XUV SPECTRA OF THE 1973 JUNE 15 SOLAR FLARE OBSERVED FROM SKYLAB. I. ALLOWED TRANSITIONS IN CHROMOSPHERIC AND TRANSITION ZONE IONS

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ABSTRACT

Spectra between 1100 and 1940 Å of the 1973 June 15 solar flare are discussed. The spectra were recorded by the NRL normal-incidence slit spectrograph on Skylab. In this paper we discuss allowed transitions in ions formed in the chromosphere and transition zone. We give the power (ergs s⁻¹) in the emission lines produced by the plasma viewed by the instrument, and we give the widths and shapes of the line profiles as a function of time during the flare. We calculate emission measures and volumes of the flare plasma for lines of Si iv, C iv, and N v. The characteristic lengths (≡ V₁/₁₂) are quite small, ranging between ~0.1 to ~1.0. The smaller values are the more reliable. The flare can be qualitatively divided into two distinct phases. An eruptive phase occurs near the beginning of the flare and lasts for about 2 minutes. Plasma is observed moving toward the observer at velocities as high as 60–80 km s⁻¹ during this phase. A continuous energy input is necessary to account for the lifetime of the moving plasma. A much longer lived quiescent phase follows the eruptive phase and lasts for about 23 minutes.

Subject headings: Sun: chromosphere — Sun: flares — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

One of the most interesting flares observed by the astronauts during the Skylab mission was the 1973 June 15 flare that occurred shortly after 14 UT. This flare occurred in McMath region 12379 at N17, W32. The Hα event was a classic two-ribbon flare of importance 1B. It was the largest flare observed with the NRL instruments. The Skylab instrumentation allowed observations of the flare originating in the chromosphere, the transition zone, the corona, and the coronal flare plasma at temperatures up to ~3 x 10⁶ K. Figure 1 shows the Solrad X-ray fluxes, along with times of the Hα event and accompanying radio bursts. These data were obtained from Horan and Dere (1976), and Solar Geophysical Data (1973). A more complete description of the radio bursts is given in Pallavicini et al. (1975). The flux (in arbitrary units) of the forbidden line of Fe xxi at 1354 Å is also shown in Figure 1. This ion is formed at temperatures of ~11 x 10⁶ K. Figure 2 shows an image of the Hα flare and a magnetogram of the area. The location of the neutral line between the two Hα ribbons is obvious from the magnetogram. Several papers that discuss this flare have already appeared (e.g., Widing and Cheng 1974; Brueckner 1976, 1977; Widing 1975a, b; Cheng and Widing 1975; Pallavicini et al. 1975).

An extensive set of slit spectra of the June 15 flare were recorded by the NRL spectrograph on Skylab operating between 1000 and 4000 Å. The projected slit area on the Sun was 2" x 60". The position and size of the slit relative to the Hα flare is shown in Figure 2. The slit lies roughly over and along the neutral line, and over part of the Fe xxiv emitting region (Widing and Cheng 1974). Brueckner (1974) has published a qualitative description of the slit spectra.

In this paper (Paper I) and in a following paper we discuss the flare spectra recorded between 1100 and 1940 Å. Because of the wealth of data available, we have decided to divide the discussion into two parts. In Paper I we present the observational results for some of the allowed lines, which consist of (a) the absolute intensities (and emission measures for lines of Si iv, C iv, and N v) of emission lines, given as a function of time during the flare (for lines representing temperatures $T_e < 2 \times 10^6$ K), (b) line profiles and full widths at half-maximum (FWHM) of the lines, (c) mass-motion velocities and effective temperatures derived from Doppler broadening and Doppler-shifted components of the emission, and (d) a discussion of the properties of the flare plasma as deduced from the line widths, shifts, and intensities. In a following paper we present similar results for intersystem, forbidden, and associated allowed lines of transition zone, quiet corona, and flare coronal regions. We estimate electron densities from the intersystem lines and derive volumes for the flare plasma viewed by the instrument.

II. THE INSTRUMENT

The NRL slit spectrograph on Skylab consists of two main systems: a telescope and the spectrograph. The instrument can operate in either of two wavelength ranges: 970–1940 Å, or 1940–3940 Å. Below 1100 Å the efficiency is very low. An off-axis paraboloidal...
mirror images the Sun on the entrance slit of the spectrograph. As mentioned, the projected slit dimensions on the Sun are $2^\circ \times 60^\circ$. The light passing through the slit is dispersed by either of two pre-dispersers, depending on the wavelength range desired. A 300 line mm$^{-1}$ predisperser is used to disperse the radiation between 970 and 1940 Å toward the main grating. This radiation is diffracted by the 600 line mm$^{-1}$ main grating and focused onto photographic film. The gratings are Bausch and Lomb aluminum replicas coated with a layer of MgF$_2$. The spectral resolution is 0.06 Å, and the dispersion at the film plane is 4.16 Å mm$^{-1}$. A complete description of the instrument is given by Bartoe et al. (1974).

III. DATA REDUCTION

The flare spectra were recorded on Kodak 104 film. Exposures of 1.25, 5, 20, and 80 s were made, in order to cover the full dynamic range of the emission-line intensities. Characteristic curves for the film were derived from spectra of a quiet region recorded immediately after the flare sequence. The method of obtaining these curves is described by Doschek et al. (1976) and Feldman et al. (1976). Briefly, the peak photographic densities of particular lines obtained from spectra with different exposure times were compared. The differences, and thus a relationship between photographic density and intensity, could be established. The intensities derived in this manner are in arbitrary units, and do not include the instrumental response as a function of wavelength. Relative intensities between different lines are accurate to better than $\pm 15\%$, and the widths of lines can be determined to better than $\pm 10\%$.

It is clearly desirable to have absolute intensities, rather than relative intensities, in order that important parameters such as the emission measure may be calculated. We have obtained an instrumental efficiency curve for the wavelength range 1350–1940 Å using the absolute intensities in the continuum published by Samain et al. (1975). The method consists of comparing our arbitrary continuum intensities in quiet Sun spectra obtained at Sun center with the intensities measured by Samain et al. (1975). The details of the method are given in Doschek, Feldman, and Cohen (1977) in connection with deriving an instrumental response curve for the 2000–3200 Å region. We estimate that the absolute intensity of measurements for the flare spectra should be accurate to within a factor of 2. (We actually convert the intensities to power [ergs s$^{-1}$] emitted by the flare plasma viewed by the instrument. See § IV.)

Below 1350 Å the quiet Sun continuum is too weak for meaningful measurements to be made. Deriving

![Figure 1](image-url)
Fig. 2.—Hα photograph and magnetogram of the June 15 event. The slit was co-aligned with the horizontal crosshair, and is shown to scale above the Hα image.
the instrumental response between 1100 and 1350 Å is a difficult problem. We have assumed that below 1350 Å the instrumental response curve has the same shape as the curve given in Bartoe et al. (1974). Support for this assumption is gained from the absolute intensity of hydrogen Lα reported by Ackerman and Simon (1973) and Prinz (1974). The quiet Sun intensity of the Lα line derived from our response curve agrees to within a factor of 2 with the intensities reported by these authors.

No light source for registering absolute wavelengths on the solar spectra was installed within the Skylab spectrograph. We have calculated all wavelengths relative to spectral lines from neutral elements such as C i and S i. The lines of these elements, while more intense in the flare than in quiet Sun spectra, do not show Doppler-shifted components or appreciable broadening.

IV. RESULTS

Most of the emission lines emitted between 1100 and 1940 Å arise from ions formed at temperatures between $8 \times 10^4$ K (C i, S i) and $2.2 \times 10^5$ K (O v). (Here and in subsequent discussions, the temperatures correspond to maximum ion concentration in ionization equilibrium, as calculated by Jordan 1969, 1970.) During solar flares, and above active regions, certain coronal forbidden lines also appear. These lines belong to ions formed at temperatures between $\sim 4 \times 10^5$ K and $3 \times 10^6$ K. During the hottest phases of flares, forbidden lines of Fe xix at 1118 Å and Fe xxi at 1354 Å also appear in the spectra. We identified these lines previously in NRL Skylab spectra (Doschek et al. 1975). The identifications were based on predictions from laboratory spectra (Feldman et al. 1975).

It is convenient to start the discussion of the results by first considering the optically thin resonance lines of ions formed in the transition zone between $7 \times 10^4$ K and $2 \times 10^5$ K. The profiles of Si iv 1402 Å ($7 \times 10^4$ K), C iv 1550 Å ($10^5$ K), and the N v doublet at 1238 and 1242 Å ($1.8 \times 10^5$ K) are shown in Figures 3, 4, and 5. The Si iv, C iv, and N v transitions are doublets with...
Fig. 4.—Profiles of the 1550 Å C iv line from spectra of the June 15 flare

Fig. 5.—Profiles of the 1238 Å and 1242 Å N v lines from spectra of the 1973 June 15 flare
XUV SPECTRA FROM SKYLAB

intensity ratios of 2:1. In the case of N v, both lines are shown in order to demonstrate that the lines are effectively thin. In this case, the ratios of the intensities of the two N v lines should be 2:1, as observed in Figure 5. We show only one line for Si iv and C iv because the same result holds for these doublets.

Inspection of Figures 3, 4, and 5 shows that the flare, as observed in these transition zone lines, may be divided into two distinct phases. In the first short-lived and eruptive phase, from \( \sim 11^{m}38^{s} \) to \( \sim 13^{m}23^{s} \), the line profiles appear to consist of two separate components. (We show below that in most cases the profiles are in fact consistent with the assumption that only two primary emitting components are viewed by the spectrograph.) One of the components is unshifted at the rest wavelength while the other one is blueshifted. Henceforth we refer to these components as the R and B-component, respectively. Between \( 12^{m}5^{s} \) and \( 12^{m}50^{s} \), the B-component is much stronger than the R-component. After \( \sim 13^{m}23^{s} \), a much longer lived and relatively quiescent phase begins.

a) The Eruptive Phase—Transition Zone Ions

The first observations at \( 11^{m}38^{s} \) and \( 11^{m}41^{s} \) commence at the cessation of the microwave bursts and near the peak of the soft X-ray flux in the 0.5 to 3 Å band (see Fig. 1). The Si iv, C iv, and N v lines at these times all show a double structure. Wavelength measurements show that the centroids of the red components (R) in the figures are at the rest wavelengths of the lines. These wavelengths are indicated by vertical arrows in the figures. The approximate centroid of the blueshifted component (B) is also indicated by vertical lines.

Consider the Si iv and N v B-components. Between \( 11^{m}38^{s} \) and \( 11^{m}41^{s} \), the intensity of the B-component of Si iv increases by about a factor of 1.5. By \( 12^{m}5^{s} \), the intensity has increased by a further factor of 2. Between \( 11^{m}41^{s} \) and \( 11^{m}54^{s} \), the B-component intensity is nearly constant for N v. Between \( 11^{m}54^{s} \) and \( 12^{m}5^{s} \), the intensity of the B-component of the N v lines increases by about a factor of 3, and then increases by about another factor of 1.3 between \( 12^{m}5^{s} \) and \( 12^{m}10^{s} \). Between \( 12^{m}5^{s} \) and \( 12^{m}50^{s} \), the B-component produces almost all of the intensity in the Si iv and C iv lines, and over two-thirds of the intensity in the N v lines. The intensity of B relative to R begins to drop around \( 13^{m}20^{s} \), and by \( 22^{m}14^{s} \) the B-component has disappeared. We regard the period of time from \( 13^{m}23^{s} \) to \( 22^{m}14^{s} \) as a transition between the eruptive and quiescent phases. In the \( 14^{m}9^{s} \) Si iv profile, a small redshifted component, in addition to the blueshifted component, is also observed. After \( 22^{m}14^{s} \), only the R component is present, and the line widths are relatively narrow. Large variations of intensity with time do not occur again until after \( \sim 28^{m}21^{s} \), after which all the line intensities begin to decrease.

During the eruptive phase, the intensity of the R-component appears to be nearly constant, and is approximately equal to the intensity of the R-component during the quiescent phase.

The above description can be made quantitative by attempting to fit the resonance line profiles with a two-component model. We assume that most of the emission arises from two Gaussian-shaped lines, one (R) at the rest wavelength, and the other (B) blueshifted. The widths, wavelengths, and peak intensities of the two components are adjusted until a least-squares fit with the observed profiles is achieved. A reasonably good fit could be made in all cases, although for a few profiles a small amount of emission from other components is indicated (e.g., the redshifted component mentioned above). Figures 6, 7, and 8 show the fits to the data at the beginning of the observations (\( \sim 11^{m}40^{s} \)), near the time of maximum intensity of B (\( \sim 12^{m}5^{s} \)), and during the decay of the B-component (\( \sim 13^{m}20^{s} \)). The wavelengths, the FWHMs of the Gaussians, and their separation in terms of Doppler velocity are given. The two Gaussian components are shown, and the combined emission from them is compared to the actual profiles.

The results of Figures 6, 7, and 8 and Gaussian fits to the data at other times over which an appreciable B-component is observed are summarized in Table 1. Columns (1) and (2) in the table give the average time of each exposure and the exposure time. Column (3) gives the power (ergs s\(^{-1}\)) produced in the lines by the portion of the flare plasma viewed by the instrument. The power in the lines for both the B and R-components is given, and quantities referring to the B-component are given in parentheses. The power is found using the expression,

\[
P = \frac{I_0}{2\pi A^\lambda} \left( \frac{\pi}{\ln 2} \right)^{1/2} W(4\pi A_\lambda),
\]

where \( P \) is the power, \( I_0 \) is the intensity at the center of the profile, \( \lambda \) is the wavelength, and \( A_\lambda \) is the FWHM of the line.

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**Fig. 6.** Resolution of Si iv and N v features into two Gaussian components (R and B; see text) near the beginning of the eruptive phase. The time is given in minutes and seconds after 14\(^{h}\) UT.
Fig. 7.—Resolution of Si iv, C iv, and N v profiles into two Gaussian components near the time of maximum intensity of the B-component. The leveling off of the N v profile at an arbitrary intensity of three is an artifact caused by film fog.

where \( I_0 \) is the peak intensity of the Gaussian, found from the fits using the arbitrary intensity units from the film characteristic curve, \( W \) is the FWHM, \( R_i \) is the instrumental response derived as described in § III, and \( A_p \) is the projected area of the slit. Multiplication by \( 4\pi A_p \) in equation (1) converts intensities in ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) to power expressed in ergs s\(^{-1}\). It is necessary to make this conversion because the shape and dimensions of the flare plasma are unknown. We have assumed isotropic emission, which is valid for optically thin lines. Also given in Table 1: column (4) gives the effective temperature \( T_i \), derived assuming...

Fig. 8.—Resolution of C iv and Si iv profiles into two Gaussian components near the end of the eruptive phase.
### TABLE 1

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### Si iv (1402 Å)

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### C iv (1550 Å)

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that the entire line width is due to thermal Doppler broadening (minus the instrumental broadening); column (5) gives the FWHM of the lines; column (6) gives the nonthermal velocity (most probable velocity), assuming ionization equilibrium; column (7) gives the separations between $B$ and $R$ in terms of velocity, i.e., $v_b = c\Delta \lambda / \lambda$; and finally, column (8) gives the emission measure of the three transition zone resonance lines, derived in § V.

The behavior of the $B$- and $R$-components that we have described for Si iv, C iv, and N v also holds for the lowest transition zone temperatures near $5 \times 10^4 \, \text{K}$, characteristic of Si iii. Figure 9 shows the line profiles of the blended Si iii lines at 1298 Å. These profiles are qualitatively similar to the Si iv lines. The Si iii lines may be broadened by opacity even though the transitions terminate on an excited level, because the $2s2p^3P$ levels are metastable. The power in the Si iii lines and the line widths are given in Table 1.

b) The Quiescent Phase—Transition Zone Ions

After the disappearance of the $B$-component near $18^h$, the intensities of the $R$-components remain fairly constant up to about $28^m20^s$, after which they begin to decrease. The widths of the lines also remain the
same to within experimental error. Figure 10 gives the combined power of the $B$- and $R$-components during the eruptive phase and the $R$-component power during the quiescent phase. The results for the $R$-component of the transition zone ions are also given in Table 1 for the quiescent phase.

c) Lines Formed in the Chromosphere

Figures 11 and 12 show representative examples of the behavior of low-temperature chromospheric lines during the flare. Figure 11 shows lines of $C\,\!$\,$i$ and $O\,\!$\,$i$. In the quiet solar atmosphere and over a polar coronal hole, most of the emission from these ions is confined to heights less than 1400 km above the white light photosphere (see the limb-brightening curves in Doschek et al. 1976 and Feldman et al. 1976). Apart from an intensity increase during the eruptive phase of the flare, the $C\,\!$\,$i$ line is not significantly broadened during the course of the event. The intensity behavior of the $O\,\!$\,$i$ line may be different from the behavior of the $C\,\!$\,$i$ line, because the $O\,\!$\,$i$ line is not an allowed line.

The widths of the $O\,\!$\,$i$ profiles are slightly greater than the instrumental width of 0.06 Å, corresponding to a nonthermal velocity of $\sim 4$ km s$^{-1}$. Because the $O\,\!$\,$i$ line is an intersystem line, the excess broadening is due to nonthermal motions, and is not an effect of opacity. Although the $C\,\!$\,$i$ line may be broadened by opacity, it is also quite narrow compared to the transition zone lines. We conclude that $\sim 10^4$ K plasmas are not present in the volume responsible for the emission of the $B$-component. However, it is not correct to conclude that relatively cold regions are totally unaffected by the flare. There are variations in emission line intensity from neutral atoms as well as from transition zone ions, in the region responsible for the $R$-component. The power in the $C\,\!$\,$i$ line during the eruptive phase ($\sim 12^m 30^s$) is several times larger than the power at the end of the observations ($\sim 36^m$). Also, variations in the intensity ratios between different $C\,\!$\,$i$ and $O\,\!$\,$i$ lines are observed (e.g., see Fig. 11), indicating fluctuations in the local electron density and/or temperature. The power in the $C\,\!$\,$i$ and $O\,\!$\,$i$ lines is given in Table 2.
Fig. 10.—Power in selected lines from spectra of the 1973 June 15 flare. The wavelengths of the lines are given in Tables 1 and 2. The B-component appears between 11m38s and 18m11s. The power shown is the sum of the B- and R-components.

Fig. 11.—Profiles of the 1355.8 Å C i and 1355.6 Å O i lines from spectra of the 1973 June 15 flare. The B-component does not appear in these profiles.
Fig. 12.—Profiles of the 1190 Å Si ii line from spectra of the 1973 June 15 flare. The B-component can be clearly seen in the profiles recorded at 12m23s and 13m8s.

The temperature at which the eruptive phase becomes detectable appears to be near $1.6 \times 10^4$ K, assuming ionization equilibrium. This is the temperature at which Si ii is abundant. A line from this ion is shown in Figure 12. The B-component is always weaker than the R-component, and is too weak to detect at 11m54s. At 12m20s the Doppler shift of the B-component corresponds to ~50 km s$^{-1}$, a value which is similar to the ~45 km s$^{-1}$ found for the Si iv and C iv lines observed only a few seconds earlier.

The power in the Si ii lines is given in Figure 10 and Table 1. The FWHM of the lines, the nonthermal velocities and effective temperatures, and the Doppler separations of the B- and R-components are also given in the Table. The behavior of this line can easily be compared with the transition zone lines by reference to Figure 10 and Table 1.

V. DISCUSSION

Inspection of the results in §IV leads to some conclusions that are independent of models of the flare plasma. We consider first the B-component. Figure 13 shows a plot against time of the velocity shift $v_b$ of the B-component for the lines of Si ii, Si iii, Si iv, C iv, and N v. Although there is considerable scatter in the data, it appears that a decrease in velocity occurs from about ~80 km s$^{-1}$ at 11m38s to ~60 km s$^{-1}$ at 13m24s, for C iv and N v. On the other hand, the velocity shift for Si iv appears to be nearly constant at ~50 km s$^{-1}$ throughout the eruptive phase. Figure 13 also shows the expected decrease in velocity, assuming that the moving plasma is slowed by gravity. (The component of the Sun's gravitational acceleration along the line of sight for the flare position N17, W32 is $\cos 17 \times \cos 32 \times g_0 = 0.22$ km s$^{-2}$.) Although the computed values of $v_b$ are less for Si iv than for the other ions, the differences may not be significant after 11m42s. (The errors in Fig. 13 correspond to an estimated error of ± 0.03 Å for the wavelength differences between the R and B-components.) It is difficult to decide whether or not the B-component is slowing down in accordance with gravitational deceleration, which would imply a single ejection event rather than a continuous plasma flow. The decrease of $v_b$ with time...
The separation in velocity between the R and B-components for the lines indicated. The errors in the wavelength separation between the two components are estimated to be ±0.03 Å. In terms of velocity, the errors are: Si ii, ±7.6 km s^{-1}; Si iv, ±6.9 km s^{-1}; Si iv, ±6.4 km s^{-1}; C iv, ±5.8 km s^{-1}; and N v, 7.2 km s^{-1}. The straight solid lines show the expected deceleration by gravity assuming velocities of 78 km s^{-1} and 55 km s^{-1} at 11^m38s.

For N v and C iv is consistent with gravitational deceleration. However, the behavior of v_b with time for Si iv shows no obvious deceleration. The kinematic results do not rule out the possibility that continuous plasma ejection occurs over a time interval comparable to the time interval over which the B-component is observed.

In addition to ambiguities in the interpretation of the velocity of the B-component, there are also different interpretations of the intensity behavior of the B-component. The impulsive emission of the B-component can be explained by one of the following assumptions:

a) The eruption of the moving plasma occurred within the field of view of the slit. The moving plasma brightened because of an increase in electron density as it moved upward (assuming a fixed number of particles), or because of an increase in time in the amount of ejected plasma.

b) The eruption of the moving plasma occurred outside the spectrograph field of view. The intensity changes of the moving plasma are due to the passage of the plasma into the field of view, followed by passage of the plasma out of the field of view.

c) A combination of (a) and (b).

It is not possible from the observations to decide conclusively which explanation is correct. The B-component is seen in the very first spectrum recorded, which was a 1.25 s exposure. The bulk of the B-component plasma was already moving at a high velocity.

No evidence of the acceleration of the plasma from zero velocity to the high velocity is observed; i.e., the profile is not consistent with a continuous distribution of velocities from zero to ~60 km s^{-1}. Thus, if the plasma erupted within the field of view, the eruption probably occurred before the first observation. The second explanation (b) is the less complicated one, because the intensity variations are simply a consequence of the occulting of the plasma by the spectrograph slit. In this case, the site of the expulsion occurs outside the field of view. (We note that either explanation appears to require an expulsion prior to 11^m38s, which would place the time of ejection during the time of the microwave and type III bursts.) Assuming that the intensity variations are due to occulting by the spectrograph slit, and that most of the plasma was ejected at about the same time, we can estimate the size of the moving plasma responsible for most of the emission in the B-component. These quantities are obtained by assuming that the plasma moves perpendicular to the slit length, and that the plasma is roughly symmetric in shape. Referring to Figure 10, from 12^m5s to 12^m50s the intensity of the B-component is fairly constant. Thus the entire mass of material is within the field of view for about 46 s. For N v, the intensity of the B-component increases by a factor of 4 between 11^m54s and 12^m10s, a 16 s time interval. At 12^m10s the N v lines have reached their maximum observed intensity. Thus, defining the characteristic length of the moving plasma as L, we have

\[
L = 16v_\perp,
\]

\[
1450 = 46v_\perp + L,
\]

where 1450 is the projected slit width in km. Solving equations (2), we get \( v_\perp = 23 \) km s^{-1}, and \( L = 390 \) km ~ 0.75. Assuming that the moving plasma is roughly symmetric in shape, the volume is \( L^2 \approx 6 \times 10^{22} \) cm^{-3}.

Another estimate of the volume can be obtained by assuming that the entire intensity increase of the B-component is due to a density increase, with the total number of particles remaining constant. Such a density increase might be caused by a plasma pinch, which would imply a cylindrical geometry for the plasma. The power in the Si iv, C iv, and N v lines is proportional to \( N_e^2 \Delta V \), where \( \Delta V \) is the plasma volume. The increase in power in these lines is about a factor of 3.5 in the 16 s time interval from 11^m54s to 12^m10s. Therefore, the increase in density and decrease in volume must also be a factor of 3.5, because we assume a fixed number of particles. If we assume cylindrical geometry and define \( \pi d_1^2 L/4 \equiv \Delta V \), we have,

\[
d_1^2 = 3.5d_2^2,
\]

where the subscripts 1 and 2 refer to values of the cylinder diameter \( d \) before and after the density increase, respectively. The volume is estimated by making a further assumption that the cylinder is viewed at right angles to its length \( L \), and that com-
pressure occurs along $d$. The maximum speed at which compression can occur is $\sim 30$ km s$^{-1}$, i.e., half the value of the nonthermal velocity $v$ given in Table 1. We may write

$$d_{2} = (d_{1} - v\Delta t), \quad (4)$$

where $v = 30$ km s$^{-1}$ and $t = 16$ s. Combining equations (3) and (4) gives $d \approx 1000$ km, $\Delta V_{1} \approx 7.8 \times 10^{22}$ cm$^{3}$, and $\Delta V_{2} \approx 2.2 \times 10^{23}$ cm$^{3}$, assuming $L \approx d$.

The question of the flare volume can be approached more precisely by attempting to derive the electron density and emission measure of the plasma, based on the absolute intensities of intersystem and allowed lines. In Paper II we estimate electron densities from the intersystem lines of ions such as O iv showing only a very weak $\beta$-component. This result is based on the fact that $\beta$-component (i.e., between $12^h 0^m 0^s$ and $12^h 0^m 50^s$) the plasma is in ionization equilibrium with hydrogen, $f_{lu}$ is the absorption oscillator strength, $N_{i}$ is the ion number density, $N_{T}$ is the element density, $<g>$ is the effective Gaunt factor, and $T_{em}$ is the transition energy in ergs. We may further assume a mean electron density and write

$$\int N_{i}e^{2}dV = <N_{i}^{2}>\Delta V, \quad (7)$$

where $<N_{i}^{2}>$ is the mean square electron density of the volume $\Delta V$ at temperature $T_{em}$, viewed by the slit.

Using equations (6) and (7), the quantity $<N_{i}^{2}>\Delta V$ can be determined for the emission lines of Si iv, C iv, and N v. We use the values of $f_{lu}$ and $<g>$ given by Dupree (1972) and the element abundances given by Ross and Aller (1976). The results are given in Table 1. (The emission lines of C i and Si ii are formed at much lower temperatures than the transition zone ions, and the excitation mechanisms may be more complicated than just electron impact excitation from the ground state. Similarly, the Si iii line involves metastable levels and requires a more detailed consideration of atomic processes.)

Inspection of the emission measure ratios of Si iv, C iv, and N v for the $R$-component in Figure 10 and Table 1 shows that the emission measure of the hottest observed material (N v) is greater relative to the emission measure of the cooler material (Si iv) than is the case for the $B$-component.

In a following paper on the intersystem lines, we derive a lower limit of $10^{18}$ cm$^{-3}$ for the electron density of the $B$-component. (This value is not critically dependent on atomic cross section data.) The volumes of the Si iv, C iv, and N v $B$-component emitting regions can be calculated by dividing the emission measures by $<N_{i}^{2}>$. At the peak intensity of the $B$-component (i.e., between $12^h 0^m 0^s$ and $12^h 0^m 50^s$) the volumes and characteristic lengths, $L$, for the Si iv, C iv, and N v regions are:

$$V(\text{Si iv}) \approx 1.1 \times 10^{21} \text{ cm}^{3}, \quad L \approx 100 \text{ km},$$

$$V(\text{C iv}) \approx 2.3 \times 10^{20} \text{ cm}^{3}, \quad L \approx 60 \text{ km},$$

$$V(\text{N v}) \approx 1.8 \times 10^{20} \text{ cm}^{3}, \quad L \approx 56 \text{ km},$$

where $L \equiv V^{1/3}$. The characteristic lengths are quite small, between 0'077 and 0'14. The volume we obtain from the Si iv line is about a factor of 5 greater than...
the volumes obtained from the C IV and N V lines. This is a reflection of the difference in emission measures between Si IV, and C IV and N V. The difference may arise from inaccuracies in the atomic data and element abundances used in the calculations.

The lengths derived from the densities and emission measures are about 8 times smaller than the lengths derived earlier. However, the lengths derived previously involved a number of assumptions regarding the shape, structure, orientation, and motion of the B-component. We feel that the volume and length estimates based on the values of \( N_e \) and \( \langle N_e \rangle \Delta V \) are more reliable, particularly since the larger volumes give much lower electron densities that are incompatible with the theory developed in Paper II. Nevertheless, it is worth pointing out that the previous estimates of volumes and lengths are also very small. They can be reconciled with the volumes based on density calculations if, for example, the plasma-emitting transition zone spectral lines were a thin sheath surrounding a larger plasma region at a temperature between \( \sim 2 \times 10^6 \) K and \( \sim 10^9 \) K. A plasma at a temperature larger than \( 10^6 \) K or smaller than \( 2 \times 10^6 \) K would be observed via spectral lines present in the 1000–2000 Å region. The values of characteristic lengths that we have obtained put an upper limit on the spatial resolution needed to resolve the fine-structure of transition zone flare plasmas.

Finally, we comment on the energy radiated by the B-component. Consider the energy radiated in the 1550 Å C IV line alone. Between 12m05s and 12m50s, the power radiated (see Table I) is about constant and is \( 7.4 \times 10^{28} \) ergs s\(^{-1}\). Therefore, in this 45 s time interval, \( 3.3 \times 10^{28} \) ergs is emitted in the 1550 Å line by the plasma within the field of view. The temperature of the plasma radiating this energy is \( \sim 10^5 \) K, the temperature of formation of C IV. The energy density of the electrons is \( 3/2 N_e k T_n \). The energy density of the protons is \( \sim m_p (v_t^2 + v_p^2) N_p \), where \( v_t \) is the thermal speed at \( 10^5 \) K, \( v \) is the turbulent speed in Table I, and \( m_p \) is the proton mass. The contribution of turbulence to the electron energy density is negligible. Substituting \( N_e = 10^{23} \) cm\(^{-3}\), \( T_n = 10^5 \) K, and \( v \approx 60 \) km s\(^{-1}\), we obtain \( \sim 650 \) ergs cm\(^{-3}\) for the electron-proton energy density. Using the previously determined plasma volume based on the electron density for C IV (\( 2.3 \times 10^{23} \) cm\(^{-3}\)), the total energy at \( \sim 10^5 \) K is \( \sim 1.5 \times 10^{29} \) ergs. This energy is about 200 times less than the power radiated in just one line at the maximum intensity of the B-component. Thus a continuous energy input appears to be necessary to explain the lifetime of the B-component.

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