EXCITATION AND IONIZATION OF HELIUM IN THE SOLAR ATMOSPHERE

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Received 1976 March 16; revised 1976 April 26

ABSTRACT

We investigate the excitation and ionization of He i and He ii for the case of a realistic solar model. The calculations are based on a simplified numerical treatment of the He i and He ii continua and the He ii X304 line. We discuss the extent to which various proposed mechanisms can account for the observed line and continuum intensities.

Subject headings: line formation — radiative transfer — Sun: atmosphere — ultraviolet: spectra

I. INTRODUCTION

The solar spectra of He i and He ii are now under intense study because they appear anomalous in several respects. Coronal holes are seen in various helium lines such as the He ii λ304 and He i λ584 resonance lines (Munro and Withbroe 1972), the He i λ10830 and λ5876 lines (Harvey et al. 1975), and the He ii λ1640 line (Feldman et al. 1975). Coronal holes are not seen prominently in any other lines formed in the chromosphere or transition region. Also, the intensities of the λ304 and λ584 lines have been reported to be at least a factor of 5 brighter than predicted theoretically (Jordan 1975).

There are fundamental questions concerning the physical mechanisms responsible for these spectra; clarification is needed of the roles played by collisional excitation, photoionization-recombination, diffusion, and photon creation at very small optical depths. We carry out the present study by means of a simplified numerical solution of the ionization equilibrium equations and the transfer equation for the X304 line.

II. IONIZATION EQUILIBRIUM

We compute the number densities \( n(\text{He} \, i) \), \( n(\text{He} \, ii) \), and \( n(\text{He} \, iii) \) by solving the ionization equilibrium equations \( n(\text{He} \, i) (R^i + C^i) = n(\text{He} \, ii) (R^ii + R_d) \), and \( n(\text{He} \, ii) (R^{ii} + C^{ii}) = n(\text{He} \, iii) R^ii \), where \( R \) and \( C \) are the photoionization and collisional ionization rates from level 1, and \( R_d \) is the radiative recombination rate to all levels of either He i or He ii. The term \( R_d \) represents the dielectronic recombination rate from He ii to He i. We have found that the ionization rates for levels \( l > 1 \) are small compared with that from the ground level in the cases considered here; we ignore these rates and the collisional recombination rates in order to simplify the analysis. The photoionization rate is given by

\[
R = 4 \pi \int_{\nu_1}^{\infty} \frac{\alpha(\nu)}{\hbar \nu} J, d\nu.
\]

We determine the mean intensity \( J, \) from the observed radiation in the spectral regions \( \nu > \nu_1^i \) and \( \nu > \nu_1^{ii} \) (\( \lambda < 504 \, \text{Å} \) and \( \lambda < 227 \, \text{Å} \)) for He i and He ii, respectively. We let

\[
J, = \frac{1}{\pi} \left( \frac{1 \, \text{AU}^2}{r_0} \right) f_g L_e,
\]

where \( f_g \) is the observed monochromatic flux at 1 AU, \( g \) is the estimated depth dependence of this flux (see below), and \( L_e \) is a limb-brightening correction which we estimate to have the value 0.5.

The solar flux in the wavelength range \( \lambda < 504 \, \text{Å} \) has three principal components: (1) emission lines formed in the corona and transition region, (2) the He ii λ304 line, and (3) the He i and He ii continua. In the first case, since the emission lines have no opacity in the chromosphere, we let \( g_\lambda = \exp (-\tau_\lambda) \), where \( \tau_\lambda \) is the monochromatic continuum optical depth. In the second case, we use the computed depth variation of \( J, \) for the λ304 line. Finally, the contributions of the He i and He ii continua to the photoionization rate are smaller than those of the emission lines by a factor of 5 or more and are ignored.

The experimental photoionization cross section for He i is given by \( \alpha^i = 7.4 \times 10^{-18} (\lambda/504)^{1.85} \, \text{cm}^2 \) (Samson 1964), and the theoretical cross section for He ii is \( \alpha^{ii} = 1.6 \times 10^{-18} (\lambda/227)^3 \, \text{cm}^2 \) (Menzel and Pekeris 1935). We obtain the He i and He ii continua to the photoionization rate are smaller than those of the emission lines by a factor of 5 or more and are ignored.

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\[
R^i = 3.5 \times 10^{-8} \phi^i \lambda_k (\lambda_k/504)^{1.85} f(\Delta \lambda) g_k
\]

and

\[
R^{ii} = 7.5 \times 10^{-6} \phi^{ii} \lambda_k (\lambda_k/227)^3 f(\Delta \lambda) g_k
\]

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where \( f(\Delta \lambda) \) is the flux in units of ergs cm\(^{-2}\) s\(^{-1}\) at 1 AU integrated over the wavelength interval \( \Delta \lambda \), and \( \lambda_k \) is the central wavelength of that interval in angstroms. In both cases \( \phi = \Sigma a g_k \), where the coefficients \( a_k \) have been normalized so that \( \phi = 1 \) at small optical depths. We use the quiet-Sun values of \( f(\Delta \lambda) \) for wavelengths between 504 and 52 Å given by Heroux, Cohen, and Higgins (1974).

The collisional ionization rates are given by \( \Omega^i n \exp[-2.86 \times 10^7/T] \) and \( \Omega^{i1} n \exp[-6.34 \times 10^7/T] \). The coefficients \( \Omega^i \) and \( \Omega^{i1} \) are slowly varying functions of temperature, and we adopt the values \( \Omega^i = 4.0 \times 10^{-9} \) and \( \Omega^{i1} = 2.3 \times 10^{-9} \) corresponding to \( T = 34,000 \) K and 63,000 K, respectively. These temperatures are such that \( C^i \approx R^i \) and \( C^{i1} \approx R^{i1} \) when \( n_\odot = 10^{10} \) cm\(^{-3}\).

The radiative recombination rate to level \( l \) can be written as \( R_l = n_a \alpha_l (T) \). Osterbrock (1974) finds for \( \alpha_l \) that \( \Sigma a_l = 4.26 \times 10^{-18} \) and \( 1.53 \times 10^{-14} \) for \( T = 5000 \) K and 20,000 K, respectively. In the case of \( \alpha_l \) being of order 7000 K. We also list the optical depths at 504 and 227 Å and the continuum source function \( S^\odot(504) \) and \( S^\odot(227) \) which are defined in the next section.

### III. Helium Continua

When stimulated emission is neglected, the level-1 continuum source function is

\[
S^\odot = \frac{n_\odot n_{\text{ion}}}{2} \left( \frac{h^2}{2 \pi m k T} \right)^{3/2} \frac{f_1}{\Omega^{i1}} \frac{\alpha_1}{2 \pi^2} \frac{2n_\odot}{m} \frac{\nu^3}{\epsilon^2} \exp \left[ -\frac{\hbar \nu}{k T} \right]
\]

where

\[
f(\nu) = \left( \frac{\nu}{\epsilon} \right)^3 \exp \left[ -h(\nu - \nu_i)/k T \right].
\]

Thus

\[
S^\odot(504) = \frac{3.2 \times 10^{-16} n_\odot n(\text{He II})}{T^{3/2} n(\text{He II})},
\]

and

\[
S^\odot(227) = \frac{1.4 \times 10^{-14} n_\odot n(\text{He III})}{T^{3/2} n(\text{He II})}.
\]

### Table 1

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From the ionization equilibrium equations of the last section,
\[ S'_{200}(\text{He}~I) = \left(1.3 \times 10^{-8} \phi^1 + 1.5 \times 10^{-6} C^{11}\right)/T^{0.26} + r_d, \]
where \( r_d = 4.8 \times 10^9 R_d/\eta T^{-3/2}, \) and
\[ S'_{202}(\text{He}~I) = \left(1.1 \times 10^{-8} \phi^1 + 1.4 \times 10^{-6} C^{11}\right)/T^{0.88}. \]
The collisional ionization terms are negligible except in the high-temperature transition region where the continuum optical depths are very small.

At chromospheric temperatures, the He I and He II continuum source functions decrease extremely rapidly with decreasing wavelength while the continuous opacities decrease slowly. Thus we obtain
\[ S'(\xi) = r_{s1}^1 S_x(\text{He}~I), \quad 504 \geq \lambda > 227 \]
\[ = r_{s1}^1 S_x(\text{He}~II), \quad 227 \geq \lambda, \]
where \( r_{s1}^1 = \kappa_3(\text{He}~I)/\kappa_3(\text{total}) \) and \( r_{s1}^{11} = \kappa_3(\text{He}~II)/\kappa_3(\text{total}) \).

From the data given in Table 1 we find that \( r_{s1}^1 = 0.44 \) and \( r_{s1}^{11} = 0 \) at the height 1900 km where \( T = 7800 \text{ K}. \) Absorption by hydrogen at 504 Å thus reduces the source function in the He I continuum. Absorption by hydrogen and He I at 227 Å reduces the source function in the He II continuum.

We evaluate the disk-center emergent specific intensities from the quantities in Table 1, and find that \( I_{504} = 2.7 \times 10^{-12} \) and \( I_{502} = 5.2 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}. \) The observed intensity at 504 Å for an average quiet region has the value \( I_{504}^{\text{obs}} = 1.3 \times 10^{-12} \) according to Vernazza and Reeves (1976). Two values of the 227 Å quiet-Sun intensity are given by Linsky et al. (1976) from OSO-7 observations: \( I_{504}^{\text{obs}} = 6.3 \times 10^{-12} \) and 8.6 \times 10^{-12}.

IV. The He II \( \lambda 304 \) Line

For an atom with two bound levels and a continuum the frequency-independent line source function is given by
\[ S = \frac{J + \chi}{1 + \epsilon}, \]
where \( \epsilon = (C_{21} + \phi_{21})/A_{21} \) and \( \chi = (C_{21} + \phi_{21})/B_{21} \) (see Athay 1972; Avrett 1971; or Vernazza, Avrett, and Loeser 1973). These expressions for \( \epsilon \) and \( \chi \) do not include stimulated emission. The collision rates are given by \( C_{21} = n_0 \Omega \exp (-h v_{21}/kT) \) and \( C_{21} = n_0 \Omega (\alpha / \phi_{21}). \) We use \( \Omega = 1.3 \times 10^{-8} \) (for a temperature of 38,000 K) based on the calculations of McDowell, Morgan, and Myrslough (1973, 1975). The term \( \phi_{21} \) is the rate of transitions from level 1 to the continuum and then to level 2:
\[ \phi_{21} = (R_{11} + C^{11})(\rho_x/\Sigma_x \Sigma_t), \]
\[ = 0.72(8.0 \times 10^{-9} \phi^1 + C^{11}), \]
where 0.72 is the ratio of the number of recombinations to level 2 to the number of recombinations to all levels.

The term \( \phi_{21} \) can be neglected in comparison with \( C_{21}. \) Finally, \( A_{21} \) and \( B_{21} \) are the Einstein emission and absorption coefficients. We use the value \( A_{21} = 7.5 \times 10^{-14} \text{ s}^{-1} \) (16 times \( A_{21} \) for hydrogen).

The quantity \( J \) is given by \( J = \int \phi dV, \) where \( J \) is the mean intensity and \( \phi \) is the line absorption coefficient normalized so that \( \int \phi dV = 1. \) We assume a depth-independent Doppler profile so that \( \phi = x^{-1/2} \) exp \((-x^2)\), where \( x = (v - v_0)/\Delta v \). We approximate the integral for \( J \) by a 14-term frequency quadrature
\[ J_{ik} = \Sigma_k a_i S_{ik}, \]
where the \( \Lambda \) weighting coefficients \( W_{ijk} \) are discussed by Avrett and Loeser (1969), \( S_i \) is the line source function specified above, and \( S_f \) is the continuum source function. Also, \( r^1 + C_{12} = R^1 + C_{12} = \rho_x/(k\lambda + C_{12} \rho_x) \) and \( r^C = \rho_x/(k\lambda + C_{12} \rho_x) \), where \( \rho_x \) and \( C_{12} \) are the line and continuum opacities, respectively.

The equation \( S_i = (J_i + \chi_i)/(1 + \epsilon_i) \) then becomes
\[ S_i = \frac{1}{\delta_i + \epsilon_i} \Sigma_j M_{ij} S_j = \frac{1}{\delta_i + \epsilon_i} (\chi_i + \sigma_i), \]
where \( \delta_i = \Sigma_k a_i r_{ik} \). We find that \( \epsilon_i, \chi_i, \delta \), which implies that collisional de-excitation does not play a role in destroying resonance-line photons, as discussed below. Also, \( \sigma_i < \chi_i \), which implies that the continuum source function is too small to affect \( S \).

The matrix coefficients are given by
\[ M_{ij} = \Sigma_k a_i W_{ijk} \lambda^{-r_{ik} L}. \]
The \( \Lambda = 1 \) weighting coefficients in this expression zero at large optical depths. When the values of \( M \) become small compared with \( \delta, S \) approaches \( \chi/\delta \). Table 2 lists the values of \( \delta, \chi/\delta, \) and \( S \) as functions of the optical depth in the center of the \( \lambda 304 \) line. In the calculation we use a more closely spaced set of depth values than those listed in Table 2 (a total of 40 values).

### Table 2: \( \lambda 304 \)-Line Source Function Parameters

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The parameter $\chi$ is the ratio of the number of resonance-line photons created to the number absorbed in the resonance transition, while $\delta$ is the ratio of the number of photons absorbed by the background continuum to the total number absorbed. Photons are created in two principal ways: (1) photoionization of He II throughout an extended region of the atmosphere, and (2) collisional excitation, and to a lesser extent collisional ionization, in the transition region where $T > 34,000$ K. Resonance-line photons either escape or are destroyed by continuous absorption due to hydrogen and He I. The ratio $\chi/\delta$ is the local photon creation rate divided by the destruction rate. An examination of the behavior of $\chi$, $\delta$, $\chi/\delta$, and $S$ from deep layers toward the surface shows that (1) $\chi$ increases and $\delta$ decreases, so that $\chi/\delta$ increases, (2) near the surface, $S$ decreases relative to $\chi/\delta$ because of the escape of resonance line photons, and (3) $\chi/\delta$ increases so rapidly that $S$ is forced to increase monotonically. The calculated line intensity therefore monotonically increases toward line center, and there is no central reversal of the $\lambda 304$ line.

Our statement that resonance line photons are created by photoionization in the chromosphere and by collisional excitation (and collisional ionization) in the transition region is based on the form of the parameter $\chi$, given explicitly by

$$\chi = 2.8 \times 10^{-3} n_0^{11} + 5.7 \times 10^{-6} (n_0/10^{10}) e^{-4.74 \times 10^3 / T} + 8.0 \times 10^{-9} (n_0/10^{10}) e^{-3.44 \times 10^3 / T}.$$

The second and third terms in this expression are due to collisional excitation and ionization, respectively. Collisional excitation becomes more important than photoionization only when the temperature exceeds about 40,000 K.

The large values of $\chi/\delta$ near the surface enhance the values of $S$ at optical depths $\tau_1$ as large as 100; i.e., a substantial number of photons created in the high-temperature transition region diffuse into the deeper layers of the atmosphere. The magnitude of this effect depends on the temperature distribution between 30,000 K and 130,000 K and on the strength of the collisional excitation rate, and thus on $n_0$, in this temperature range.

**V. RESULTS AND DISCUSSION**

Computed continuum and line intensities at disk center are listed in Table 3 for the standard model (designated S) described in § II. Also listed in Table 3 are the continuum spectral slopes $I_{\alpha 51} / I_{\lambda 604}$ and $I_{\beta 40} / I_{\lambda 604}$ and color temperatures $T_c$ computed assuming the continua are optically thin (such that $I_{\alpha 51} / I_{\lambda 604} = \lambda_5^0 B_{\alpha 51} / \lambda_6^0 B_{\lambda 604}$) and optically thick (such that $I_{\beta 40} / I_{\lambda 604} = B_{\beta 40} / B_{\lambda 604}$). In addition to model S, we list models computed assuming that the He II collisional excitation rate $C$, the He I and He II photoionization rates $R$, and the transition-region temperature gradient $dT/dh$ are each increased or decreased by a factor of 3. In calculating the $\lambda 304$ line intensities we again ignore variations in the Doppler width and assume $\Delta v_D = 0.028$ Å, based on $T = 30,000$ K and $V' = 25$ km s$^{-1}$. The computed line widths (full widths at half-maximum) range from 0.09 to 0.11 Å, in approximate agreement with the observed value 0.10 Å at Doschek, Behring, and Feldman (1974) for quiet regions and the values 0.12 and 0.10 Å for quiet and active regions of Cushman, Godden, and Rense (1975).

Comparing the computed intensities with the observations cited in Table 3, we conclude the following:

1. The He I and II continua are formed by recombinations following photoionization by coronal lines, and, in the case of He I, by the $\lambda 304$ line. Optical depths unity (Table 1) occur in the chromosphere near 7000 K, but there is sufficient contribution to the emission at temperatures up to 20,000 K to produce color temperatures near 10,000 K for He I and 13,000 K for He II. Milkey, Heasley, and Beebe (1973) have previously shown that the He I continuum is formed by the photoionization-recombination (PR) process and that $I_{\lambda 604}$ increases and $T_c (\text{He I})$ decreases with increasing $R$.

2. The intensity of the He II $\lambda 304$ line is insensitive to changes in $R$ and thus is clearly not formed by the PR process as proposed by Zirin (1975). The reason why the PR process does not work despite sufficient ionizing radiation shortward of 227 Å is that most of this radiation is absorbed by H I and He I (cf. Linsky et al. 1976). We find that at least part of the discrepancy can be accounted for by extending the calculated $I_{\alpha 51} / I_{\lambda 604}$ could be due in part to the presence of unresolved weak emission lines near 475 Å. The He II continuum computations are in excellent agreement with the Linsky et al. (1976) data for both calibrations cited even though $I_{\beta 40}$ is extremely sensitive to $R$. The calculations imply that the He I and He II continua should appear dark in coronal holes, as observed.

3. Collisional excitation calculations which ignore the transfer of line radiation yield $\lambda 304$ intensities which are a factor of 5 or 6 smaller than observed (Jordan 1975; Linsky et al. 1976). We find that at least part of this discrepancy can be accounted for by extending the computations well into the upper transition region to temperatures of at least 500,000 K. The increased emission results from the very large local photon creation rate $\chi/\delta$ in the transition region due to collisional excitation and ionization at the high temperatures. Consequently, $I_{\beta 40}$ for model S is only a factor of 2 or 3 lower than observed (see Table 3). We still need to increase $I_{\beta 40}$ by such a factor to account for...
### Table 3

**Computed and Observed Intensities**

<table>
<thead>
<tr>
<th>Model</th>
<th>$I_{604 \lambda}$ (10$^{-19}$)</th>
<th>$T_e$ (K)</th>
<th>$I_{304 \lambda}$ (10$^{-19}$)</th>
<th>$T_e$ (K)</th>
<th>$I_{\Delta \lambda [\text{He II} \lambda 304]}$ (10$^{-19}$)</th>
<th>$\int I_{\Delta \lambda [\text{He II} \lambda 304]} d\lambda$ (10$^{10}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Thin</td>
<td>Thick</td>
<td>Thin</td>
<td>0.00 Å</td>
<td>0.02 Å</td>
</tr>
<tr>
<td>S</td>
<td>2.7</td>
<td>0.17</td>
<td>9830</td>
<td>8930</td>
<td>5.2</td>
<td>0.078</td>
</tr>
<tr>
<td>C×3</td>
<td>2.6</td>
<td>0.17</td>
<td>9830</td>
<td>8930</td>
<td>5.0</td>
<td>0.079</td>
</tr>
<tr>
<td>C/3</td>
<td>3.0</td>
<td>0.16</td>
<td>9510</td>
<td>8660</td>
<td>5.6</td>
<td>0.075</td>
</tr>
<tr>
<td>R×3</td>
<td>8.5</td>
<td>0.14</td>
<td>8860</td>
<td>8130</td>
<td>39.4</td>
<td>0.038</td>
</tr>
<tr>
<td>R/3</td>
<td>0.9</td>
<td>0.20</td>
<td>10820</td>
<td>9750</td>
<td>0.8</td>
<td>0.181</td>
</tr>
<tr>
<td>$(dT/dh) \times 3$</td>
<td>3.2</td>
<td>0.16</td>
<td>9510</td>
<td>8660</td>
<td>5.8</td>
<td>0.061</td>
</tr>
<tr>
<td>$(dT/dh)/3$</td>
<td>2.7</td>
<td>0.17</td>
<td>9830</td>
<td>8930</td>
<td>5.4</td>
<td>0.116</td>
</tr>
</tbody>
</table>

**Observed Values**

<table>
<thead>
<tr>
<th></th>
<th>0.6</th>
<th>0.25</th>
<th>12570</th>
<th>11140</th>
<th>...</th>
<th>...</th>
<th>...</th>
<th>...</th>
<th>(Dupree and Reeves 1971)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>0.22</td>
<td>11500</td>
<td>10300</td>
<td>...</td>
<td>...</td>
<td>8.6</td>
<td>0.079</td>
<td>12710</td>
<td>12000)</td>
</tr>
<tr>
<td>Linsky et al. 1976</td>
<td>8.6</td>
<td>0.079</td>
<td>12710</td>
<td>12000)</td>
<td>4.4</td>
<td>(Dupree et al. 1973)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Hz$^{-1}$.

†Ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$. 
the observed value. This could be done by increasing the collisional excitation cross section (or $n_i$), by postulating a temperature plateau at $T \approx 80,000$ K (Linsky et al. 1976; Milkey, Heasley, and Beebe 1973), by decreasing the transition-region temperature gradient, or by introducing the diffusion-enhanced collisional excitation mechanism of Shine, Gerola, and Linsky (1975). Another possibility is a larger ratio of helium to hydrogen in the low corona and the upper transition region due to the kinematics of solar wind acceleration (cf. Giss, Hirt, and Leutwyler 1970; Nakada 1970; Benz and Gold 1976).

4. There is no observational evidence for a self-reversal in $\lambda$304 (Cushman, Godden, and Rense 1973) as would be expected for an optically thick photoionization-dominated resonance line. The absence of a self-reversal, however, naturally follows from photon creation in the transition region as explained in § IV. The absence of self-reversal is a strong argument against the PR process as an interpretation of the $\lambda$304 line (Milkey 1975).

5. Like typical chromospheric and transition-region lines, $\lambda$304 appears bright in the chromospheric network and plage regions. This is consistent with line formation by collisional processes since the emission measure at each temperature must be larger in the network and plage regions than in supergranulation cells.

6. Unlike typical chromospheric and transition-region lines, $\lambda$304 is less intense in coronal holes. We find that the computed $I_{\lambda304}$ is proportional to $P_e^2 (dT/dh)^{-1}$, where the $P_e^2$ dependence comes from the collisional excitation rate and the density, each being proportional to $P_e$. However, Withbroe and Gurman (1973) find that the quantity $P_e^2 (dT/dh)^{-1}$ is the same in pores as in the quiet Sun. A plausible explanation is the diffusion mechanism proposed by Shine, Gerola, and Linsky (1975) in which the holes appear dark in the He I and He II lines because the diffusion enhancement of the lines is weak where the transition-region temperature gradient is small, as in coronal holes. Further work is needed to establish whether this or some other mechanism adequately explains the different appearance of the helium lines in coronal holes compared with quiet regions.

We thank Rudolf Loeser for his assistance with all of the computational work reported here, and acknowledge the support of NASA through contract NAS 5-3949 with Harvard College Observatory and through grant NGL-06-003-057 to the University of Colorado.

REFERENCES


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