LYMAN CONTINUUM OBSERVATIONS OF SOLAR FLARES

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Abstract. A study is made of Lyman continuum observations of solar flares, using data obtained by the Harvard College Observatory EUV spectrophotometer on the Apollo Telescope Mount. We find that there are two main types of flare regions: an overall 'mean' flare coincident with the Hα flare region, and transient Lyman continuum kernels which can be identified with the Hα and X-ray kernels observed by other authors. It is found that the ground level hydrogen population in flares is closer to LTE than in the quiet Sun and active regions, and that the level of Lyman continuum formation is lowered in the atmosphere from a mass column density \( m \approx 5 \times 10^{-6} \text{ g cm}^{-2} \) in the quiet Sun to \( m \approx 3 \times 10^{-4} \text{ g cm}^{-2} \) in the mean flare, and to \( m \approx 10^{-3} \text{ g cm}^{-2} \) in kernels. From these results we derive the amount of chromospheric material 'evaporated' into the high temperature region, which is found to be \( \approx 10^{15} \text{ g} \), in agreement with observations of X-ray emission measures. A comparison is made between kernel observations and the theoretical predictions made by model heating calculations, available in the literature; significant discrepancies are found between observation and current particle-heating models.

1. Introduction

The Lyman continuum has proven to be a very useful tool to investigate the structure of the upper chromosphere and lower part of the transition region. In this study, we use data obtained by the HCO experiment on Skylab to investigate the behavior of the continuum in solar flares. By this approach, we intend to gain some insight into the mechanisms of energy transfer and dissipation, and chromospheric evaporation.

To interpret the Lyman continuum data, an Eddington–Barbier relation can be used as a very good approximation to determine the physical conditions in the atmosphere at the level where the emission originates. The validity of this approximation has already been demonstrated (Noyes and Kalkofen, 1970; Vernazza and Noyes, 1972). It permits us to write the monochromatic intensity in the Lyman continuum (LC) as

\[
I_\lambda(\mu) \equiv S_\lambda(\tau_\lambda = \mu) = \frac{B_\lambda(T_e(\tau_\lambda = \mu))}{b_1(\tau_\lambda = \mu)} = \frac{B_\lambda(T_c)}{b_1(\tau_\lambda = \mu)},
\]

(1)

where \( S_\lambda \) is the continuum source function, \( B_\lambda \) is the Planck function, \( b_1 \) is the departure coefficient of the first level of hydrogen, \( T_e \) is the color temperature of the observed continuum emission, and \( \mu \) is the cosine of the angle of emergence. Then from the slope and absolute intensity of the continuum one obtains a measure of \( b_1 \) by

\[
b_1(\tau = 1) = B_\lambda(T_c)/I_\lambda(\mu = 1).
\]

(2)
A model synthesis approach can be used to determine other atmospheric parameters (see Noyes and Kalkofen, 1970).

In this paper we study LC data from two types of flare plasma: (a) the overall 'mean' flare as delineated, for example, by the region of Hα emission observed in the visual, and (b) LC 'kernels', which we identify with the bright Hα kernels that are localized in space and last for short times within the overall Hα flare.

The data (Table I) are obtained from the three main observational modes of the EUV spectroheliometer: the spectral scan (SS) mode, in which a spectrum of a 5'' square area, covering 300–1335 Å, is obtained in 3.8 min; the raster mode, in which simultaneous spectroheliograms (SHG) of a 5' square area are made in several wavelengths with 5'' resolution and 5.5 min time resolution; and the line scan (LS) mode in which a region 5' long and 5'' wide is scanned once every 5.5 s. Further details on the instrument can be found in Reeves et al. (1977). The first two types of data are used to study the characteristics of the mean LC flare, while the last is used to study LC kernels.

### TABLE I
List of investigated flares

<table>
<thead>
<tr>
<th>Date</th>
<th>Hα class</th>
<th>Hα development&lt;sup&gt;b&lt;/sup&gt; beg. – max – end</th>
<th>Observations beg.–end</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 28</td>
<td>1N</td>
<td>1746 –(1750)–1802</td>
<td>1732–1828</td>
<td>SHG</td>
</tr>
<tr>
<td>July 2</td>
<td>–F</td>
<td>1807 – 1809 –1815</td>
<td>1738–1855</td>
<td>SHG</td>
</tr>
<tr>
<td>Aug. 31</td>
<td>–F</td>
<td>2202 – 2203 –2205</td>
<td>2218–2222</td>
<td>SS</td>
</tr>
<tr>
<td>Sept 2</td>
<td>–B</td>
<td>0042 – 0045 –0050</td>
<td>0044–0055</td>
<td>SHG-LS</td>
</tr>
<tr>
<td>Sept. 2 (a, b)</td>
<td>–F</td>
<td>0157 – 0159 –0203</td>
<td>0156–0216</td>
<td>SS</td>
</tr>
<tr>
<td>Sept. 2 (c)</td>
<td>–N</td>
<td>0223 – 0231 –0247</td>
<td>0235–0239</td>
<td>SS</td>
</tr>
<tr>
<td>Sept. 2 (d)</td>
<td>1N</td>
<td>(1904)– 1904 –1925</td>
<td>1858–1902</td>
<td>SS</td>
</tr>
<tr>
<td>Sept. 4</td>
<td>—</td>
<td>—</td>
<td>0218–0221</td>
<td>SS</td>
</tr>
<tr>
<td>Sept. 7 (a, b)</td>
<td>2B</td>
<td>1206 – 1225 –1335</td>
<td>1255–1258</td>
<td>SS</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>–F</td>
<td>(1609)– 1609 –1614</td>
<td>1530–1629</td>
<td>SHG</td>
</tr>
</tbody>
</table>

<sup>a</sup> All dates are in 1973; letters refer to Table II. The September 4 event was not reported as an Hα flare in *Solar Geophysical Data*.

<sup>b</sup> Numbers in parenthesis are uncertain.

### 2. Observations of the Mean LC Emission in Flares

Six of the flares listed in Table I were observed in the spectral scan mode. In each case, the SS was obtained over an area of relatively uniform Hα emission, rather than over a bright Hα kernel as studied by Vorpahl (1972). These were calibrated to get absolute intensities, color, temperatures, and the total energy output in the continuum.

Table II gives the measured color temperature values, together with the $b_1$ factors calculated by means of Equation (2). From this table we see that the

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TABLE II
Lyman continuum data for the flares observed in the SS mode

<table>
<thead>
<tr>
<th>Flare</th>
<th>$T_c$ (K)</th>
<th>$b_1$</th>
<th>$T_c$ (790–700 Å)</th>
<th>LC flux (erg cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 31</td>
<td>8480</td>
<td>10</td>
<td>15 000</td>
<td>$5.0 \times 10^5$</td>
</tr>
<tr>
<td>Sept. 2a</td>
<td>8380</td>
<td>6</td>
<td>11 600</td>
<td>$7.0 \times 10^5$</td>
</tr>
<tr>
<td>Sept. 2b</td>
<td>8100</td>
<td>3</td>
<td>11 300</td>
<td>$6.5 \times 10^5$</td>
</tr>
<tr>
<td>Sept. 2c</td>
<td>9160</td>
<td>3</td>
<td>12 000</td>
<td>$7.8 \times 10^6$</td>
</tr>
<tr>
<td>Sept. 2d</td>
<td>7960</td>
<td>3</td>
<td>12 000</td>
<td>$5.8 \times 10^5$</td>
</tr>
<tr>
<td>Sept. 4</td>
<td>8770</td>
<td>7</td>
<td>10 000</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>Sept. 7a</td>
<td>9100</td>
<td>55</td>
<td>14 000</td>
<td>$3.7 \times 10^5$</td>
</tr>
<tr>
<td>Sept. 7b</td>
<td>7795</td>
<td>3</td>
<td>10 800</td>
<td>$3.2 \times 10^6$</td>
</tr>
<tr>
<td>Sept. 10</td>
<td>8200</td>
<td>8</td>
<td>12 500</td>
<td>$4.8 \times 10^5$</td>
</tr>
</tbody>
</table>

Temperature close to the continuum head, for which the determination is the most reliable, lies between 7900 and 9000 K in most cases, with an average value of 8450 K. This is essentially the same as the quiet Sun (Noyes and Kalkofen, 1970) and about 500 K hotter than active regions (Noyes, 1971). The values of $b_1$ should be compared with the value $b_1 \sim 200$ for the quiet Sun (Noyes and Kalkofen, 1970; Vernazza and Noyes, 1972) and with the value $b_1 \sim 15$ for active regions (Noyes, 1971). We see that for flares, the ground level populations are driven much closer to LTE than in the quiet Sun and somewhat closer than in active regions at the level of optical depth unity in the continuum. Some of the spread in the measured $T_c$ values seems to be real, as indicated by the fact that the brightest flare emission (Sept. 2c) shows the largest color temperature, while the value of $b_1$ is of the same order as that observed in the other cases.

The relatively large value of $b_1$ obtained for the Sept. 7a spectrum may be due to an optically thin contribution to the emergent intensity from overlying material. The presence of an overlying hydrogen cloud can be detected in the SHG observations of the O IV λ554 Å line which show strong LC absorption effects in the region where the first spectral scan was taken. These effects are absent in the place where the second scan (Sept. 7b, which gives more typical $T_c$ and $b_1$ values) was obtained.

The results reported in Table II may be crudely understood as an increase in temperature and electron density over the active region values at the level in which the LC emission is produced. Linsky et al. (1976) have found an increase in both $T_c$ and optical thickness in the He II Lyman continuum of a flare, in qualitative agreement with our findings.

We have estimated the radiative power in the Lyman continuum for all the events, as listed in Table II; the average power is $1.7 \times 10^6$ erg cm$^{-2}$ s$^{-1}$, but with a large variation from flare to flare. This number should be compared with Lyα fluxes in flares, which are typically of the order of 3 to 6 times $10^6$ erg cm$^{-2}$ s$^{-1}$. The Lyman continuum flux is then somewhat lower, but, as the thickness of the atmospheric region over which the observed Lyα fluxes are spread is larger than that in LC, it appears that LC losses are comparatively important at their level of
formation, in agreement with the theoretical computations by Kostyuk (1976) and Brown et al. (1978). The Hα fluxes are also observed to be of the same order, with a value about $10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$ for a large 3B flare according to Zirin and Tanaka (1973).

We also see in Table II that the color temperature increases with decreasing wavelength in a way similar to the quiet Sun spectrum (Vernazza and Noyes, 1972). This behavior gives evidence for the presence of a substantial amount of overlying material at small optical depths, with temperatures of the order of $2 \times 10^4 \text{ K}$, and large $b_1$ values, as has been suggested for the quiet Sun (cf. Vernazza and Noyes, 1972). Below 700 Å the continuum is weak and nearly obliterated by emission lines, making the uncertainties in $T_c$ very large.

Additional information about the Lyman continuum emission in flares may be gained from the spectroheliograms (SHG), which preserve spatial information at the expense of detailed spectral information. The data discussed here are those for which pairs of simultaneous SHG's are obtained at two wavelengths in the Lyman continuum (many more SHG's of flares exist in which only one wavelength in the Lyman continuum was observed, but these data are not discussed here). In all but one case of those listed in Table I, the HCO experiment simultaneously recorded the continuum intensity at two wavelengths in the Lyman continuum by means of detectors centered at $\lambda \lambda 871$ and 818 Å. In the remaining case (September 2, 00 : 42 UT) the same two detectors covered the $\lambda \lambda 895$ and 840 Å regions. These SHG's allowed us to build maps with 5 arc sec resolution, giving intensity, color temperature, and departure coefficient at 5.5 min intervals throughout the flare.

The spatially averaged brightness of the events recorded in the SHG's was in general between $\frac{1}{3}$ and $\frac{1}{10}$ of that of the brightest points, such as we discuss in Section 4 below, and the emission was visible for more than 15 min, except in the October 15th flare, where it lasted a shorter time ($\leq 10$ min).

We determined the total energy output in the Lyman continuum for the two flares with best time and spatial coverage, by extrapolating the observed intensities to all wavelengths in the Lyman continuum and integrating over wavelength, space, and time. For the June 28 and July 2 events we found the total energy radiated in the continuum to be $E_{LC} \approx 4 \times 10^{27} \text{ erg}$, which, in agreement with the results from SS data, is slightly lower than the energy output of small flares in Hα (Kane, 1974).

Part of the differences in the values of $T_c$ and $b_1$ obtained for the June 28 flare compared to July 2 must be due to its closeness to the limb (S 06 E 75) which makes us observe higher levels in the atmosphere. The July 2 event, on the other hand, was very faint both in LC and Hα observations, and we were able to observe the continuum enhancement over the plage background for a longer time than the reported Hα event. This is certainly due to the inability of Hα patrol observations to detect small increases in the line flux. It also shows that as most of our observations refer to small, faint flares or to the late phases of a large one (September 7), some differences in the physical parameters can be expected from those for major events, such as those whose spectra have been extensively studied.
in the literature (Švestka, 1976, Chapter II). In Table III we give average $T_e$, $b_1$, and flux values for the flares with best time coverage in the SHG mode. These values are averaged over the flare area and thus represent mean flare intensities rather than those in Hα kernels.

### TABLE III

<table>
<thead>
<tr>
<th>Flare</th>
<th>UT</th>
<th>$\langle T_e \rangle$</th>
<th>$\langle b_1 \rangle$</th>
<th>LC flux (erg cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 28</td>
<td>1749</td>
<td>8700</td>
<td>25</td>
<td>$6.1 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>1754</td>
<td>8600</td>
<td>20</td>
<td>$6.3 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>1800</td>
<td>8350</td>
<td>15</td>
<td>$4.3 \times 10^5$</td>
</tr>
<tr>
<td>July 2</td>
<td>1758</td>
<td>7700</td>
<td>3</td>
<td>$3.9 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>1809</td>
<td>7800</td>
<td>3.5</td>
<td>$3.3 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>1815</td>
<td>7700</td>
<td>3</td>
<td>$3.9 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>1820</td>
<td>7750</td>
<td>3</td>
<td>$4.0 \times 10^5$</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>1606</td>
<td>8985</td>
<td>67</td>
<td>$3.5 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>1612</td>
<td>8450</td>
<td>29</td>
<td>$1.7 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>1617</td>
<td>7950</td>
<td>11</td>
<td>$1.5 \times 10^5$</td>
</tr>
</tbody>
</table>

The physical parameters derived from the observation of one of the data sets in Table III (October 15) are unusual by comparison with the other SHG data and the SS data, in that they show very high $b_1$ values, which decrease considerably as the flare progresses and both $T_e$ and the intensity decay. We also note that only an extremely weak Hα event was reported at this time. We shall return in Section 5 to a possible interpretation of this event.

### 3. Observations of LC Kernels in Flares

In the LS observational mode the 5.5 s time resolution allowed us to obtain Lyman continuum data on the time variation of small-scale chromospheric flare structures and the response of the atmosphere to an impulsive energy input. Only two of the flare observations listed in Table I had LS data, and only one (September 10th) had enough time coverage to observe impulsive events during the flare development.

The September 10th event has a long and complicated structure, both in radio (microwaves) and soft X-rays (SOLRAD); this behavior seems to coincide with the EUV data, but is not suggested by Hα reports. The LS observations were obtained between 02:37 and 02:51 UT and covered a bright knot observed in the Hα film. The observations were made during the cooling phase of this flare, but in this case the decay phase proved to be rather active with two successive impulsive brightenings at the knot region.

Figure 1, showing the behavior of $T_e$, $I_{871}$, and $b_1$, versus time, reveals the interesting fact that when the intensity increased the color temperature decreased. This is most evident in the first impulsive event which occurred between 02:39:30

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Fig. 1. Lyman continuum kernel observations. Intensity (●) and color temperature (×) as a function of time. Mean $b_1$ values are given for different time intervals.

and 02:43:30 UT. As we see in the figure, the value of $b_1$ decreased from around 20 before the event to around unity at the emission peak. The second event, starting at 02:43:50 UT, shows a more complicated structure and the $T_c$ measurements present larger scattering, although they again show evidence for a decrease at the peak of the intensity curve.

This observational fact suggests that the material responsible for the observed emission is located or comes from deeper, and hence cooler, levels in the chromosphere. One possibility is that a mass of cool dense material is ejected upward from layers below the level $\tau_{LC} = 1$. This material, although it has a lower temperature, could produce brighter emission due to its greater density and low value of $b_1$ (Equation (1)). However, two pieces of evidence argue against this possibility. First, the LC brightening is accompanied by a simultaneous increase in the intensity of the Ne vii line $\lambda 465.2$ Å which, being formed at higher elevations where $T \sim 6 \times 10^5$ K, suggests that the responsible agent comes from high altitudes rather than low. Second, we do not have any evidence for mass motion along the line scan direction, which would be observed except in the unlikely case that the ejection fortuitously had no component in that direction.

A second possibility is that the exciting agent which produces the chromospheric brightening overionizes the top of the chromosphere, allowing us to see the cooler, denser material below. This possibility looks much more likely, for several observational reasons. As mentioned above, the observations were made on a bright Hα knot; this we tentatively identify as an Hα kernel such as has been observed by Zirin et al. (1971) and Vorpahl (1972). In support of this identification we note that the area of the enhanced LC emission is of the order of $5 \times 10^{17}$ cm$^2$, which compares quite well with the $3 \times 10^{17}$ cm$^2$ reported for kernels by Vorpahl. The duration of each of the enhancements also agrees with Vorpahl’s estimate of 150 s average lifetime for Hα kernels. Finally, the energy released in the first Lyman continuum brightening, integrated over wavelength, area, and lifetime, is of the order of $2 \times 10^{28}$ erg, comparable with the $5 \times 10^{28}$ erg obtained by Vorpahl from
H$\alpha$ measurements and in agreement with our previous estimate of LC vs H$\alpha$ flux ratios. We note also that in the Lyman continuum events the peak intensities at $\lambda$ 871 Å were about $6 \times 10^3$ erg cm$^{-2}$ s$^{-1}$ ster$^{-1}$ Å$^{-1}$, about 5 times larger than the average intensities of flares listed in Table II. Zirin and Tanaka (1973), Vorpahl (1972) and several others (see Kane, 1974 or Švestka, 1976, for reviews) have noted that H$\alpha$ kernels are about 3 to 9 times as bright as the surrounding flare emission, and have deduced that H$\alpha$ kernels are regions of enhanced energy deposition, most probably due to particle heating, in which we see deep regions of the solar chromosphere where the hydrogen density is of the order of $10^{13}$ cm$^{-3}$. The density was derived from the large widths of H$\alpha$ and other hydrogen lines due to Stark broadening and large optical thickness of the emitting region. This identification then supports our second view for the interpretation of the Lyman continuum kernel.

Kahler et al. (1976) and Vorpahl et al. (1975) have studied the behavior of impulsive X-ray kernels with sizes and lifetimes similar to the H$\alpha$ observations. Neither found the correlation between the appearance of these kernels and flash phases of flares, which was suggested by Vorpahl's (1972) study. In our case we also find no correlation between the flash phase of the September 10 flare and the EUV emission. Kahler et al. (1976) also found that the kernels were loop-like structures of 5 to 7 arc sec diameter with high electron densities. We studied the morphology of the flare region in a SHG taken after the second brightening (02:52 UT), both in the Lyman continuum and Ne vii, and found that the kernel region corresponded to a small ($\approx 15''$) loop-like structure adjacent to a larger loop which was also part of the flare. The color temperatures measured along the small loop lie between 7500 and 8500 K in agreement with the LS data and the SS taken a few minutes later (see Table II).

We can summarize our discussion by saying that we have strong evidence that LC kernels have a common origin with the more familiar H$\alpha$ kernels. It seems likely that during impulsive events the top of the chromosphere is over-ionized due to an increase in energy flux, with a consequent decrease in opacity in both the Lyman continuum and H$\alpha$. We then see the lower part of the flare which was previously hidden by the overlying optically thick material. This deeper region is also heated somewhat by the same mechanism operating at the higher altitudes. This region, due to its high density, is much closer to LTE than the overlying material; therefore although its temperature is lower than that of the overlying material whose emission it replaces, its actual emitted intensity is larger, in accordance with observations. The increase in total emission of course reflects the fact that more energy is being released in the atmosphere. The loop geometry of the region and its closeness to a larger loop formation supports the picture developed by Kahler et al. (1976) at least for this event.

As a final comment on the kernel brightenings in Figure 1, we note that the observational data show a very clear negative correlation between $I_\lambda$ and $T_e$ for the first event but a not-so-good one for the second, which also has a more complicated temporal structure. The recombination times for hydrogen in these layers can be
easily calculated to be between 1 and 10 s, and the dynamical (expansion) time of the order of 40 s, with an even larger time for relaxation back to pre-burst conditions. Hence it may well be that the second event is 'contaminated' by the first; also by the same token $T_c$ does not return immediately to pre-burst values. Petross et al. (1977) also observed two successive brightenings in an X-ray kernel with the second one being clearly affected by the first.

5. Interpretation of the Results

We may summarize our observational results by noting that two basic flare structures are revealed by the Lyman continuum data:

(a) An 'average' flare atmosphere occupying the bulk of the emitting area, and characterized by relatively long lifetime ($\approx 15$ min), color temperatures ranging from 7900 to 9000 K, relatively high electron densities (indicated by low $b_1$ values), and relatively low emergent fluxes ($\approx 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$). (The numbers quoted may be found in Tables I and II and in the text.) This 'average' flare atmosphere coincides with the region of overall flare emission seen in H$\alpha$ and Ca II H and K.

(b) Lyman continuum 'kernels' covering a small fraction of the flare area and characterized by relatively short lifetime ($\sim 2$ min), relatively low $T_c$ compared to the flare's average value, extremely high electron densities (indicated by $b_1 \sim 1$), and relatively high emergent fluxes ($\sim 8 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$) (the numbers quoted may be found in Figure 1 and in the text). These kernels seem to coincide both with the H$\alpha$ kernels, which show relatively high H$\alpha$ emission and broad profiles characteristic of high electron density, and also with the soft X-ray kernels consisting of small loop structures ($\sim 10''$ length) of high emission measure ($\approx 10^{48} \text{ cm}^{-3}$) and temperature ($\sim 10^7$ K).

We can now try to interpret the observed properties of the Lyman continuum emission by comparing them with predictions of existing models based on radiative transfer solutions for flares. A major shortcoming of this approach is that the solutions may not be unique, and we must investigate the range of variation of different parameters under which the observations can still be explained.

For this purpose we consider four different chromospheric flare models available in the literature, for which enough details are available to make meaningful comparisons with the observations. The first two (1 and 2 in Figure 2) are electron-heating models of Brown et al. (1978) and were obtained for non-thermal electron fluxes $F_{20} = 10^9$ and $10^{10}$ erg cm$^{-2}$ s$^{-1}$ where $F_{20}$ is the flux above 20 keV. The third and fourth models (3 and 4 in Figure 2) are based on two of the semiempirical flare models calculated by Machado and Linsky (1975), assuming a three-level plus continuum representation of the hydrogen atom, considering the Lyman lines transitions to be in detailed balance, a fairly good approximation according to our experience. Model 3 is similar to the subflare model in Machado and Linsky's paper, with slightly lower temperatures in the chromosphere between 1300 and 800 km, which were reduced in order to get better agreement between observed
and computed Hα and K line fluxes for small flares. Model 4 is essentially the same as Model 3 in Machado and Linsky’s paper, and approximately reproduces line observations and the physical parameters deduced from them in bright regions of large solar flares.

Models 1 and 2 produce too strong Hα emission compared with average flare regions, as noted by Brown et al. (1978) and also too strong Ca II emission according to our computations. On the other hand, the energy fluxes in Hα and Ca II, as well as the extended Hα line wings, are consistent with kernel observations. We note also that the physical basis underlying models 1 and 2, particle heating, agrees with the second picture developed in Section 4 to explain the behavior of the Lyman continuum kernel. Figure 2 also shows that for these models the level of $\tau_{LC} = 1$ moves deeper for increasing energy deposition, in qualitative agreement with the observations.

In disagreement with both kernels and average flare observations, however, we find that Brown et al.’s (1978) models predict too large color temperatures and extremely high Lyman continuum fluxes ($>5 \times 10^7$ erg cm$^{-2}$ s$^{-1}$). Even in the case
of $F_{20} = 10^8$ erg cm$^{-2}$ s$^{-1}$ (not shown, see Brown et al., 1978), these are still too large compared with observations.

The discrepancy between the predicted Hα, Ca, i, and LC emission of models 1 and 2 and observed average flare intensity suggests that the major part of most flares (outside of kernels) is not energized by particle heating. The only way that we are able to match both the low Hα emission and the observed intensity and color temperature in the Lyman continuum is by a model such as model 3, which has low temperature in the middle chromosphere where Hα is emitted, coupled with a steep temperature gradient at $\tau_{LC} \sim 1$. This depth occurs at temperatures of the order of 8400 K (in accordance with average values obtained from SS data) and at a mass column density of $\sim 3 \times 10^4$ g cm$^{-2}$ (in order to get the low $b_1$ value).

Švestka (1973) concluded from several considerations that heat conduction is able to bring enough energy into the chromosphere to produce the observed emission. We have also found (Machado, 1978) evidence that much of the chromospheric heating is due to soft X-rays, while heat conduction dominates at the feet of magnetic loops. Looking at Model 3 we see that it has a steep rise in temperature at the top of the chromosphere, suggestive of a high conductive flux from coronal layers; hence, a likely explanation is that the observed mean flare is energized by the combined effect of heat conduction and soft X-ray heating.

We return now to the event of October 15 reported in Section 3, which showed anomalously high $T_e$ and $b_1$ values. We may perhaps interpret this as a purely thermal event dominated by heat conduction, in which we see the edge of a thin shell structure at the top of the chromosphere as described by Shmeleva and Syrovats’kii (1972). Because of the relatively low density in these layers for such a small event, $b_1$ should be, as observed, very large. SOLRAD-9 data for this event show that the associated soft X-ray increase was extremely small. This agrees with our interpretation because it implies that the high temperature emission measure was very small, and therefore that the soft X-ray contribution to the heating (which has its greatest importance deep in the atmosphere at $10^{-3} \leq m \leq 5 \times 10^{-2}$ g cm$^{-2}$) was negligible.

As mentioned before, the comparison between the Brown et al. (1978) electron heated models for $F_{20} = 10^9$ to $10^{10}$ erg cm$^{-2}$ s$^{-1}$ and observations gives reasonable agreement with Hα kernel properties, in terms of flux and physical parameters, like the electron density deduced from Stark broadened wings of Balmer lines. However, these models disagree with our observations of the Lyman continuum emission in that they give too large fluxes and color temperatures. We find in contrast that a model like 4 in Figure 2, which is essentially the large flare model in Machado and Linsky’s (1975) paper, gives quite good agreement with both Hα and LC observations. The Lyman continuum parameters for this model are, $T_e = 8350$ K and $b_1 = 1.05$ which are in good agreement with the LC kernel observations and also give the correct intensity at $\lambda 871$ Å in the continuum. Also, the maximum densities obtained in this model are $n_e = 2.3 \times 10^{13}$ cm$^{-3}$, in agreement with the observations.
The disagreement between the Brown et al. (1978) models and our observations may be due to their disregard of several important effects like direct ionization by non-thermal particles (Lin and Hudson, 1976) and, probably most important, heat conduction from the overheated material above the chromospheric flare region. In this regard, the work by Kostyuk and Pikel’ner (1975) and Kostyuk (1975) is on a better physical basis because the effect of conduction was included in their hydrodynamic calculations. The fact that these authors overestimated the chromospheric radiative losses, and the lack of detailed information in their papers, prevents a detailed comparison with observations.

Looking now in detail at the evaporation process in both kernels and the mean flare we can estimate the amount of material ‘evaporated’ to higher temperatures. From the LC observations above, we can deduce the amount of material heated to a temperature high enough to ionize most of the neutral hydrogen and make it transparent to LC radiation. This is given by:

\[ M_T = \alpha m_{\text{ev}} A_f = 2.4 \times 10^{15} \alpha \text{ g}, \]

where \( m_{\text{ev}} \) is the mass column density above the LC level (\( \approx 3 \times 10^{-4} \text{ g cm}^{-2} \) in model 3), \( A_f \) is the flare area which we estimated as \( 6 \times 10^{18} \text{ cm}^2 \) for a small flare, and \( \alpha \) is the fraction of the flare area effectively evaporated. A certain fraction of the mass \( M_T \) is heated all the way to high enough temperatures to contribute to the soft X-ray emission. During the impulsive events \( m_{\text{ev}} \) is larger (as it could also be in more energetic flares), reaching as high as \( 10^{-3} \text{ g cm}^{-2} \). However \( \alpha \) becomes of the order of 0.1 or smaller and the evaporated material does not contribute in a substantial way to the soft X-ray emission. On the other hand, for the mean flare \( \alpha \) can be considered of the order of unity, and \( M_T \) can be compared with the amount of material at high temperatures, which is \( \approx 10^{15} \text{ g} \) for most small events (Pallavicini et al., 1977). Thus for small events a fraction of the heated chromospheric material reaches soft X-ray emitting temperatures. In larger events, the amount of material in the interplanetary blast can be as large as \( 10^{17} \text{ g} \) (Lin and Hudson, 1976) which most certainly cannot be supplied by direct evaporation of chromospheric material (as in Brown (1973)), but could be driven by other mechanisms probably related to prominence disappearances.

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