THE SOLAR XUV SPECTRUM OF He II

JEFFREY L. LINSKY* AND DAVID L. GLACKIN

Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado, Boulder, Colorado

AND

R. D. CHAPMAN, W. M. NEUPERT, AND R. J. THOMAS

Laboratory for Solar Physics and Astrophysics, Goddard Space Flight Center, Greenbelt, Maryland

Received 1975 June 16

ABSTRACT

OSO-7 observations of the first five Lyman lines and the Lyman continuum of He II are given for the quiet Sun, a coronal hole, prominences, filaments, and the 1972 August 7 flare. These data are calibrated and given in specific intensity units together with color and brightness temperatures for the He II continuum. We find that He II is overionized in all features except the flare, and that the continuum is formed at temperatures near 14,000 K. The He II–He III ionization equilibrium appears to be dominated by photoionizations and radiative recombinations. Schematic calculations for realistic chromosphere and transition-region models can account for the observed intensities of Lβ–Lγ, the Lyman continuum, and its color temperature. To account for the intensity of Lα, either an implausible 100 km plateau at temperatures near 80,000 K is needed or, more likely, the incorporation of diffusion-enhanced collisional excitation into the models.

Subject headings: atomic processes — Sun: corona — Sun: flares — Sun: prominences — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

One of the most poorly understood regions of the solar outer atmosphere is the temperature range 10⁴–10⁵ K, including the middle and upper chromosphere and the lower transition region. The ion He II is abundant somewhere in this region. Little has been learned of this region by analyzing the He II spectrum, however, since the mechanisms governing the ionization and excitation equilibria of He II are unclear, in large part, because the He II Lyman continuum has never been accurately measured in any solar structure. We present measurements of the He II Lyman continuum and the first five Lyman lines obtained from OSO-7 XUV spectra, and infer from these data some properties of the solar atmosphere. The determination of empirical parameters for the He II continuum is very difficult and at the limit of capability of the OSO-7 instrument. Nevertheless, the importance of such data warrants this effort, but future observations are clearly needed.

The first eight members of the Lyman series have been observed by Behring et al. (1972) and others, and recently at very high resolution Feldman and Behring (1974), Doschek et al. (1974), and Cushman et al. (1975) have reported widths for these lines. The Lyman continuum shortward of 228 Å is weak and nearly obliterated by the overlying coronal emission-line spectrum. Athay (1965) has estimated a total flux in the continuum of 930 ergs cm⁻² s⁻¹ at the Sun based on Hinteregger's spectra. In view of the relative weakness of the Lyman continuum compared with the coronal spectrum, we have concentrated on OSO-7 spectra of regions where the coronal spectrum is weak including quiet Sun regions, coronal holes, quiescent prominences, and filaments. Surprisingly, the continuum is clearly present in flare spectra, and we have therefore analyzed a spectral scan of the 1972 August 7 class 3B flare.

II. OBSERVATIONS AND DATA REDUCTION

The data consist of spectral scans in the medium-wavelength channel of the Goddard Space Flight Center extreme-ultraviolet spectroheliograph on OSO-7 (cf. Underwood et al. 1971). The spectral range of the scans is 186–318 Å and the spectral resolution about 0.8 Å, considerably broader than the solar emission lines. Each spectral scan, except for the flare, is an average of three to seven separate scans made with a 20'' × 20'' aperture and 125 ms gate time. The flare data consist of only one separate scan made with a 10'' × 20'' aperture from 15h37m28s to 15h42m39s UT, after flare maximum. Since the flare scan was not digitized it is more uncertain, and the procedure described below after (3) was not followed. Figure 1 contains the spectrum of a quiet region in which the lines of interest are not. We have derived Lyman line and continuum intensities from this and other spectral scans by means of the following steps:

1. The wavelength scale was converted from grating steps to λ(Å).
2. The count rates were corrected for the relative wavelength sensitivity of the instrument as measured prior to flight.

3. We determined the instrumental profile by a least-squares fit of a Gaussian profile to the observed \( \lambda 304 \) line. A Gaussian with a FWHM = 0.63 Å is accurate to \( \pm 10 \) percent over a relative intensity range of 45.

4. The scattered light level was determined from the average intensity minima in five spectral intervals away from apparent emission lines. This value was

2.9 counts per step in the quiet Sun scan as noted in Figure 1 and somewhat different in the other scans, depending on the total line flux.

5. Since the instrument does not resolve the lines, the maximum count rate measures the line or close blend total flux. To derive the true \( \text{He} \ II \) line fluxes we must correct for blends, which add a component to the measured \( \text{He} \ II \) flux equal to the product of the blended line flux and the instrument profile function for the wavelength separation. The line list of Behring et al. (1972) was used to identify possible blends. We
found in the data three lines in the red wing of Lβ, two in the red wing of Ly, none for Lδ, and one in the blue wing of Le. Because Le is both weak and blended, its intensity is more uncertain than the other lines. The measured line fluxes of the blended lines and instrumental profile function were used in removing the effect of the blends on the He II line fluxes.

The Lα line was treated separately because no significant blends are apparent, but the Si xi λ303.32 Å line is only 0.46 Å to the blue of Lα and unresolved. Chapman and Neupert (1974) argue that the Si xi line is approximately equal in strength to the Fe xv λ284.2 Å line, and the two lines should vary in strength approximately equally with solar activity. Consequently, we subtract from the measured Lα signal an amount equal to the Fe xv signal at a wavelength separation of 0.46 Å. For the prominence data the Fe xv line is nearly as strong as the λ304 blend so that the Lα flux is poorly determined.

6. The continuum data were corrected for emission lines in a manner similar to the lines. This procedure is illustrated in Figure 2, which shows the coronal hole spectrum before and after removal of seven emission lines located at 217.2, 218.4, 219.4, 220.3,

![Figure 2](image1.png)

**Fig. 2.**—The coronal hole spectrum before and after removal of seven blended emission lines as described in the text. The vertical line designates the He II continuum head and the sloping line is our estimate of the continuum shape based on the “windows” at 223–224 and 227 Å between the emission lines and the scattered light level at 216 Å as an upper limit to the continuum flux. The error bar designates our estimate of the continuum head intensity and the two other sloping lines show our estimate of the uncertainty in determining the continuum slope.

![Figure 3](image2.png)

**Fig. 3.**—He II continuum spectra for different solar structures obtained as described in Figure 2. Note that the scattered light level has been subtracted. The spikes in the flare spectrum at 220 Å and 230 Å are instrumental effects.
221.8, 224.9, and 227.3 Å. The vertical line designates the theoretical continuum head, and the sloping lines the estimated true continuum and its estimated uncertainty in slope. The error bar designates the estimated error in continuum head intensity. We drew the continuum line as a best visual fit to the continuum with the aid of the continuum “windows” at 223–224 and 227 Å, using the scattered light level at 216 Å as an upper limit to the continuum flux at that wavelength. Note that the continuum drawn in this way is slightly below a continuum line one might construct from the original data alone due to the effect of the instrumental profile wings of the seven emission lines on the continuum “windows.” Although there is a certain element of subjectivity in this procedure, we feel that the He II continuum is clearly in the data, and the resultant color and brightness temperatures derived from the data are relatively insensitive to realistic changes in the way the continuum might be drawn.

7. The resulting continuum was then subtracted from the superposed emission-line fluxes. These new line fluxes were then used to obtain a new estimate of the continuum flux as described in (6).

In Figure 3 we show the 214–245 Å spectra of different solar structures, including the estimated He II continuum derived in the manner just described. Note that the flare continuum is very strong, with a different slope from the other data, and that the quiescent prominence continuum is too weak to be separated from the emission lines. We determine color temperatures $T_\text{e}$ from the slopes of the continuum lines in these semilog plots using the Wien approximation to the Planck function and for the cases of optically thin [$I \approx B_\lambda(T_\text{e})\lambda^2$] and optically thick [$I \approx B_\lambda(T_\text{e})$] continua. These color temperatures, which are sensitive to the scattered light correction, are listed in Table 1 together with the journal of observations. The errors cited for $T_\text{e}$ are our best estimates, which perhaps should be increased to allow for possible errors in the scattered light correction. $T_\text{e}$ for the flare is very much larger than for the nonflare regions, which are all approximately 14,000 K for $\tau_0 \ll 1$ and 13,000 K for $\tau_0 \gg 1$, where $\tau_0$ is the continuum head optical depth.

III. ABSOLUTE RADIOMETRIC CALIBRATION

To proceed further, we must convert the relative line and continuum counting rates to specific intensities. We take two approaches.

The first approach rests upon other determinations of the $\lambda304$ blend specific intensity from the whole Sun. This approach is feasible because the He II line is not strongly dependent on solar activity and the Si XI component of the $\lambda304$ blend is usually weak compared with He I $\lambda3$ (cf. Timothy and Timothy 1970). The $\lambda304$ specific intensity for the whole Sun or quiet Sun has been measured by Hall et al. (1969), Hall and Hinteregger (1970), Chapman and Neupert (1974), Timothy and Timothy (1970), Dupree and Reeves (1971), Dupree et al. (1973), Heroux et al. (1974), and Timothy (1974) with values ranging from 2,280 to 10,500 ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$, assuming no limb darkening. It is most likely that a major part of the discrepancy among the data is due to errors in absolute calibration rather than to differing solar activity, since the range in $\lambda304$ intensity measured by Chapman and Neupert (1974) is only 8180–10,500 ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ covering the full range of activity as seen by OSO-3.

To our knowledge the most accurately calibrated measurement is $8600 \pm 30$ percent ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for the $\lambda304$ blend obtained by Timothy (1974) as a part of the Harvard Calroc program for ATM. This measurement is consistent within his stated errors with the Chapman and Neupert (1974), Timothy and Timothy (1970), and Heroux et al. (1974) data. The disagreement with the Harvard OSO-4 (Dupree and Reeves 1971) and OSO-6 (Dupree et al. 1973) data is probably not significant as these data were obtained at the extreme edge of the spectral range of the instruments. On the assumption that the OSO-7 instrumental efficiency does not change with time, the Timothy (1974) $\lambda304$ blend quiet Sun data lead to the specific intensities given in Table 1. Also given is $I_\lambda(228)$, the specific intensity per unit frequency at the continuum head. The quantity $I_\lambda(228)$ is the integrated continuum specific intensity assuming the given color temperatures. The data are probably accurate to $\pm 50$ percent in absolute intensities, allowing for instrumental sensitivity drift with time. Those data that are less certain are in parentheses, including $I_\lambda(228)$ for the prominence spectra in which $T_\text{e} = 13,000$ K was assumed. Brightness temperatures $T_\text{b}$ were computed by setting $I_\lambda(228)$ equal to a Planck function at that temperature. Note that $T_\text{b} = 20,100$ K for all the disk regions except the flare.

Ratios of line intensities obtained from the same spectral scan are more accurately determined, and we estimate errors of $\pm 20$ percent in $I(\lambda3)/I(\Lambda3)$ and $I(\Lambda3)/I(\Lambda8)$, $\pm 30$ percent in $I(\Lambda8)/I(\Lambda9)$, and $\pm 50$ percent in $I(\Lambda9)/I(\Lambda8)$. We also estimate errors of $\pm 30$ percent in $I(\Lambda9)/I(\Lambda8)$.

A second approach is based on a linear regression of $\lambda304$ blend flux against 2800 MHz flux derived by Chapman and Neupert (1974) from OSO-3 observations. This approach obviates the need for assuming no change in instrumental sensitivity with time, but relies on a regression line about which there is considerable scatter and some skepticism (Timothy and Timothy 1970). Nevertheless, the resultant disk data in Table 2 are quite similar to those in Table 1 and the average $T_\text{b}$ for nonflare disk regions is only 300 K cooler.

IV. DISCUSSION

a) Analysis of the He II/He III Ionization Equilibrium

The source function $S_\lambda(\tau_0)$ for a bound-free continuum can be simply related to the Planck function
### TABLE 1

#### He II Specific Intensities (Timothy [1974] Calibration)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Date</th>
<th>$I_{\text{Line}}$ (ergs/cm$^2$/s/str)</th>
<th>$I_{c}(228)$ ((10^{-13}\text{ergs/cm}^2/\text{s/str/Hz}))</th>
<th>$I_{c}(228)$ (ergs/cm$^2$/s/str)</th>
<th>$T_{B}$ (°K)</th>
<th>$T_{C}(N_{o}&lt;1)$ (°K)</th>
<th>$T_{C}(N_{o}&gt;1)$ (°K)</th>
<th>$b_{1}(T_{c})/N_{o}$</th>
<th>$b_{1}(T_{c}-1)/N_{o}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet Sun</td>
<td>15 Dec</td>
<td>8170</td>
<td>370</td>
<td>110</td>
<td>68</td>
<td>49</td>
<td>2.02 ± 0.04</td>
<td>1.35 ± 0.18</td>
<td>1.27 ± 0.15</td>
</tr>
<tr>
<td>Hole</td>
<td>15 Dec</td>
<td>6150</td>
<td>260</td>
<td>62</td>
<td>38</td>
<td>35</td>
<td>2.01 ± 0.04</td>
<td>1.53 ± 0.20</td>
<td>1.44 ± 0.17</td>
</tr>
<tr>
<td>Fl 1</td>
<td>27 Jul</td>
<td>3970</td>
<td>250</td>
<td>58</td>
<td>32</td>
<td>29</td>
<td>2.00 ± 0.04</td>
<td>1.40 ± 0.18</td>
<td>1.31 ± 0.15</td>
</tr>
<tr>
<td>Fl 2</td>
<td>27 Jul</td>
<td>5020</td>
<td>300</td>
<td>81</td>
<td>47</td>
<td>33</td>
<td>2.01 ± 0.04</td>
<td>1.39 ± 0.18</td>
<td>1.30 ± 0.15</td>
</tr>
<tr>
<td>Fl 3</td>
<td>27 Jul</td>
<td>7340</td>
<td>360</td>
<td>110</td>
<td>50</td>
<td>42</td>
<td>2.01 ± 0.04</td>
<td>1.35 ± 0.18</td>
<td>1.27 ± 0.15</td>
</tr>
<tr>
<td>Flare</td>
<td>7 Aug</td>
<td>(19000)</td>
<td>(35000)</td>
<td>(3100)</td>
<td>2400</td>
<td>2.3 ± 0.1</td>
<td>2.5 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Prim 1</td>
<td>26 Sep</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(130)#</td>
<td>1.98 ± 0.07</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Prim 2</td>
<td>26 Sep</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(70)#</td>
<td>1.94 ± 0.07</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Prim 3</td>
<td>2 Feb</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(180)#</td>
<td>2.00 ± 0.07</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Prim 4</td>
<td>2 Feb</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(137)</td>
<td>(2.05 ± 0.07)</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

Footnote: Prominence values derived assuming $T_{C} = 13,000$ K.

### TABLE 2

#### He II Specific Intensities (Chapman-Neupert [1974] Calibration)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Date</th>
<th>$I_{\text{Line}}$ (ergs/cm$^2$/s/str)</th>
<th>$I_{c}(228)$ ((10^{-13}\text{ergs/cm}^2/\text{s/str/Hz}))</th>
<th>$I_{c}(228)$ (ergs/cm$^2$/s/str)</th>
<th>$T_{B}$ (°K)</th>
<th>$T_{C}(N_{o}&lt;1)$ (°K)</th>
<th>$T_{C}(N_{o}&gt;1)$ (°K)</th>
<th>$b_{1}(T_{c})/N_{o}$</th>
<th>$b_{1}(T_{c}-1)/N_{o}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet Sun</td>
<td>15 Dec</td>
<td>6810</td>
<td>310</td>
<td>89</td>
<td>57</td>
<td>41</td>
<td>2.00 ± 0.04</td>
<td>1.35 ± 0.18</td>
<td>1.27 ± 0.15</td>
</tr>
<tr>
<td>Hole</td>
<td>15 Dec</td>
<td>5120</td>
<td>210</td>
<td>51</td>
<td>32</td>
<td>29</td>
<td>2.00 ± 0.04</td>
<td>1.53 ± 0.20</td>
<td>1.44 ± 0.17</td>
</tr>
<tr>
<td>Fl 1</td>
<td>27 Jul</td>
<td>1950</td>
<td>120</td>
<td>29</td>
<td>16</td>
<td>14</td>
<td>1.96 ± 0.04</td>
<td>1.40 ± 0.18</td>
<td>1.31 ± 0.15</td>
</tr>
<tr>
<td>Fl 2</td>
<td>27 Jul</td>
<td>2460</td>
<td>150</td>
<td>41</td>
<td>23</td>
<td>17</td>
<td>1.97 ± 0.04</td>
<td>1.39 ± 0.18</td>
<td>1.30 ± 0.15</td>
</tr>
<tr>
<td>Fl 3</td>
<td>27 Jul</td>
<td>3600</td>
<td>175</td>
<td>54</td>
<td>23</td>
<td>20</td>
<td>1.97 ± 0.04</td>
<td>1.35 ± 0.18</td>
<td>1.27 ± 0.15</td>
</tr>
<tr>
<td>Flare</td>
<td>7 Aug</td>
<td>(16900)</td>
<td>(4840)</td>
<td>(2730)</td>
<td>2400</td>
<td>2.3 ± 0.1</td>
<td>2.5 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Prim 1</td>
<td>26 Sep</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(78)#</td>
<td>1.95 ± 0.07</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Prim 2</td>
<td>26 Sep</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(41)#</td>
<td>1.91 ± 0.07</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Prim 3</td>
<td>2 Feb</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(47)#</td>
<td>1.92 ± 0.07</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Prim 4</td>
<td>2 Feb</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>(3.6)</td>
<td>(1.97 ± 0.07)</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

Footnote: Prominence values derived assuming $T_{C} = 13,000$ K.
at the local electron temperature \( b_1(T_e) \) and the ground-state departure coefficient \( b_1(\tau_0) \), by

\[
S(\tau_0) = \frac{B_1[T_e(\tau_0)]}{b_1(\tau_0)} 
\]  

Equation (1)

(Pottasch and Thomas 1959), where \( \tau_0 \) is the continuum head optical depth. We now consider separately the case \( \tau_0^M \ll 1 \) and \( \tau_0^M \gg 1 \), where \( \tau_0^M \) is the total thickness at the continuum head. We expect, however, that the He II continuum is optically thin, as this is the case for all the realistic solar models described below. If \( S(\tau_0) \) varies with \( \tau_0 \) no more rapidly than the first power, then for \( \tau_0^M \gg 1 \) the Eddington-Barbier relation is valid, and

\[
I(\nu) \approx S_0(\tau_0 = 1) = b_0(\nu)T_0 \quad (\tau_0^M \gg 1) 
\]  

Equation (2a)

defines the brightness temperature of the continuum edge. For the optically thin case we have

\[
I(\nu) \approx S_0(\tau_0)\tau_0^M = b_0(\nu)T_0 \quad (\tau_0^M \ll 1) 
\]  

Equation (2b)

where \( S_0(\tau_0) \) is a mean value of the source function in the continuum-forming region. Further, \( T_0 \approx T_\infty(\tau_0 = 1) \), as Noyes and Kalkofen (1970) have shown for the optically thick hydrogen Lyman continuum, and \( T_\infty \approx T_\infty(\tau_0) \) for the optically thin case when \( T_0 \) is computed assuming \( \tau_0^M \ll 1 \). As a result,

\[
b_1(\tau_0 = 1) \approx \frac{b_0(T_\infty)}{[b_0(T_\infty)]} \quad (\tau_0^M \gg 1, \nonumber \tau_0^M \ll 1) 
\]  

Equation (3a)

or

\[
b_1(\tau_0) \approx \frac{\tau_0^M b_0(T_\infty)}{b_0(T_\infty)} \quad (\tau_0^M \ll 1, \nonumber \tau_0^M \gg 1) 
\]  

Equation (3b)

and the values of \( b_1 \) in Tables 1 and 2 are derived from these expressions. These values of \( b_1 \) are only approximate because at 228 Å the Planck function varies extremely rapidly with temperature and the Eddington-Barbier relation must be inaccurate. Note that \( b_1(\tau_0^M \ll 1) \) in Tables 1 and 2 is an upper limit, since \( \tau_0^M \ll 1 \).

The statistical equilibrium equation for a one-level atom (He II) plus continuum (He III), ignoring the stimulated emission, can be solved for \( b_1 \):

\[
b_1 = \frac{4\pi}{\tau_0^M} \int_\nu^\infty \left[ a_\nu B_\nu(T_\infty) \right] h\nu d\nu + N_\nu \Omega_{1K} 
\]

\[
= \frac{4\pi}{\tau_0^M} \int_\nu^\infty \left[ a_\nu B_\nu(T_\infty) \right] h\nu d\nu + N_\nu \Omega_{1K} 
\]

Equation (4)

(Mihalas 1970), where \( T_\infty \) is a temperature characterizing the radiation field \( \left[ J_\nu = B_\nu(T_\infty) \right] \), \( N_\nu \Omega_{1K} \) is the electron collisional ionization rate, and \( a_\nu \) is the photoionization cross section. The He I–He II ionization equilibrium does not affect \( b_1 \), since we ignore any direct channel between He I and excited states of He II or between He I and He III, so that the two ionization equilibria are separate. We find that the collisional ionization rate (Sampson 1969) at \( T_\infty \) is orders of magnitude less than the photoionization and recombination rates in all features including flares, and can thus be ignored. The ground-state population of He II and thus the He II–He III ionization equilibrium is dominated by the radiative rates as previously noted by Hirayama (1972), Heasley et al. (1974), and others in the context of prominences.

We have estimated \( T_\infty \) in the quiet Sun from the measured spectral flux at 52-227.7 Å (Heroux et al. 1974), weighting each spectral interval by the factor \( \nu_0^3 \nu^{-1} \) in equation (4). We obtain \( T_\infty = 22,420 \pm 540 \) K, with the errors corresponding to a conservative factor of 2 error in the spectral flux. The corresponding photoionization rate is \( 1.5 \times 10^{-8} \) s\(^{-1}\). Thus \( T_\infty \gg T_\infty \) and from equation (4) \( b_1 \approx 6 \times 10^{-5} \), of the same order as the values of \( b_1 \) derived from equations (3a) and (3b). In all solar features, except for the flare, He II is greatly overionized compared with LTE where the continuum is formed due to the strong coronal radiation field. In the flare, conditions are different, and LTE appears to be a good approximation for the He II–He III ionization equilibrium. Since collisional ionization is unimportant for He II at 25,000 K, LTE must be established because the coronal radiation field has heated the region where He II is formed such that \( T_\infty = T_\infty \). This is clearly a superficial statement and detailed calculations are needed.

b) Comparison with Other Data

The hydrogen Lyman continuum has been extensively studied in the quiet Sun (Noyes and Kalkofen 1970; Vernazza and Noyes 1972), coronal holes (Huber et al. 1974), prominences (Noyes et al. 1972), and flares (Noyes 1975). From these data we have compiled values of \( T_\infty \) and \( b_1 \) computed from equation (3b) in Table 3. There are some data on the He I continuum from Gulyaev (1972) and Milkey et al. (1973) which are also included together with the He II results for the optically thin case based on the Timothy (1974) calibration. We have not included the filament data since it is impossible to separate the filament and disk emission in the OSO-6 and OSO-7 observations.

c) Schematic Models and the He II Spectrum

There is now much discussion in the literature concerning the basic mechanisms responsible for the observed spectra of He II. Essentially three mechanisms have now been proposed: The first is the photoionization–recombination (P–R) mechanism suggested by Zirin (1975a, b) and previously by Hirayama (1972) and Heasley et al. (1974) in the context of prominences. According to this mechanism the He II Lyman lines result from photoionization of He II by coronal XUV radiation shortward of 227.7 Å, followed by recombination of He III and cascade. This mechanism has been recently criticized on the grounds that reversals are not seen in the Lyman line profiles (cf. Milkey 1975), and the observed shape of the He II λ1640 Å line cannot be reasonably accounted for (Feldman et al. 1975). The second is direct collisional excitation (CE) from the He II ground state as originally proposed by Athay (1965). Third, Jordan (1975) has noted that for recently proposed models of the solar chromosphere and transition region the computed 304 Å flux is a factor of 5.5 less than observed. In other words, there is insufficient emission.
measured at temperatures of 30,000–150,000 K to account for the observed intensity by collisional excitation assuming local ionization equilibrium. She therefore proposes mixing low and high temperature material to enhance the collisional excitation rate. A somewhat similar idea has been proposed by Gerola and Shine (1975) and by Shine et al. (1975). They suggest that thermal and concentration diffusion can significantly increase collisional excitation rates and thus the strengths of the Lyman lines.

In this paper we have presented absolute intensities for the first five Lyman lines, integrated Lyman continuum, $I_\lambda(228)$, and $T_c$. With this new data base we can now critically discuss these mechanisms and decide which are more plausible. At present, detailed calculations are underway (Avery et al. 1975) in order to explain the data. Here we present He II continuum calculations for a series of schematic models in order to shed light on the physics underlying the formation of the He II Lyman lines and continuum.

We solve the statistical equilibrium equation for a 12-level He II ion plus continuum, including photoionization from all levels as specified by constant radiation temperatures, electron collisional excitation and ionization from the ground state only, radiative recombination to all levels, and cascades. In these schematic computations we ignore photoexcitation and collisional excitation from excited states and assume that all photons created leave the atmosphere. This latter assumption is good for $L_\alpha$ and for the optically thin continuum, and its validity for $L_\beta$ will be discussed later. We assume the oscillator strengths of Allen (1963) and the collisional rates of Mihalas and Stone (1968) and Mihalas (1970). The photoionization radiation temperatures are $T_k$ from the ground state, 6500 K from $n = 2$, and 5000 K from $n = 3, 4, 5, \ldots$. For all models we adopt $P_e = n_e T_e = 6 \times 10^{14}$ (Dupree 1972).

Assuming that all line photons escape in the line, the integrated line specific intensities are

$$I(L_n) = (h/\mu) A_{UL} \int N_e(h)dh \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$

This results from the surface line flux $F(L_n) = \pi I(L_n)$, assuming no limb darkening or brightening. In addition, there is a factor of 2 loss of photons which are inwardly directed if the creation of photons is uniform with line optical depth. If the creation is mainly at small optical depths, all photons escape.

We have assumed the latter. We compute the emergent continuum specific intensity from

$$I_c(\lambda) = \frac{2h\nu^3}{c^2} \int \left[ \exp \left( -\frac{h\nu}{kT_c(t_c)} \right) - \exp \left( -t_c \right) dt_c, \right.$$  

the color temperature $T_c$ as described above, and the integrated continuum specific intensity $I_c(\lambda)$ from $I_c(\lambda)$ and $T_c$.

We first consider isothermal slabs of 100 km thickness in which we assume helium to be either He II or He III but not He I. For these models $T_e$ equals the slab electron temperature. Cited in Table 4 are first a series of models ignoring photoionization but including collisional excitation and ionization for temperatures 10,000–200,000 K. These models are thus purely of the CE variety. Hereafter for simplicity we have abbreviated $I(L_n)$ to $j$ and $I(228)$ to $k$. For these models $\alpha/\beta$ decreases and $\alpha/\beta$ increases with increasing temperature due to the $e^{-E/kT}$ dependence of collisional excitation rates. For temperatures near 80,000 K the line strengths and line ratios are close to observed values, but $I(k)$ is far too weak and $T_e = T = 80,000$ K is too large.

Next we consider only the P–R mechanism by ignoring collisional excitation and ionization. For these models the line ratios and $\alpha/\beta$ are nearly independent of $T$ and $T_k$ and far from the observed values. For a 100 km slab of material at 14,000 K, $I(\alpha)$ and $T_k$ would be in agreement with observations, $I(\beta)$ somewhat low, and $I(\epsilon)$ a factor of 12 too low. To match the observed $I(\epsilon)$, approximately 1200 km of material at 14,000 K would be needed, but then $I(\epsilon)$ and the intensities of the higher Lyman lines would be far too large. Also, there is no evidence for this much material at 14,000 K. It can be argued that for these cool P–R models the $\alpha/\beta$ ratio will be much larger than 2.8 due to breakdown of $L_\beta$ photons into $L_\alpha$ and 1640 Å photons, as $\tau(L_\beta)$ is large. This cannot solve the problem of the weak $I(\alpha)$, however.

I Also included in Table 4 are isothermal slabs with both mechanisms operative. For $T < 30,000$ K P–R is dominant, and for $T > 60,000$ K CE is dominant. For such slabs there is no way of simultaneously matching $I(\alpha)$, $I(\epsilon)$, and $T_e$.

In Table 5 He II spectra are given for more realistic solar models. The basic temperature structure for Model I is that of Vernazza et al. (1973) below 30,000 K and of Dupree (1972) above 30,000 K (cf. Fig. 4).
There is some uncertainty as to how to join together these two models, as the former model is poorly defined above the hydrogen temperature plateau at 20,000 K and the latter model is based on only two lines below 40,000 K. By joining the models at 30,000 K we include almost 100 km of material at 25,000–40,000 K, which may not be real. The model also includes the 160 km wide plateau at 20,000 K proposed by Vernazza et al. (1973). We approximately account for He I in this model by assuming the same He I/He II + He III ratio from Milkey et al. (1973) at each temperature.

First given in Table 5 is the He II spectrum for Model I with no additional material added. For this model I(\(\alpha\)) and I(227.7) are very close to observed values and \(T_c\) is about 4000 K larger than observed. Also given are computations ignoring photoionizations and ignoring collisions. It is clear that the continuum is formed by the P-R mechanism. Included in Table 5 are computations for Model II, which differs from Model I only in that the Vernazza et al. (1973) and Dupree (1972) temperature structures are joined smoothly at 35,000 K instead of 30,000 K, which removes 114 km of material at temperatures 25,000–40,000 K (cf. Fig. 4). The effect is to decrease I(\(\alpha\)) and I(227.7) somewhat and to decrease \(T_c\) to 14,260 K. Thus it is easy to fit I(\(\alpha\)), I(227.7), and \(T_c\) within their stated errors for realistic chromosphere and transition-region models.

The strengths of the He II Lyman lines are more
No. 2, 1976

SOLAR EXTREME-ULTRAVIOLET SPECTRUM

TABLE 5

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Pe (\textdegree K)</th>
<th>\Delta \text{h} (\text{km})</th>
<th>T_e (\textdegree K)</th>
<th>a/\beta</th>
<th>\gamma/\beta</th>
<th>\delta/\beta</th>
<th>c/\beta</th>
<th>e/\beta</th>
<th>I(\alpha) (\text{ergs/cm}^2 \text{s}^{-1} \text{sr}^{-1})</th>
<th>I(\beta) (\text{ergs/cm}^2 \text{s}^{-1} \text{sr}^{-1})</th>
<th>\tau(227.7 \text{ Å})</th>
<th>\tau(1350 \text{ Å})</th>
<th>\tau(630 \text{ Å})</th>
<th>T_c (\text{K})</th>
</tr>
</thead>
<tbody>
<tr>
<td>I QUIT SUN DATA</td>
<td>22220</td>
<td>22.1</td>
<td>0.30</td>
<td>0.13</td>
<td>0.65</td>
<td>8170</td>
<td>370</td>
<td>240</td>
<td>8.6(-13)</td>
<td>13,500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II ERROR(\textdegree)</td>
<td>540</td>
<td>4.4</td>
<td>0.06</td>
<td>0.05</td>
<td>0.07</td>
<td>0.19</td>
<td>2450</td>
<td>111</td>
<td>120</td>
<td>4.3(-13)</td>
<td>1,800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III NO PLATEAU</td>
<td>21,200</td>
<td>12.7</td>
<td>0.42</td>
<td>0.23</td>
<td>0.15</td>
<td>0.80</td>
<td>1060</td>
<td>82</td>
<td>66</td>
<td>3.6(-13)</td>
<td>0.75</td>
<td>502</td>
<td>81</td>
<td>17,920</td>
</tr>
<tr>
<td>IV NO Photoionization</td>
<td>22,200</td>
<td>5.86</td>
<td>0.48</td>
<td>0.29</td>
<td>0.19</td>
<td>1.05</td>
<td>1372</td>
<td>234</td>
<td>246</td>
<td>6.2(-13)</td>
<td>0.71</td>
<td>477</td>
<td>77</td>
<td>17,448</td>
</tr>
<tr>
<td>V NO Collisions</td>
<td>23,200</td>
<td>3.96</td>
<td>0.51</td>
<td>0.30</td>
<td>0.20</td>
<td>1.13</td>
<td>2423</td>
<td>680</td>
<td>769</td>
<td>2.0(-12)</td>
<td>0.61</td>
<td>410</td>
<td>66</td>
<td>16,737</td>
</tr>
<tr>
<td>VI NO Photoionization</td>
<td>33.14</td>
<td>0.21</td>
<td>0.08</td>
<td>0.04</td>
<td>0.15</td>
<td>929</td>
<td>28</td>
<td>4.16</td>
<td>1.7(-15)</td>
<td>0.71</td>
<td>511</td>
<td>82</td>
<td>73,105</td>
<td></td>
</tr>
<tr>
<td>VII NO Collisions</td>
<td>21,200</td>
<td>2.82</td>
<td>0.52</td>
<td>0.31</td>
<td>0.20</td>
<td>1.16</td>
<td>155</td>
<td>55</td>
<td>64</td>
<td>1.6(-13)</td>
<td>0.76</td>
<td>504</td>
<td>81</td>
<td>17,649</td>
</tr>
<tr>
<td>VIII NO Photoionization</td>
<td>22,200</td>
<td>2.82</td>
<td>0.52</td>
<td>0.31</td>
<td>0.20</td>
<td>1.16</td>
<td>595</td>
<td>211</td>
<td>245</td>
<td>6.2(-13)</td>
<td>0.72</td>
<td>478</td>
<td>77</td>
<td>17,401</td>
</tr>
<tr>
<td>IX NO Collisions</td>
<td>23,200</td>
<td>2.82</td>
<td>0.52</td>
<td>0.31</td>
<td>0.20</td>
<td>1.16</td>
<td>1866</td>
<td>663</td>
<td>769</td>
<td>2.0(-12)</td>
<td>0.61</td>
<td>410</td>
<td>66</td>
<td>16,730</td>
</tr>
<tr>
<td>40,000 100</td>
<td>21,200</td>
<td>15.58</td>
<td>0.40</td>
<td>0.23</td>
<td>0.14</td>
<td>0.78</td>
<td>1650</td>
<td>106</td>
<td>83</td>
<td>3.1(-13)</td>
<td>1.04</td>
<td>644</td>
<td>103</td>
<td>19,399</td>
</tr>
<tr>
<td>II 60,000 50</td>
<td>22,200</td>
<td>6.87</td>
<td>0.48</td>
<td>0.28</td>
<td>0.18</td>
<td>1.05</td>
<td>2027</td>
<td>293</td>
<td>308</td>
<td>7.0(-13)</td>
<td>0.94</td>
<td>606</td>
<td>97</td>
<td>19,368</td>
</tr>
<tr>
<td>III 60,000 100</td>
<td>23,200</td>
<td>3.86</td>
<td>0.51</td>
<td>0.30</td>
<td>0.20</td>
<td>1.13</td>
<td>3191</td>
<td>826</td>
<td>935</td>
<td>2.2(-12)</td>
<td>0.78</td>
<td>508</td>
<td>82</td>
<td>18,417</td>
</tr>
<tr>
<td>IV 80,000 50</td>
<td>22,200</td>
<td>12.99</td>
<td>0.33</td>
<td>0.17</td>
<td>0.10</td>
<td>0.51</td>
<td>3233</td>
<td>145</td>
<td>74</td>
<td>1.7(-13)</td>
<td>0.85</td>
<td>542</td>
<td>87</td>
<td>19,061</td>
</tr>
<tr>
<td>V 80,000 100</td>
<td>22,200</td>
<td>14.18</td>
<td>0.40</td>
<td>0.23</td>
<td>0.14</td>
<td>0.78</td>
<td>5179</td>
<td>365</td>
<td>284</td>
<td>6.6(-13)</td>
<td>0.86</td>
<td>544</td>
<td>87</td>
<td>18,864</td>
</tr>
<tr>
<td>VI 100,000 50</td>
<td>22,200</td>
<td>6.23</td>
<td>0.48</td>
<td>0.28</td>
<td>0.18</td>
<td>1.04</td>
<td>5087</td>
<td>827</td>
<td>950</td>
<td>2.1(-12)</td>
<td>0.70</td>
<td>456</td>
<td>73</td>
<td>17,729</td>
</tr>
<tr>
<td>VII 100,000 100</td>
<td>22,200</td>
<td>20.49</td>
<td>0.29</td>
<td>0.14</td>
<td>0.08</td>
<td>0.33</td>
<td>4859</td>
<td>237</td>
<td>79</td>
<td>1.7(-13)</td>
<td>0.78</td>
<td>515</td>
<td>83</td>
<td>19,996</td>
</tr>
<tr>
<td>VIII 100,000 50</td>
<td>22,200</td>
<td>12.55</td>
<td>0.39</td>
<td>0.21</td>
<td>0.14</td>
<td>0.70</td>
<td>4666</td>
<td>372</td>
<td>262</td>
<td>6.4(-13)</td>
<td>0.74</td>
<td>488</td>
<td>78</td>
<td>18,090</td>
</tr>
<tr>
<td>IX 100,000 100</td>
<td>22,200</td>
<td>5.98</td>
<td>0.47</td>
<td>0.28</td>
<td>0.18</td>
<td>1.01</td>
<td>4675</td>
<td>782</td>
<td>789</td>
<td>2.1(-12)</td>
<td>0.63</td>
<td>417</td>
<td>67</td>
<td>17,012</td>
</tr>
<tr>
<td>100,000 100</td>
<td>22,200</td>
<td>11.11</td>
<td>0.26</td>
<td>0.12</td>
<td>0.06</td>
<td>0.24</td>
<td>8672</td>
<td>392</td>
<td>93</td>
<td>1.8(-13)</td>
<td>0.81</td>
<td>527</td>
<td>85</td>
<td>21,886</td>
</tr>
<tr>
<td>100,000 100</td>
<td>22,200</td>
<td>15.62</td>
<td>0.35</td>
<td>0.18</td>
<td>0.11</td>
<td>0.54</td>
<td>7954</td>
<td>509</td>
<td>277</td>
<td>6.5(-13)</td>
<td>0.76</td>
<td>498</td>
<td>80</td>
<td>18,716</td>
</tr>
<tr>
<td>100,000 100</td>
<td>22,200</td>
<td>7.84</td>
<td>0.45</td>
<td>0.26</td>
<td>0.17</td>
<td>0.91</td>
<td>9293</td>
<td>883</td>
<td>808</td>
<td>2.1(-12)</td>
<td>0.64</td>
<td>424</td>
<td>68</td>
<td>17,263</td>
</tr>
</tbody>
</table>

(difficult to match for realistic models. For Model I, \(I(\alpha) = 1373 \text{ ergs/cm}^2 \text{s}^{-1} \text{sr}^{-1}\) or a factor of 6.0 lower than observed in agreement with Jordan's (1975) calculation, but \(I(\beta) = 234 \text{ ergs/cm}^2 \text{s}^{-1} \text{sr}^{-1}\), or only a factor of 1.6 low. We find that in this model \(I(\alpha)\) is formed more by the CE than by the P-R mechanism, but \(I(\beta)\) and the higher series members are formed mainly by the P-R mechanism. Zirin (1975b) computes \(I(\alpha)\) in agreement with observed values, assuming only the P-R mechanism. His computations are in error, however, because he assumes the He \(\Pi\) continuum to be optically thick so that most of the solar flux shortward of 227.7 Å is converted to 304 Å photons. In fact, the He \(\Pi\) continuum is optically thin, typically \(\tau_{227.7} = 0.07\), so that only a small fraction of the \(\lambda < 227.7 \text{ Å}\) flux is converted to \(L_{\alpha}\). The rest is absorbed by the \(H \alpha\) and \(He \alpha\) continua. All optical depths are measured above the layer where \(T = 8300 \text{ K}\), corresponding to \(\tau_{630} \approx 1\). One way of raising \(I(\alpha)\) and to a lesser extent the intensities of the other Lyman lines is to add to Model

\(© American Astronomical Society • Provided by the NASA Astrophysics Data System\)
idealized isothermal plateaus. Computed spectra for various temperature plateaus are given in Table 5. \( I(\alpha) \) can be matched with the thinnest plateau for temperatures near 80,000 K. For the 100 km 80,000 K plateau model the Lyman line ratios are close to observed values, \( I(\alpha) \) is only slightly increased over the no-plateau case, but \( T_c \) is increased to 18,720 K. Also \( I(\omega) \) remains P-R controlled, as do lines higher than \( Ly \). Better agreement between computed \( T_c \) and \( I(\beta) \) and observed values is obtained for Model II with a 100 km 80,000 K plateau, in which case \( T_c = 15,950 \) K is only slightly beyond the observed error bars.

In all variants of Models I and II the line center optical depth of the L\( \beta \) line is of order 50 above the chromospheric layer where \( T = 8300 \) K. Since L\( \beta \) can break down to L\( \alpha \) and a 1640 Å (H\( \alpha \)) photon, we may have made a considerable error in the computed \( \alpha/\beta \) ratio. It is possible to estimate this error empirically. Jordan (1975) estimates that no more than 1/3 of the measured 1640 Å blend intensity of Kohl et al. (1973) is due to the He II line. The H\( \alpha \)/L\( \beta \) flux ratio is then no more than 1.18. In all of our models we compute 0.77 for this ratio. As a result, no more than 21 percent of the L\( \beta \) photons are degraded to L\( \alpha \) + H\( \alpha \). Thus the \( \alpha/\beta \) ratio could be 20 percent larger than computed. Note that the Lyman line optical depths are sensitive to the amount of material at 25,000–40,000 K, a quantity which is poorly known.

d) Formation of the He II continuum

We find in this paper that the He II continuum must be formed in the chromosphere at temperatures near 14,000 K. This requires a P-R process and thus considerable overionization of He II in this region and \( b_\perp \ll 1 \). This is the opposite of the case for He I and H I, and is due in part to the large ionization potential of He II and the location of the He II continuum edge close to the strong coronal and transition-region XUV emission spectrum. We also find that \( \tau_{27,7} \approx 0.07 \) for all models, even when we add 100 km of hot material, and that such hot plateaus affect \( T_c \) and \( I(\alpha) \) by only a small amount. If \( \tau_{27,7} \approx 0.07 \), then from Table 1 \( b_\perp \approx 10^{-8} \), in agreement with the estimate in § IVa.

In the coronal hole \( T_c \) may be slightly hotter than in the quiet Sun, 15,300 ± 2,000 K as compared with 13,500 ± 1,800 K. In the calculations in Table 5, \( T_c \) increases as \( T_B \) decreases, because He II exists higher in the atmosphere when the coronal radiation field is weaker. Thus a slightly hotter \( T_c \) is expected for coronal holes since \( T_{\text{corona}} \) and thus \( T_c \) are small in holes.

In flares \( T_c = 25,000 \) K, and there is evidence for LTE in He II as well as in He I and H I. In flares \( n_e \) could be more than 100 times larger than the quiet Sun, accounting for the formation of the He II continuum at higher temperatures as observed.

The continuum edge specific intensities in prominences are not measurably different from the quiet Sun intensity, consistent with the idea that the coronal radiation field is the dominant ionization mechanism.

e) Formation of the He II Lyman line spectrum

Model I accounts for two thirds of \( I(\text{L} \beta) \) and essentially all of the higher Lyman-line specific intensities. The problem is \( I(\text{L} \alpha) \), where the model falls a factor of 6 below observed values. We have shown that the addition of a 100 km thick plateau of material at temperatures near 80,000 K would account for the observed \( L \alpha \) intensity and at the same time be consistent with the other He II data. The problem with such a plateau is that there is no independent evidence for its existence, and that it could clearly be incompatible with the EUV transition region spectrum and the centimeter radio emission (Zirin 1975b). On the other hand, Milkey et al. (1973) were led to assume a 200 km thick plateau at temperatures of 40,000–60,000 K in order to explain the observed He I 584 Å resonance line flux. Clearly some physical process is enhancing the He I and He II resonance line intensities, but not transition-region line intensities, in a manner similar to the addition of a plateau or plateaus at temperatures of 40,000–80,000 K. Jordan (1975) has reached a similar conclusion.

Gerola and Shine (1975) and Shine et al. (1975) show that the He I and He II velocities in the lower transition region due to thermal and concentration diffusion are sufficiently large that these atoms and ions can travel to regions of significantly higher temperature before they are collisionally excited or destroyed by ionization or recombination. As a result,
collisional excitation, which as we have seen requires temperatures of at least 60,000 K to be important, occurs in atmospheric regions where He i and He ii would not ordinarily exist in significant densities considering only local ionization balance, and where the atmosphere behaves as if it had a plateau of higher temperatures. In our local equilibrium calculations helium is predominantly in the form of He iii in the 80,000 K plateau; thus 100 km of material was needed to raise I(α) to its observed value. Diffusion could make He ii the dominant species at this temperature so that far less material is needed, and it is possible that the little material in existing transition-region models would be sufficient. Shine et al. (1975) find that this diffusion-enhanced collisional excitation mechanism works well for He i and He ii where E/kT is large for the resonance lines, but poorly for typical transition region lines where E/kT and the diffusion velocities are smaller. They also suggest that this diffusion mechanism may account for the weak helium lines in coronal holes.

Another possible way of strengthening I(α) in the quiet Sun is to consider a two-component model consisting of network and cells. NRL spectroheliograms in Lo (cf. Tousey et al. 1973) clearly show a bright network occupying ~1/3 the surface areas, and they give the impression that most of the quiet Sun 304 Å flux comes from the network. There are four effects that may be important.

1. The transition region XUV spectrum, but not the coronal spectrum, is brighter in the network increasing Tα. If the flux shortward of 227.7 Å were enhanced a factor of 4 in the network, which is probably an overestimate since the XUV flux is mainly coronal, then Tα is increased by 1000 K and I(α) by a factor of 1.8, but I(α) by a factor of 2.9. This mechanism is clearly insufficient and has the undesirable effect of increasing I(α) more than I(α).

2. Since the transition temperature gradient in plages (Withbroe and Gurman 1973) is steeper than in the quiet Sun, we would expect the temperature gradient in the network to be similarly enhanced. This would strengthen I(α) but not I(α) by the diffusion mechanism, making the network bright and probably also increasing the averaged quiet Sun I(α).

Calculations of this effect should be pursued.

3. In plages P α is larger than in the quiet Sun (Shine and Linsky 1974; Withbroe and Gurman 1973). Again we would expect the same to be true for the network. This would strengthen I(α) by both the P-R and CE mechanisms. An increase in P α low in the chromosphere will increase τ227.7 proportionally and thus both I(α) and I(α) by the same factor, since τ227.7 is ordinarily very small. This P-R mechanism effect does not solve our problem since even if it should increase I(α) by a factor of 6 (taking the network filling factor into account), it would also increase I(α) by a factor of 6, which is inconsistent with observations.

4. The intensity of Lo is proportional to Pα(dT/αh)−1 for the CE mechanism, but transition line intensities are proportional to the same factor. The transition region pressure Pα = nαT = 6 × 1014 (Dupree 1972; Jordan 1975) was derived assuming a one-component quiet Sun and thus refers to a spatial average of the quantity Pα(dT/αh)−1. This places a constraint on two-component models. Also Withbroe and Gurman (1973) find for active and quiet regions (dT/αh) ≈ Pα, so that I ≈ Pα, 2. If we assume that the network occupies a fractional area x, has a pressure β(6 × 1014), and the cell pressure is γ(6 × 1014), then the above constraints lead to the equation

\[ xβ^{0.2} + (1 - x)γ^{0.2} = 1. \]  

(5)

If we take x = 1/3 and β = 20, a rather large value, then γ = 0.0713 and the network/cell contrast due only to the CE mechanism is β^{0.2}/γ^{0.2} = 3.1. We find that this mechanism can explain the network contrast, but it does not increase the spatially averaged I(α). Thus the most plausible explanation for the computed weak I(α) is the diffusion-enhanced collisional excitation mechanism of Shine et al. (1975).

A third possible way of increasing the Lyman line intensities is by increasing the collisional excitation rates. An increase in these rates will increase the population of He ii excited states and thus strengthen the Lyman lines. It will also increase the amount of He iii relative to He ii due to photoionization from excited states and thus decrease the line optical depths but enhance the P-R process. Recent calculations by McDowell et al. (1973, 1975) suggest that the Lo and L8 collisional excitation rates should be increased by factors of 1.4 and 1.9, respectively, compared with the Mihalas-Stone formula. These changes cannot solve the basic discrepancy between the observed and computed values of I(α), but they do alter the Lyman line ratios somewhat, depending on what rates one assumes for the higher transitions. Future calculations should include these new rates when a self-consistent set of collisional excitation rates to the first five excited states are available.

We are grateful to R. W. Noyes, R. Steinitz, J. G. Timothy, J. E. Vernazza, and E. H. Avrett for helpful discussions, and for the assistance of W. January. We acknowledge support of the National Aeronautics and Space Administration through grant NGL-06-003-057 to the University of Colorado.

REFERENCES


© American Astronomical Society • Provided by the NASA Astrophysics Data System


R. D. CHAPMAN, W. M. NEUPERT, and R. J. THOMAS: Laboratory for Solar Physics and Astrophysics, Goddard Space Flight Center, Greenbelt, MD 20771

DAVID L. GLACKIN and JEFFREY L. LINSKY: Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, CO 80302

© American Astronomical Society • Provided by the NASA Astrophysics Data System