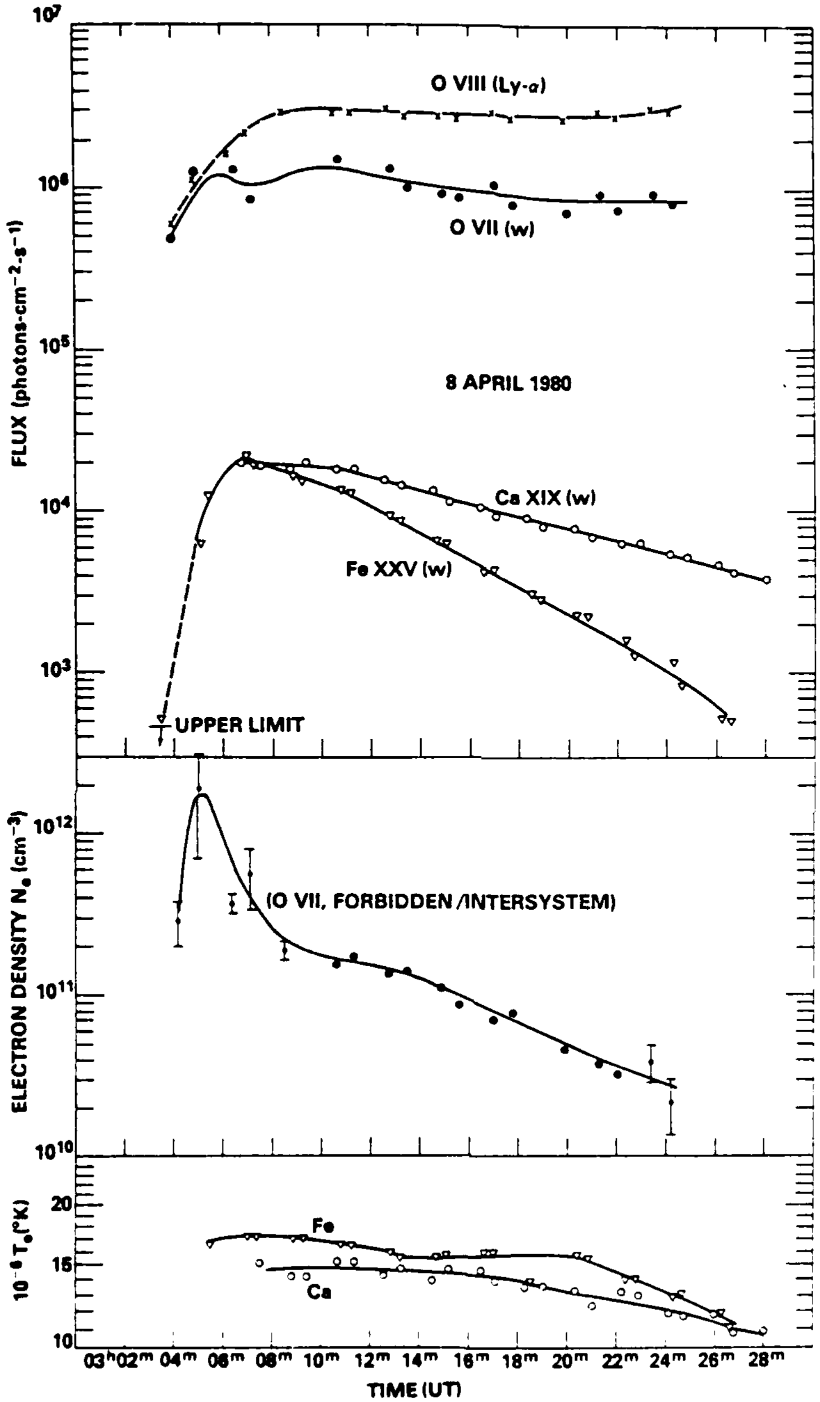

Figure 4 - Line fluxes, electron density and temperature, as a function of time for 1980 April 8 flare. The smooth curves are eye estimate fits to the data.

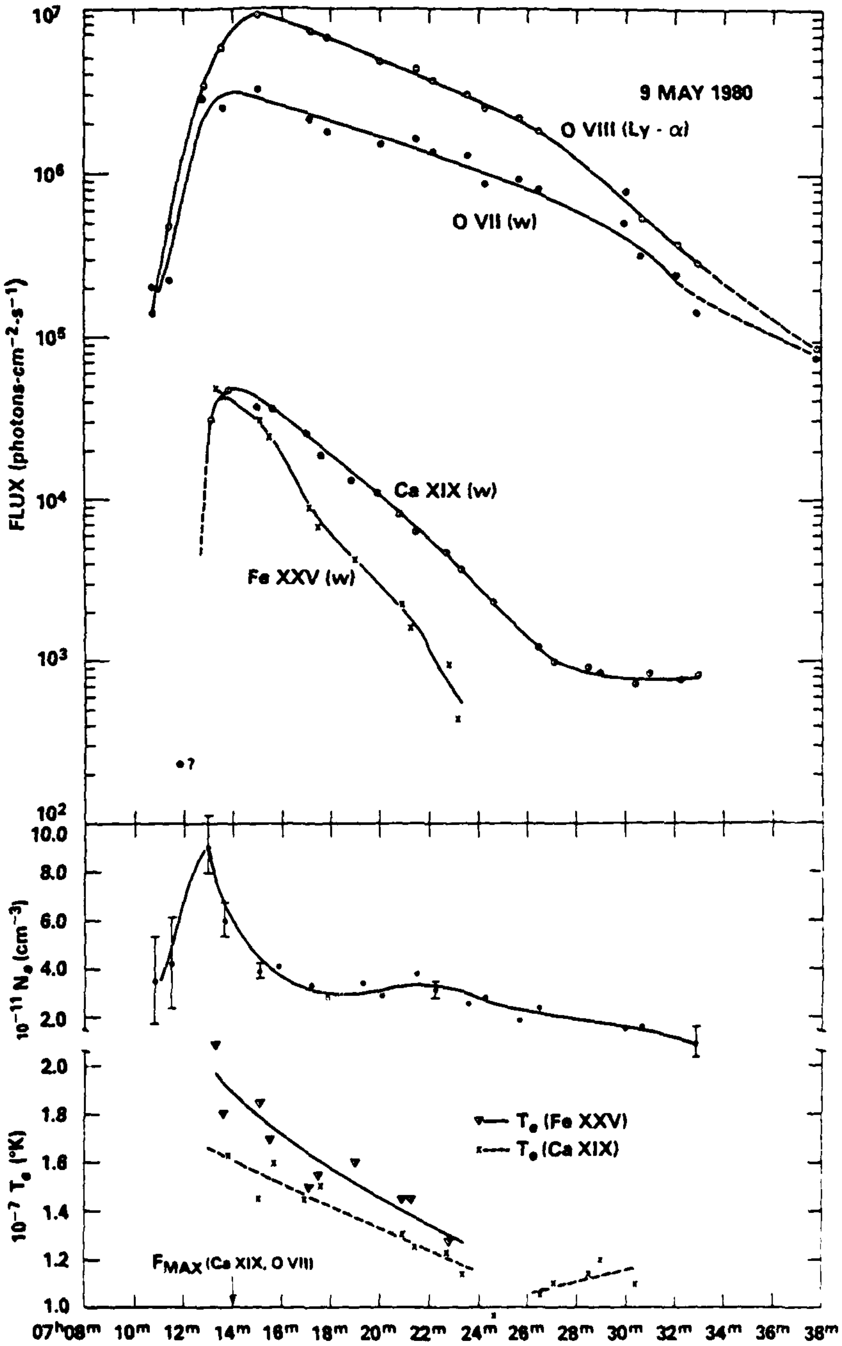

Figure 5 - Same as Figure 4 for the 1980 May 9 flare.

plasma component for the two flares. Both flares have fast rise times, and because of this there are virtually no temperature measurements available during the rise phases. However, after the time of peak flux in the Fe XXV resonance line (line w) the temperature behavior is different for the two flares. The May 9 event cools more rapidly; the temperature determined from j/w drops from about 2.0×10^7 K to about 1.3×10^7 K in 10 minutes. In the April 8 flare, this temperature remains nearly constant at about 1.6×10^7 K for about 15 minutes after the time of peak line flux for Fe XXV, i.e., from $03^h\ 05.5^m$ to $03^h\ 21.0^m$ UT. These results are typical of the temperature behavior in intense soft x-ray flares (Doschek et al. 1980, Feldman et al. 1980). The constancy of the temperature with time in some flares may imply continuous heating in flare plasma, to a greater or lesser extent. Our results are qualitatively consistent with less heating in the May 9 event than in the April 8 flare, because the temperature for the May 9 event is declining monotonically over the period for which we have measurements, while the April 8 temperature remains constant for about 15 minutes.

What about temperatures during the rise phases of the flares? The results given in Doschek et al. (1980) and Feldman et al. (1980) indicate that the temperature should be nearly constant or increase slightly over most of the rise phase until peak flux in Fe XXV line w is reached. It is not likely that the Fe XXV temperatures were much higher than the largest temperatures shown in Figures 4 and 5. The temperatures obtained from the k/w Ca XIX ratios are a few million degrees lower than the Fe XXV j/w temperatures, as obtained by us previously for other M and X class flares. In summary, the line fluxes and temperature behavior with time obtained by the SOLFLEX spectrometers are very similar to the results reported by us previously for X and M flares.

The most interesting aspect of Figures 4 and 5 is the behavior of the electron density with time, derived from the O VII forbidden to intercombination line ratio. In both flares there is a rather rapid rise in density, followed by a nearly equally rapid fall, near the times of peak fluxes in the resonance lines. In both flares the maximum density is around 10^{12} cm^{-3}, implying an electron pressure p of 2×10^6 K $\cdot$ 10^{12} cm^{-3} = 2×10^{18} cm^{-3} K. This is a very high pressure, and if the pressure is considered constant over all regions of the flare plasma, densities of 2×10^{13} cm^{-3} are calculated for 10^5 K. We note that such high transition zone densities have been reported in connection with the 1973 June 15 flare by Feldman, Doschek and Rosenberg (1977). Following the drop in density from its peak value, in the May 9 flare there is a period of time in which the density is nearly constant before beginning a monotonic decrease. In the April 8 flare, there is a rapid decrease in density after peak density is reached which then slows down to a more gradual decrease. In both flares, the density behavior with time is characterized by an almost impulsive increase and subsequent decrease in density during the rise phase. Although the peak density is higher in the April 8 event than in the May 9 flare, the density remains at higher values for longer periods of time in the May 9 flare than in the April 8 flare.

It is natural to inquire if there is a physical connection between the flare plasma near temperatures of $\approx 15 \times 10^6$ K in which the Fe XXV and Ca XIX lines are formed, and the lower temperature plasma around 2×10^6 K where the O VII lines are formed. We state at the outset that we cannot give a definitive answer to this question, for two reasons. First, because we lack good spatial resolution, we are unable to tell whether all the emission arises from a single multithermal loop or a set of multithermal loops, or if the emission arises in a set of physically distinct isothermal loops. (We assume based on the results from Skylab that the emission is in fact confined to magnetic flux tubes or loops.) We know that in many cases more than one loop is involved (e.g., see Dere and Cook 1979). Secondly, because the SOLEX B spectrometer is collimated to 60", and the SOLFLEX spectrometers are uncollimated, there is the chance that not all the O VII and O VIII flare emission is observed by the SOLEX instruments. We nevertheless proceed under the assumption that at least the latter uncertainty is not important, i.e., we assume that all the oxygen emission is observed by SOLEX. We consider later the possibility that the low and high temperature lines arise in a single loop or set of multithermal loops, i.e., the connection between low and high temperature regions occurs along, and not across, magnetic field lines.

However, without making any assumptions regarding morphology we can calculate the distribution of emission measure with temperature. The flux F at earth (photons-cm^{-2}-s^{-1}) in an allowed or resonance line is given by,

$$F = \frac{1}{4\pi R^2} \int_{\Delta V} N_e N_1 C_{12} dV, \tag{1}$$

where R = 1 A.U., N_1 is the number density of the ground state of the ion, C_{12} is the excitation rate coefficient (cm^3-s^{-1}) and ΔV is the volume over which the line is formed. Using well-known expressions for N_1 and C_{12}, the flux F can be written as,

$$F = \frac{8.63 \times 10^{-6}}{\omega_1 \; 4\pi R^2} \; 0.8 \; A_H \int_{T_1}^{T_2} \bar{\Omega} \; (T_e) G(T_e) \; N_e^2 (dV/dT_c) dTe, \tag{2}$$

and where $G(T_e)$, the contribution function, is given by

$$G(T_e) = \frac{F(T_e)}{\sqrt{T_e}} \; e^{-\Delta E_{12}/kT_e} \; , \tag{3}$$

where ΔE_{12} is the energy of the spectral transition, $F(T_e)$ is the fraction of the element in the ionization stage from which the spectral line is emitted, $\bar{\Omega}(T_e)$ is the collision strength averaged over a Maxwellian distribution, k is Boltzmann's constant, A_H is the element abundance relative to hydrogen, 0.8 is the proton to electron number density ratio, ω_1 is the statistical weight of the ground state, and the quantity $N_e^2\ dV/dT_e$ is defined as the differential emission measure. The quantities $F(T_e)$ that we use are taken from the calculations of Jacobs et al. (1977, 1978, 1980). We use the abundance values given by Ross and Aller (1976). The limits T_1 and T_2 must be taken small enough and large enough, respectively, to cover the temperature range over which $G(T_e)$ is not insignificantly small.

We obtain an idea of the functional dependence of $N_e^2\ dV/dT_e$ on T_e by evaluating equation (2) using the Pottasch (1964) approximation for the lowest and highest temperature lines we have available (O VII (line w) and Fe XXV (line w)):

$$F = \frac{6.90 \times 10^{-6}}{4\pi R^2} A_H \left[0.7\ G(T_e)\ \bar{\Omega}(T_e)\right] \Big|_{T_{max}} N_e^2\ \Delta V \tag{4}$$

where $T_{max} \equiv$ the temperature at which $G(T_e)$ is a maximum. ($\bar{\Omega}(T_e)$ is a slowly varying function of temperature compared to $G(T_e)$). We obtain an estimate of the differential emission measure at $T = 2 \times 10^6$ K by using equation (4) to derive $N_e^2\ \Delta V$ and dividing this by $\Delta T_e = 1.5 \times 10^6$ K, the full width at half maximum of $G(T_e)$ for O VII line w. For Fe XXV $G(T_e)$ is a rapidly increasing function at the temperature, T_e (j/w), derived from the j/w line ratio. As discussed in Doschek, Feldman and Cowan (1980), this implies the existence of a virtual high temperature cutoff in the differential emission measure at T_e(j/w). Thus Fe XXV line w is predominatly formed in a narrow range ΔT_e about

$T_e(j/w)$; we estimate that $\Delta T_e \approx 3 \times 10^6$ K. For Fe XXV equation (4) may be used to define an estimate for the differential emission measure by omitting the factor 0.7 and substituting $T_e(j/w)$ for T_{max}. We find that for the April 8 flare the ratio of the differential emission measure at $T_e(j/w)$ to that at 2×10^6 K varies from 3 to 12, and for the May 9 flare the same ratio varies from less than 2 to 5. For both flares the maximum values of the ratio occur near the time of peak x-ray emission. This is not surprising; it just verifies that the flares cool during the decay phase. We point out that f_c, the SOLEX collimator angular response averaged over the O VII emitting region, could easily be less than 0.33 (f_c = 1.00 for a point source on axis, and 0.25 for a uniform source filling the field of view). Thus it is possible that late in the flares, the differential emission measure at $T_e(j/w)$ did not exceed that at 2×10^6 K.

We may attempt to fit the differential emission measure to the form

$$N_e^2 \, dV/dT_e = a \, T_e^b, \; T_1 < T_e < T_2 \qquad (5)$$
$$N_e^2 dV/dT_e = 0, \; T_e > T_2,$$

where a and b are constants and $T_2 = T_e(j/w)$. T_1 may be set to any value below 10^6 K. By using the results of the previous paragraph (assuming $f_c = 1$) we find $0.5 < b < 1.2$ for the April 8 flare and $0.2 < b < 0.7$ for the May 9 flare. If $f_c < 1$ these b values would be smaller. Nowhere are the data consistent with b = 1.5, the value found by Jordan (1980) for a system in energy balance and hydrostatic equilibrium. The O VIII Ly-α line is formed over a broad temperature range so that equation (4) is not applicable. We can, however, apply equation (2) to both O VII line w and O VIII Ly-α with $N_e^2 \, dV/dT_e$ from equation (5). Varying parameters, we find that O VII and O VIII fluxes are never consistent with b much larger than zero; in many cases we require that $b<0$. This means that the O VII lines are indeed formed at around 2×10^6 K, and the use of equation (4) for O VII line w is justified. The exact shape of the differential emission measure function cannot be derived because our observations are confined to too few lines.

The calculated emission measures, $N_e^2 \Delta V$, (not differential emission measures) for line w of O VII, Ca XIX and Fe XXV for the two flares are plotted in Figures 6 and 7. We point out that the volumes ΔV are the approximate volumes over which the resonance lines of O VII, Ca XIX and Fe XXV are formed. Note that the Ca XIX emission measure exceeds that of Fe XXV. This may be due to the use of the Ross and Aller (1976) element abundances for Ca and Fe. As we discussed in Doschek et al. (1980), there is some evidence indicating that the Ca abundance of Ross and Aller is too small relative to Fe. This would result in an overestimate of the Ca line w emission measure. Because of this abundance uncertainty the Ca measurements really give us no useful information on the form of the differential emission measure.

Because electron densities have also been determined from the O VII lines, we can divide the O VII emission measures by N_e and N_e^2 to obtain the number of particles $N_e \Delta V$, and the volume ΔV over which O VII emission occurs centered at temperatures near 2×10^6 K, as a function of time for the flares. These results are shown in Figures 8 and 9 and are quite interesting. Both flares show a large increase in $N_e \Delta V$ and ΔV early in the decay phase. These increases could be due to to evaporation of cool gas from the chromosphere heated to $\approx 2 \times 10^6$ K, expanding flux tubes, cooling plasma originally at much higher temperatures (i.e., cooling flux tubes of fixed size), or the excitation of more loops. The increase in $N_e \Delta V$ and ΔV is much larger for the April 8 flare because N_e remains high for long periods in the May 9 event. Note that errors in $N_e \Delta V$ and particularly ΔV depend on errors in the measurement

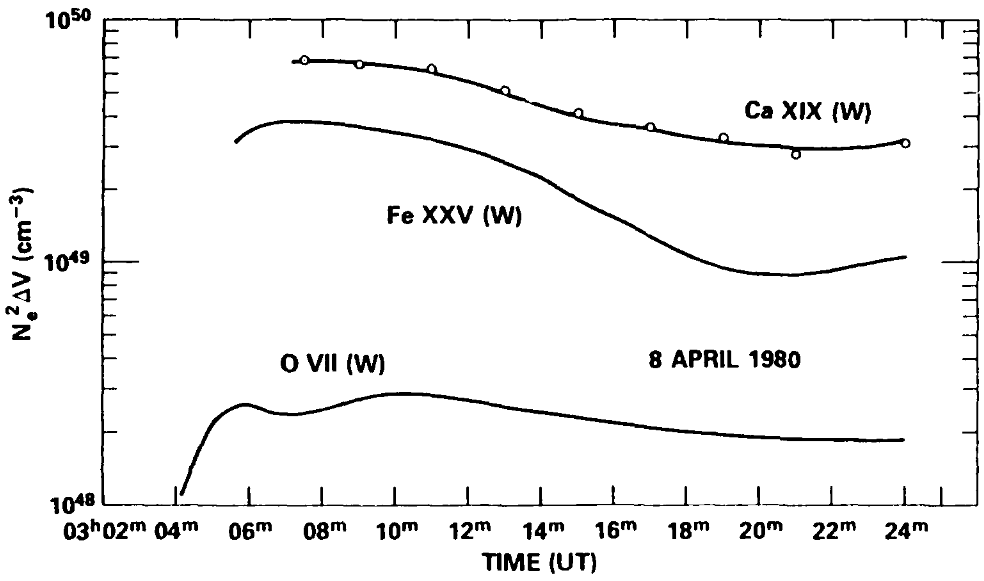

Figure 6 - Volume emission measures as a function of time for the 1980 April 8 flare. The volumes ΔV refer to the volumes over which appreciable emission in the resonance lines occurs. The smooth curves were obtained by using the smoothed flux curves in Figure 4.

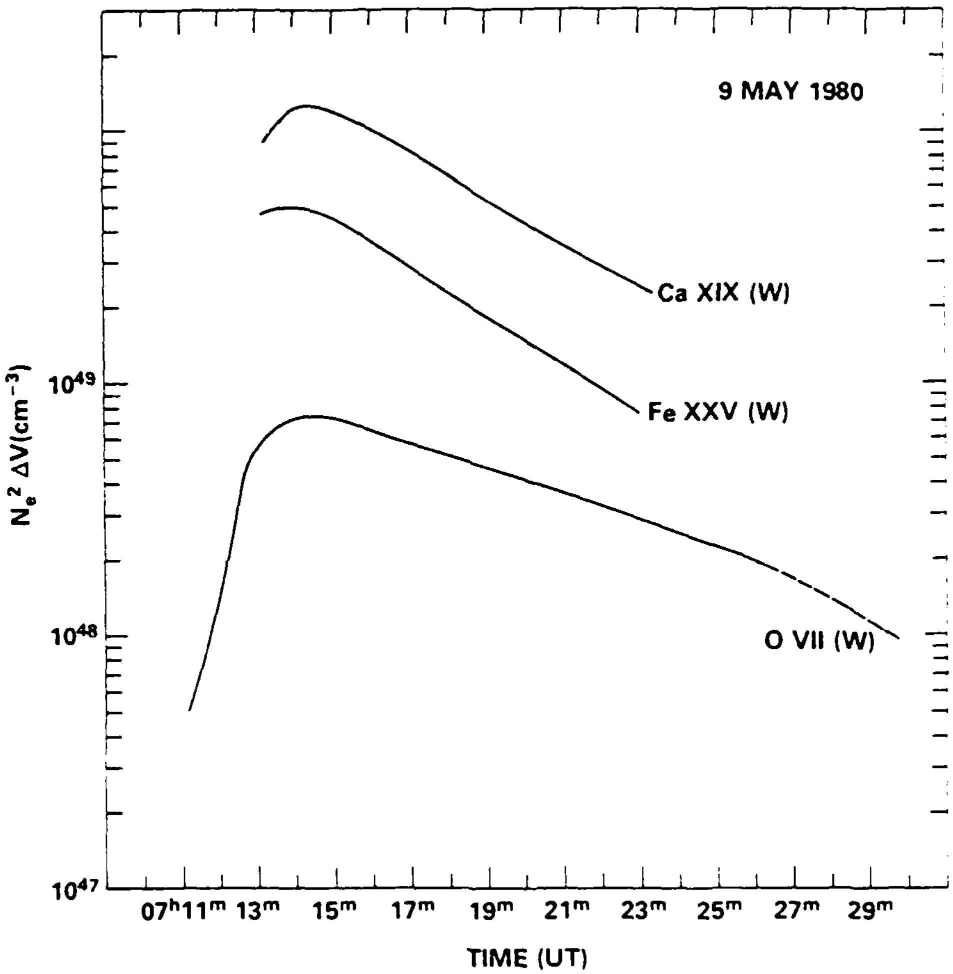

Figure 7 - Same as Figure 6 for the 1980 May 9 flare.

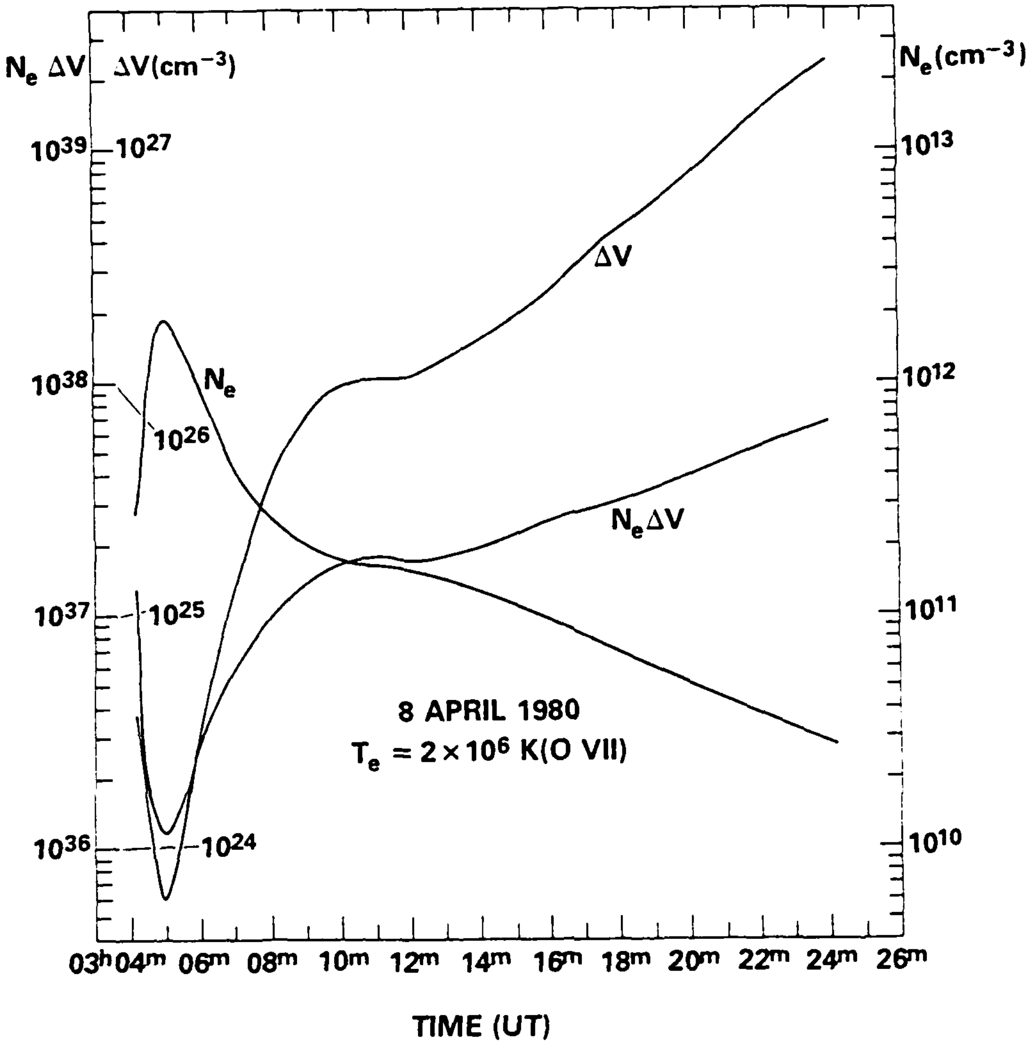

Figure 8 - Number of electrons $N_e\Delta V$ and volume ΔV as a function of time for the 1980 April 8 flare. The volume ΔV refers to the plasma volume in which the O VII line is emitted. The temperature of this plasma is about 2 x 10^6 K. The electron density in this volume is also shown, adapted from Figure 4. The curves were obtained by using the smoothed curves for density and emission measure in Figures 4 and 6.

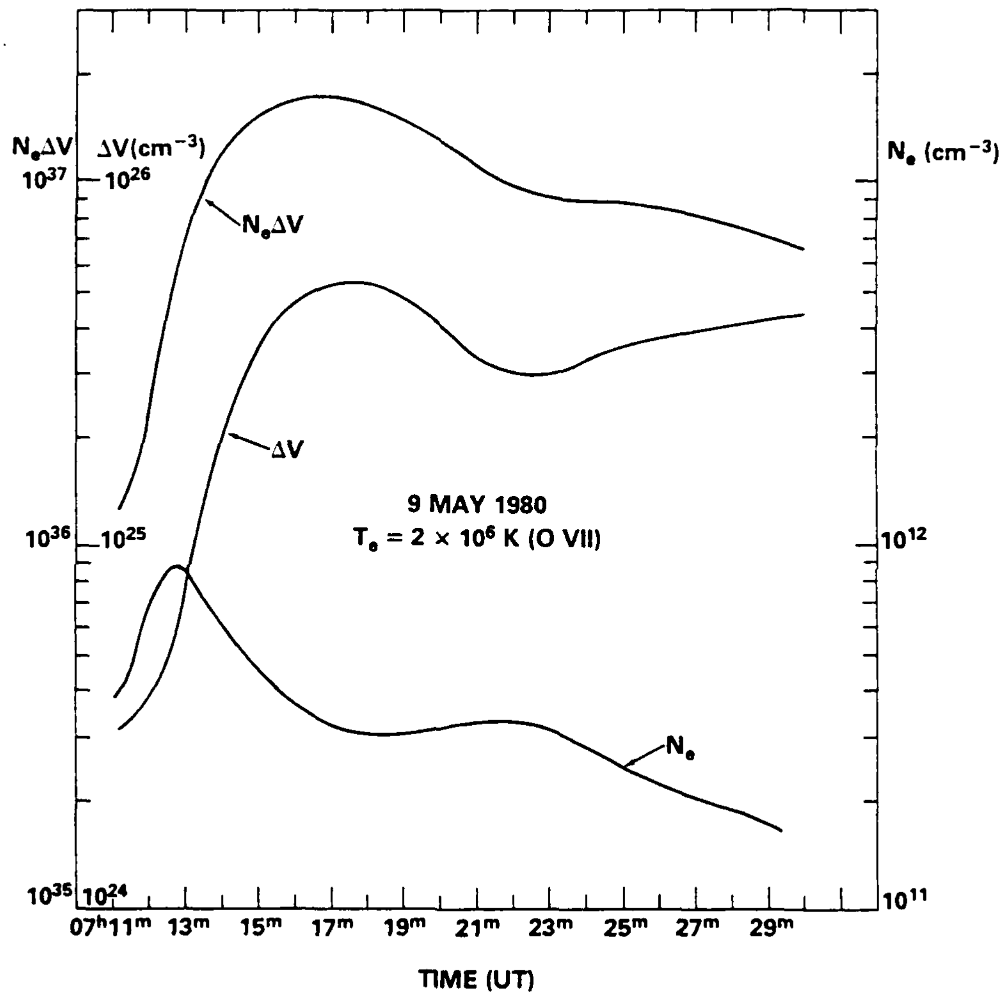

Figure 9 - Same as Figure 8 for the 1980 May 9 flare.

of N_e^2 ΔV and the determination of N_e. Because of the high counting rates, statistical errors are small for the line fluxes and therefore non-systematic errors are small for N_e^2 ΔV. Estimated errors for N_e are shown in Figures 4 and 5. While these errors could alter the precise shapes of the curves in Figures 8 and 9, the conclusion that N_e ΔV and ΔV must increase by large amounts as the flares progress is valid.

An interesting aspect of Figure 8 is the apparent decrease in both N_e ΔV and ΔV at 03^h 05^m UT, before the large increases that follow. This decrease reflects the very high density at 03^h 05^m UT. If this result is real and is not due to cumulative errors in N_e^2 ΔV or N_e, then this is evidence for compression of plasma near 2×10^6 K as suggested by the kinematic model discussed by Feldman, Doschek and Kreplin (1980), or in situ heating at very low and dense levels of the chromosphere. The interpretation is complicated, however, by the smaller but evident simultaneous decrease in $N_e \Delta V$. In the simplest compression model, N_e ΔV should remain constant.

An obvious question that suggests itself is whether the behavior of electron density deduced from the O VII lines also occurs in the higher temperature plasma where the Fe XXV and Ca XIX lines are formed. The answer would be yes if constant pressure were valid. In this case N_e can be derived for the Fe XXV region by simply reducing the O VII densities by the temperature ratios,

$$N_e(\text{Fe XXV}) = \frac{2 \times 10^6 \text{ K}}{T_e(j/w)} N_e(\text{O VII}). \tag{6}$$

We do not have a direct density diagnostic for the high temperature plasma; however we may use equation (6) and examine the consequences. Use of equation (6) enables us to calculate ΔV for the Fe XXV region, using the Fe XXV emission measures given in Figures 6 and 7. We may then compare the Fe XXV densities and volumes with available observations from Skylab, where these quantities were estimated using the NRL spectroheliograph data on the Fe XXIV lines at 192Å and 255Å. These lines should be formed in nearly the same region as the Fe XXV lines.

Previous Skylab observations indicate that the densities in the Fe XXIV (Fe XXV) region are high during the decay phases of flares, $\simeq 3 \times 10^{11}$ cm^{-3} (e.g., see Widing and Cheng 1974, Cheng and Widing 1975, Widing and Dere 1977, Dere et al. 1979, and Widing and Spicer 1980). However, equation (6) gives densities about an order of magnitude lower than obtained from Fe XXIV images. The Fe XXIV images have characteristic dimensions of a few tens of arc seconds. More recently Landecker and McKenzie (1980) measured the spatial extent of a very intense X-ray flare (X5) during the rise phase and found a characteristic size of about 30". However characteristic lengths found from equation (6) reach values >100" late in the decay phase of the April 8 event, which seems incompatible with the above results from Skylab.

In summary, equation (6) leads to densities and volumes for the Fe XXV region which contradict the earlier Skylab results. The Skylab results should be reliable because the Skylab densities, if in error, are probably underestimated since unit filling factors were assumed. The measurements of size are quite accurate since direct images of the Fe XXIV emitting plasma were obtained. The following possibilities may clarify the situation:

a) The pressure is not constant and increases with temperature. In this case the density would be greatest at the highest temperatures and much smaller derived volumes would be obtained. However, it is difficult to understand why the density should increase, rather than decrease with temperature, in a flare model in which the magnetic field is parallel to the direction in which a temperature gradient exists, i.e., a simple loop. b) Either constant pressure or hydrostatic equilibrium is valid, and densities are $\approx 10^{11}$ cm^{-3} in the high temperature region. This implies that the densities obtained from the O VII lines pertain to regions or loops that are physically distinct from the loops in which the high temperature emission occurs. This is a reasonable probability since for $(N_e^2 \Delta V)_O \approx 2 \times 10^{48}$ cm^{-3}, the forbidden O VII line would be very weak if $N_e \gtrsim 10^{12}$ cm^{-3}. Neighboring loops at comparable emission measures and densities $N_e \approx 10^{11}$ cm^{-3} would provide strong forbidden line emission that could be misinterpreted as arising in the high temperature loop or loops. In fact, the Skylab flare images frequently show the presence of multiple loops. Only a very high resolution X-ray imaging spectrograph with arc second resolution (significantly higher than currently available) could clarify this issue.

In summary, by assuming a static loop model we obtain unacceptably small densities and large volumes for the regions at temperatures $> 10^7$ K. Clarification of this problem requires density measurements for plasma regions $> 10^7$ K, along with high spatial resolution imaging (<3"). The imaging is necessary for the density measurements as well as for understanding the spatial relationship of the high temperature plasma relative to the O VII emitting regions. As discussed in Doschek and Feldman (1979), there are no good solar density diagnostic line ratios for $T_e \approx 2 \times 10^7$ K. Thus densities must be obtained by determining an emission measure for a spatially resolved image from which ΔV can be estimated. Densities determined in this manner are lower limits because of the necessary assumption of a unit filling factor.

We feel there is a good possibility that static loop models are not valid representations of flare loops. We note that the scaling laws developed by

Rosner, Tucker and Vaiana (1978), which appear to be valid for quiet Sun and active region loops, fail completely when applied to flare loops. This fact was pointed out by the above authors, and may be the consequence of motions within the flare flux tubes.

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