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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ABSTRACT

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 the 18.4–23.0 Å range, which includes the Lyα 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 $2 \times 10^6$ K. 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 $10^{12} \text{cm}^{-3}$. Electron temperature $T_e$ as a function of time is determined from the Fe and Ca spectra. Peak temperature for both flares is about $18 \times 10^6$ K. Differential emission measures and volume emission measures are determined from the resonance lines of O vii, Ca xix, and Fe xxv. The number of electrons $N_e \Delta V$ and the volume $\Delta V$ 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.

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

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). Analysis of these spectra allows physical conditions to be determined in flare plasmas, such as electron temperature and density. 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 to Fe xxv. The longer wavelength region covers 1s–2p type transitions in Ca xvii to Ca xix. In the flare plasma at electron temperatures $T_e > 10^6$ K, the dominant ions are Fe xviii to Fe xxv and Ca xviii to 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 (1981). Brief descriptions of the NRL spectrometers are given in these papers. The Aerospace Corporation’s spectrometers (SOLEX) cover the wavelength region between 3 Å 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 spectrograms 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 $2 \times 10^6$ K (O vii lines). Clearly it is desirable to combine data sets from the two experiments in order to extend the temperature range observed and thereby attempt to understand the physical relationship between the high temperature thermal regions of flares ($\approx 20 \times 10^6$ K) and the cooler thermal flare regions ($\approx 2 \times 10^6$ K). 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°).
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II. OBSERVATIONS

Spectra were obtained from flares that occurred on 1980 April 8 and 1980 May 9. The 1980 April 8 flare occurred near 03 UT at N12, W10 and was a class M7 event. Observations of the 1980 April 8 flare began before the onset of the flare was too fast for good temporal coverage, and we do not have many observations for this period. Observations of the 1980 May 9 event began slightly before the rise phase of the 1980 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 consists of repeated scans of the iron and calcium lines (a complete scan was accomplished in 56 s). 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 (1981), where the theory originally developed for Ca xix and Fe xxv is extended to the less ionized iron ions, Fe xxii and Fe xxiv. Average temperatures of the flare region emitting lines of Fe xxv can be derived from the intensity ratio, j/w (see Fig. 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 xix transitions, 1s^22p^2 2P_{3/2}-1s2s^2 2D_{5/2} and 1s^22p^2 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 Feldschek, Feldman, and Cowan (1981). 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 Pressyakov (1975). Once temperatures are determined from line ratios, volume emission measures

\[ N_e \Delta V = \left( \int \frac{N_e}{A} dV \right) \]

where \( N_e = \) electron density and \( \Delta V = \) approximate plasma volume in which the lines are formed, can be derived using relationships given in Doschek et al. (1980) and discussed further in § 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 1981 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. (1977, 1980) differ only slightly from the results of Jordan (1970) and Landini, and Monsignori 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 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 in typical flares 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 Å 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 1980 April 8 and 1980 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 helium-like O vi resonance (1s^2 1S_0-1s2p 1P_1), intercombination (1s^2 1S_0-1s2p 3P), and forbidden (1s^2 1S_0-1s2s^2 3S) lines at 21.60, 21.80, and 22.10 Å, respectively, are included in this range as is the O vi Lyα 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 § III. Since in this case $N_e$ is known, the number of particles $N_e \Delta V$, and the volume $\Delta V$, 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 $2 \times 10^6$ 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 helium-like ions by Pradhan, Norcross, and Hummer (1981). 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. (1980a), and therefore densities derived in that paper should be reduced by about 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 ratio $R$ of forbidden to intercombination lines 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 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 1980 May 9 event. The times shown in each panel are the times at which the resonance line was scanned. The flux in the O vii resonance line increases markedly near 07h12m56s.
UT, and the ratio of forbidden to intercombination lines is quite small, implying a very high density. As the flare progresses, this line ratio increases as the density decreases. These results are discussed quantitatively in § III.

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 1980 April 8 and May 9 events, this is relatively straightforward. For the 1980 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 1980 May 9 event one background spectrum is available, just prior to the flare (the spectrum obtained at 07h08m40s UT in Figure 3), and this spectrum has been subtracted to obtain the results discussed in § III.

In summary, the SOLEX spectra allow $N_e$ and $N_{ei}ΔV$, and therefore $N_eΔV$, $ΔV$, to be determined as functions of time for the flare plasma near $2 \times 10^6$ K. The electron pressure $p$ ($= N_e T_e$) can then be calculated at $2 \times 10^6$ 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 AND DISCUSSION

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 xxxv, Ca xix, O vii, 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 the iron and calcium lines, respectively. The smooth curves are eye estimate fits to the data.

Consider first the variation with time of the high temperature 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 xxxv resonance line (line w), the temperature behavior is different for the two flares. The 1980 May 9 event cools more rapidly; the temperature determined from $j/w$ drops from about $2.0 \times 10^7$ K to about $1.3 \times 10^7$ K in 10 minutes. In the 1980 April flare, this temperature remains nearly constant at about $1.6 \times 10^7$ K for about 15 minutes after the time of peak line flux for Fe xxxv, i.e., from 03h05m5 to 03h21m0 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 plasmas, to a greater or lesser extent. Our results are qualitatively consistent with less heating in the 1980 May 9 event than in the 1980 April 8 flare, because the temperature for the 1980 May 9 event is declining monotonically over the period for which we have measurements, while the 1980 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 for most flares the temperature should be constant (near $20 \times 10^6$ K) or increase slightly over most of the rise phase until peak flux in Fe xxxv line w is reached. Based on these observations, it is not likely that the Fe xxxv temperatures were much higher than the largest temperatures shown in Figures 4 and 5. The temperatures obtained from the $k/w$ Ca xix, O vii forbidden to intercombination line ratios are a few million degrees lower than the Fe xxxv $j/w$ temperatures, as obtained by us previously for other M and X class flares. (Ca xix is formed in lower temperature regions than Fe xxxv.) 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 increasing 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 $2 \times 10^6$ K x $10^{12}$ cm$^{-3}$ = $2 \times 10^{18}$ 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 $2 \times 10^{13}$ 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 1980 May 9
Fig. 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.
flare there is a period of time in which the density is nearly constant before beginning a monotonic decrease. In the 1980 April 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 1980 April 8 event than in the 1980 May 9 flare, the density remains at higher values for longer periods of time in the 1980 May 9 flare than in the 1980 April 8 flare.

It is natural to inquire if there is a physical connection between the flare plasma near temperatures of $\sim 15 \times 10^6$ K in which the Fe xxv and Ca xix lines are formed, and the lower temperature plasma around $2 \times 10^6$ 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 nearly 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 of the O viii 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 multi-thermal 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 $\mathcal{F}$ at Earth (photons cm$^{-2}$ s$^{-1}$) in an allowed or resonance line is given by

$$\mathcal{F} = \frac{1}{4\pi R^2} \int \frac{N_e N_1 C_{12} dV}{c} ,$$

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

$$\mathcal{F} = \frac{8.63 \times 10^{-6}}{4\pi R^2 \omega_1} (0.8 A_n) \int_{T_1}^{T_2} \frac{dV}{dT_e} dT_e ,$$

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

$$G(T_e) = \frac{F(T_e)}{(T_e)^{1/2}} \exp \left(-\frac{\Delta E_{12}}{k T_e}\right) ,$$

where $\Delta E_{12}$ 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, $\Omega$ is the collision strength averaged over a Maxwellian distribution, $k$ is Boltzmann’s constant, $\omega_1$ is the element abundance relative to hydrogen, 0.8 is the proton to electron number density ratio, $A_n$ 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 estimate 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 temperatures lines we have available (O vii [line w] and Fe xxv [line w]):

$$\mathcal{F} = \frac{6.90 \times 10^{-6}}{4\pi R^2} A_n [0.7 G(T_e) \Omega(T_e) |_{T_{\text{max}}}] N_e^2 \Delta V ,$$

where $T_{\text{max}}$ is the temperature at which $G(T_e)$ is a maximum [$\Omega(T_e)$ is a slowly varying function of temperature compared to $G(T_e)$]. We obtain an estimate of the differential emission measure at $T_e = 2 \times 10^6$ 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 (see Fig. 11 in Doschek et al. 1980). As discussed in Doschek, Feldman, and Cowan (1981), 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 predominantly formed in a narrow range $\Delta T_e$ about $T_e(j/w)$; we estimate $\Delta T_e \approx 3 \times 10^6$ 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 $T_{\text{max}}$. We find that for the 1980 April 8 flare the ratio of the differential emission measure at $T_e(j/w)$ to that at $2 \times 10^6$ K varies from 3 to 12, and for the 1980 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. However, 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 ($f_c = 1$ for a point source on axis, and $f_c = 0.25$ 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 $2 \times 10^6$ K, and the emission measure ratios given above should be regarded as upper limits.

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

$$N_e^2 dV/dT_e = a T_e^b , \quad T_1 \leq T_e \leq T_2$$

$$N_e^2 dV/dT_e = 0 , \quad T_e > T_2 ,$$

where $a$ and $b$ are constants and $T_1 = T_e(j/w)$. $T_2$ may be set to any value below $10^6$ K. By using the results of the previous paragraph (assuming $f_c = 1$) we find $0.5 \leq b \leq 1.2$ for the 1980 April 8 flare and $0.2 \leq b \leq 0.7$ for the 1980 May 9 flare. If $f_c < 1$, these $b$ values would be smaller. The O viii Ly$\alpha$ 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$\alpha$ 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 $b < 0$. All of these results indicate that the O vii lines are indeed formed at around $2 \times 10^6$ 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 expression $a T_e^b$ does not always provide a good fit to all of the resonance line data.

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 shown in Figures 6 and 7. These emission measures are derived from equation (4). We point out that the volumes $\Delta V$ 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 in part 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 (1976) is too small relative to Fe. This would result in an overestimate of the Ca line emission measure. These abundance uncertainties should be kept in mind when deriving differential emission measures using lines of different elements. Also, the contribution functions for Ca xix and Fe xxv are considerably different (see Fig. 11 in Doschek et al. 1980), and therefore the Ca xix and Fe xxv emission can arise in somewhat different temperature regions that may have different emission measures.

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 $\Delta V$ over which O vii emission occurs, centered at temperatures near $2 \times 10^6$ K, as a function of time for the flares. These results are shown in Figures 8 and 9 and are quite interesting. The smooth curves were obtained by using the smooth curves in Figures 4, 5, 6, and 7. In order to indicate the spread of values for $N_e \Delta V$, $N_e \Delta V$, and $\Delta V$ that result by using the actual data points in Figures 4 and 5, we have also shown the values of $N_e \Delta V$, $N_e \Delta V$, and $\Delta V$ that are obtained from the data points for the 1980 April 8 flare. The scatter for the 1980 May 9 flare is less because the smooth curve for $N_e$ in Figure 5 fits the data more closely than is the case for the 1980 April 8 flare.

Both flares show a large increase in $N_e \Delta V$ and $\Delta V$ early in the decay phase. These increases could be due to evaporation of cool gas from the chromosphere heated to $2 \times 10^6$ 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 $\Delta V$ is much larger for the 1980 April 8 flare because $N_e$ remains high for long periods in the 1980 May 9 event. Note that errors in $N_e \Delta V$ and particularly $\Delta V$ depend on errors in the measurement of $N_e \Delta V$ and the determination of $N_e$. Because of the high counting rates, statistical errors are small for the line fluxes, and therefore nonsystematic errors are small for $N_e \Delta V$. 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 $N_e \Delta V$ and $\Delta V$ must increase by large amounts as the flares progress is valid.

An interesting aspect of Figure 8 is the apparent decrease in both $N_e \Delta V$ and $\Delta V$ at 03h05m UT, before the large increases that follow. This decrease reflects the very high density at 03h05m UT. If this result is real and is not
due simply to the fact that there is only one observation prior to the decrease, then this is evidence for compression of plasma near $2 \times 10^6$ 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, $N_e \Delta V$ should remain constant. We regard the drop in $\Delta V$ as an uncertain result and feel that further observations of other flares are required to confirm it.

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,

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

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 $\Delta V$ 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 192 Å and 255 Å. 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 rise and maximum phases of flares, $\sim 3 \times 10^{11}$ cm$^{-3}$ (e.g., see Widing and Cheng 1974; Cheng and Widing 1975; Widing and Dere 1977; Dere et al. 1979; Widing and Spicer 1980). However, at least for the 1980 April 8 flare, equation (6) gives densities about an order of magnitude lower than obtained from Fe xxiv images at around 03:09 UT, a time quite close to maximum flux in the Fe xxiv line. The Fe xxiv images have characteristic dimensions of $\leq 20$ arc seconds. More recently Landecker and McKenzie (1980) measured the spatial extent of a very intense X-ray flare of importance X5 during the rise phase and found a characteristic size of about 30'. Since they were measuring continuum radiation near 6 Å, a range of temperature regions could be represented in the result. However, the hottest flare regions produce Fe xxv emission, and based on the Skylab images in many different lines, the cooler regions produce larger images. Therefore the 30' size should be regarded as an upper limit to the size of the Fe xxv and Fe xxiv emitting regions. However the characteristic length found from equation (6) for the 1980 April 8 flare around 03:09 is about 60', which seems somewhat too large. Later in the decay phase of the event, characteristic lengths reach values $> 100'$, which implies either that the Fe xxiv region expands during cooling or that equation (6) cannot be directly applied to the data.

The Skylab density results should be reliable because the Skylab densities, if in error, are probably underestimated since unit filling factors were assumed. The measurements of size should be accurate since direct images of the Fe xxiv emitting plasma were obtained. The following possibilities may clarify the situation:

1. 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.

2. Either constant pressure or hydrostatic equilibrium is valid, and densities are $\sim 10^{11}$ cm$^{-3}$ in the high temperature region. This implies that the densities obtained from the O vii lines are affected by regions or loops that are physically distinct from the loops in which the high temperature emission occurs. In this case the O vii line emission would represent the composite emission arising from a set of physically distinct loops. The derived densities would then be average values in some sense. If a number of relatively cool loops exist (no Fe xxiv emission present), with densities lower than in the loop or loops in which Fe xxv is formed, then the derived O vii densities would be lower than the density at $2 \times 10^6$ K in the hot loop or loops. This would result in underestimating the density at which Fe xxv is formed using equation (6). In fact, as is well known, 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) can clarify this issue.

3. The density behavior with time derived from the...
O vi lines is mirrored at high temperatures, and all the Skylab measurements were coincidentally made at times when the density was highest. Equation (6) may then be valid, and the loops would slowly expand as the flare cools. A study of many events using the flat crystal spectrometers in the flare imaging mode on the Solar Maximum Mission (SMM) spacecraft may clarify this issue.

In summary, by assuming a static loop model we obtain somewhat questionable 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 ($< 3\arcsec$). 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 $\Delta V$ 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 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, seem to fail 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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