A BURST MODEL FOR LINE EMISSION IN THE SOLAR ATMOSPHERE.
I. XUV LINES OF He I AND He II IN IMPULSIVE FLARES

J. M. LAMING and U. FELDMAN
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5000

Received 1991 April 8; accepted 1991 August 15

ABSTRACT

A model in which the solar chromosphere is heated by explosive events is developed and used to interpret XUV spectra of He I and He II in impulsive flares observed by the Skylab spectroheliograph. From a comparison of relative line intensities from He I and He II emitted within the flares, the model establishes sizes, durations, and frequencies for the individual events and, by comparison with lines from other elements observed in the same flares, is demonstrated to be consistent with a helium abundance relative to hydrogen of 0.1 for burst temperatures of 15–18 eV.

Subject headings: Sun: chromosphere — Sun: flares — ultraviolet: solar system

1. INTRODUCTION

The emission lines from neutral and singly ionized helium have long presented a problem to solar physicists. Since the first excited levels in these species lie close to the ionization limit, calculations based on the assumption of ionization equilibrium and collisional excitation tend to predict relatively weak intensities for the resonance lines in these ions. Observations reveal much larger intensities in these lines than would be expected; for instance, Jordan (1975) noted that such calculations predicted line fluxes around a factor of 15 lower than obtained from observations. She suggested a mechanism which causes the helium atoms and ions to be excited by electrons with temperatures greater than the one established by the ionization equilibrium values. Several authors (Hirayama 1971; Kohl 1977; Raymond, Noyes, & Stopa 1979; Zirin 1975) have suggested that the 1640 Å (21–31') multiplet and others in the He II Balmer series come partially also from recombination, presumably following photoionization by coronal XUV radiation, the exact importance of which varies with solar region. Porter, Gebbie, & November (1989) have argued similarly that emission in the He II Lyman series observed in the 1973 June 15 flare arises from a combination of collisional excitation and recombination. Feldman et al. (1975) and Seely & Feldman (1985) studied the relative intensities of the individual components of the 1640 Å multiplet in various solar regions. They showed that the multiplet is primarily excited by electron collisions and self-absorption of the 1s–3p He II 256 Å photons.

In this paper we investigate a third possibility, conceptually similar to Jordan’s suggestion, in that the temperature of line excitation is raised, while the ionization balance is kept close to that corresponding to a lower quiescent temperature. We assume that the chromosphere is heated by frequent small explosive events, hereafter referred to as bursts. Evidence for the presence of explosive events, although of a rather different nature to the ones to be discussed here, is to be found in data taken with the High-Resolution Telescope and Spectrograph (HRTS) instrument (Bartoe & Brueckner 1975; Brueckner, Bartoe, & VanHoosier 1977; Cook 1991). These and other observations have been reviewed and discussed by Parker (1988) in the context of a so-called nanoflare model of the solar X-ray corona. The problems regarding the helium emission can be resolved somewhat if a certain population of bursts raises the temperature of small regions of the plasma in times short compared to the ionization equilibrium time for He ++ in quiescent conditions at the newly raised temperature. We consider here the problem of helium emission-line intensities in detail. Previous theoretical work has concentrated on modeling the differential emission measure curve (Sturrock et al. 1990), assuming a power-law form for the injection of heated electrons, and on the general features of the XUV and X-ray spectrum resulting from microflare heating of the corona, using this power-law electron spectrum (Raymond 1990). The next section defines the properties of the burst model we calculate for helium. Section 3 discusses the interpretation of spectra of the 1s² 1S_0 — 1snp PJ (3 ≤ n ≤ 11) series in He I and the Lyman (1s² S_1/2 — np² P_1/2,3/2, 4 ≤ n ≤ 10) series in He II from the 1973 December 2 impulsive solar flare, and the He II Lyman series in the impulsive flares of 1973 December 22 and 1974 January 21, all observed by Skylab. We compare intensities of helium lines with those from other elements (e.g., O I–O IV, Ne II–Ne VII, Mg VI–Mg X) in an attempt to produce a model consistent with a solar abundance of helium of 0.1. In subsequent papers we will discuss the helium emission in other regions of the solar atmosphere.

2. BURST MODEL

The ionization balance for helium is calculated according to a nine-level model which includes the following states: He I (1s² 1S, 1s2s 3S, 1s2s 3P, 1s2p 1P), He II (1s² 1S, 2s 3S, 2s 3P, 2p 1P), and He ++ , numbered in order.

Electron collisional excitation rates for He I come from Berrington & Kingston (1987) for temperatures less than 30,000 K. At temperatures greater than this, rates for n = 1 to n = 2 excitation are taken from Aggarwal, Kingston, & McDowell (1984), and for excitations within the n = 2 manifold from the tabulation of Janev et al. (1987), both scaled to match the Berrington & Kingston (1987) results at 30,000 K. For He II, electron collisional rates are calculated from the cross sections of Golden & Sampson (1971) for n = 1 to n = 2 transitions. Electron collisional de-excitation rates are calculated from the excitation rates, using the principle of detailed balance. Rates for transitions between 2s and 2p induced by proton collisions are taken from Zygelman & Dalgarno (1987). Ionization rates for the ground states of He and He ++ are taken from Arnaud &...

\[ A \text{-coefficients for allowed transitions in He I are taken from} \]
\[ \text{Wiese, Smith, \& Glennon (1966), and those for He II from} \]
\[ \text{Bethe \& Salpeter (1957). Intercombination transition} \]
\[ A \text{-coefficients for He I come from} \]
\[ \text{Drake \& Dalgarino (1969). The decay rate of the He I \( 2^2S_1 \) level is} \]
\[ 1.2 \times 10^{-4} \text{ s}^{-1} \] (Feinberg \&
\[ \text{Sucher 1971), that of the} \]
\[ 2^2S_0 \text{ level is} \]
\[ 50.8 \text{ s}^{-1} \] (Van Dyck, 
\[ \text{Johnson, \& Shugart 1971), and the two-photon decay rate of the} \]
\[ \text{He II} \]
\[ 2^2S_{1/2} \text{ level is} \]
\[ 5.2661 \text{ s}^{-1} \] (Drake \&
\[ \text{Goldman 1981).} \]

Radiative recombination is taken from Seaton (1959a) for He\textsuperscript{+} and from Aldrovandi and Péguynot (1973a, b) for He. Dielectronic recombination is taken from Mewe \& Schrijver (1978). Photoionizations from the He and He\textsuperscript{+} ground states are taken from Avrett, Vernazza, \& Linsky (1976). Other photoexcitation and photoionization rates are estimated, assuming the solar radiation to be a blackbody spectrum with temperature 0.5 eV,

\[ f(\omega)d\omega = \frac{\omega^2}{n^3} \frac{d\omega}{\omega (h\omega/k_B T) - 1} , \]

where \( f(\omega)d\omega \) is the number density of photons with frequency between \( \omega \) and \( \omega + d\omega \), \( k_B \) is Boltzmann’s constant, 
\[ h \text{ is Planck’s constant divided by} \]
\[ 2\pi, \text{and} \]
\[ c \text{is the speed of light.} \]

\[ \text{Photoionization cross sections for} \]
\[ n = 2 \text{ levels are taken from} \]
\[ \text{Seaton (1959a).} \]
\[ \text{The various atomic rates are assembled into a} \]
\[ 9 \times 9 \text{ matrix,} \]
\[ \text{the elements,} \]
\[ a_{ij}, \text{of which are the total rates for transfer of population from level} \]
\[ i \text{ to level} \]
\[ j \text{. The equation for the ionization balance is} \]
\[ n_i = \sum_j C_{j\rightarrow i} n_j - n_i \sum_j C_{i\rightarrow j} = 0 \]

in steady state conditions, where \( n_i \) is the fraction of helium atoms or ions in level \( i \), and \( C_{j\rightarrow i} \) is the sum of all processes transferring population from level \( j \) to level \( i \). These nine equations cannot be solved immediately for the level populations, because they are not linearly independent. Another constraint exists to remedy this situation, that being that the total population must be conserved. Thus replacing any of the above equations (we replace the first) with the equation

\[ \sum_i n_i = 1 \]

gives a set of linearly independent equations, allowing solution by matrix inversion.

The resulting ionization balance agrees well with the calculations of Avrett et al. (1976), and, in the absence of radiation, with those of Arnaud \& Rothenflug (1985). Neither of these calculations include the \( n = 2 \) levels. Omitting these from our calculation also makes very little difference to the resulting quiescent ionization balance. Table 1 shows the ionization balance calculated at an electron density of \( 10^{10} \text{ cm}^{-3} \) with and without the \( n = 2 \) levels in He I and He II.

The burst is simulated by replacing the electron temperature coming into the collisional excitation of levels, \( k_B T_{\text{ex}} \), by a higher value, which is assumed to be a weighted average over the He\textsuperscript{+} lifetime within the burst. The electron temperature coming into the ionization and recombination rates remains at the quiescent value. We assume that during the burst, the electrons and ions maintain identical temperatures, by assumed similar heating rates and Coulomb equilibration. This equilibration time is given by (Spitzer 1962)

\[ t_{\text{burst}} = 3 \left( \frac{10^n}{n_e} \right) \left( \frac{k_B T_{\text{ex}}}{3} \right)^{3/2} , \]

where \( n_e \) is the electron density in cm\textsuperscript{-3}. The lifetime of an ion within the burst is given by its ionization equilibration time at the temperature \( k_B T_{\text{ex}} \). The plasma is assumed to cool radiatively, characteristically for which is

\[ 3 \times 1.6 \times 10^{-12} k_B T_{\text{ex}}/n_e \Lambda(T) , \]

where \( \Lambda(T) \) is the radiative cooling function given approximately by

\[ \Lambda(T) = 10^{22} T_6^{0.7} + 2.3 \times 10^{-24} T_6^4 \text{ ergs cm}^2 \text{ s}^{-1} . \]

The ionization equilibration times (neglecting metastable levels) for He and He\textsuperscript{+} are shown in Figure 1 as a function of \( k_B T_{\text{ex}} \) at an electron density of \( 1.0 \times 10^{10} \text{ cm}^{-3} \). Values for these various time scales are given for different temperatures in Table 2. A sample matrix of population transfer rates for an

\[ \begin{array}{c|c|c|c|c}
\hline
k_B T_{\text{ex}} & t_{\text{burst}} & t_{\text{cool}} & t_{\text{eqex}} & t_{\text{equil}} \\
\hline
6 & 0.044 & 4.5 & 0.88 & 210 \\
9 & 0.081 & 8.9 & 0.18 & 21 \\
11 & 0.11 & 13 & 0.097 & 6.7 \\
13 & 0.14 & 17 & 0.062 & 2.9 \\
15 & 0.17 & 21 & 0.044 & 1.6 \\
17 & 0.21 & 26 & 0.032 & 0.99 \\
19 & 0.25 & 32 & 0.026 & 0.68 \\
21 & 0.29 & 38 & 0.022 & 0.50 \\
23 & 0.33 & 44 & 0.019 & 0.38 \\
25 & 0.38 & 50 & 0.017 & 0.31 \\
\hline
\end{array} \]

Note.—All times are given in seconds, \( t_{\text{eqex}} \) and \( t_{\text{equil}} \) are defined in the text, \( t_{\text{cool}} \) and \( t_{\text{eqex}} \) are the ionization equilibration times by collisional processes only for He I and He II, respectively. The electron density is \( 10^{10} \text{ cm}^{-3} \).
electron density of $10^{10}$ cm$^{-3}$, a quiescent temperature of 2 eV and an excitation temperature of 8 eV is shown in Table 3. The atomic rates in the top row are replaced by the equation

$$\sum n_i = 1$$

as discussed previously.

Although we have said that the heating takes place on a time scale short compared to the ionization equilibration time in quiescent conditions, the effect of the metastable levels in neutral He should be discussed further. In essence these are the only metastable levels to be considered, since at the electron densities relevant here, the 2s population in He$^+$ is effectively transferred to the 2p level by proton collisions. During the burst, these metastable levels are populated much more effectively and thus cannot be ignored. The ionization rates from these levels are much higher than from the ground state, and so the increased population in these levels means that the complete ionization rate will also be increased. The ionization balances for a variety of quiescent and excitation temperatures calculated at an electron density of $10^{10}$ cm$^{-3}$ are given in Table 4. At quiescent temperatures less than ~4 eV, once the excitation temperature reaches ~4 eV, the ionization balance for He and He$^+$ is essentially constant. As the quiescent temperature increases above ~4 eV, the effect of increasing the excitation temperature becomes reduced, and the ionization balance resembles that in Table 1, with no bursts. For ionization balances where He$^+$ is dominant, the He$^+$ fraction, $F_{He^+}$, given by

$$F_{He^+} = \frac{1}{\left( \frac{\alpha_e}{\alpha_i} + 1 + \frac{\beta_r}{\beta_i} \right)},$$

(7)

where $\alpha_{e,i}$ are recombination and ionization rates for He/He$^+$, respectively, and $\beta_{r,i}$ are those for He$^+/He^{++}$, depends only weakly on the ionization rates which are principally due to photoionization. We have used photoionization rates appropriate for the quiet sun, whereas below we shall use the model to interpret spectral line intensities from flares, where these rates will be larger due to the increased X-ray and XUV flux. We estimate that the photoionization rates need to increase by a factor of 260 in the flare (increased from 10$^{15}$ cm$^{-3}$ to 2.6 x 10$^{12}$ cm$^{-3}$), making the collisional ionization more important.

### Table 4

**Ionization Balance During Burst Events**

<table>
<thead>
<tr>
<th>$k_n T_{eq}$ (eV)</th>
<th>$k_n T_{ex}$ (eV)</th>
<th>He$^+$</th>
<th>He$^+$</th>
<th>He$^{++}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.532</td>
<td>0.456</td>
<td>1.19 x 10$^{-2}$</td>
</tr>
<tr>
<td>0.5</td>
<td>2.0</td>
<td>0.465</td>
<td>0.522</td>
<td>1.36 x 10$^{-2}$</td>
</tr>
<tr>
<td>0.5</td>
<td>4.0</td>
<td>3.00 x 10$^{-2}$</td>
<td>0.945</td>
<td>2.46 x 10$^{-2}$</td>
</tr>
<tr>
<td>0.5</td>
<td>8.0</td>
<td>3.56 x 10$^{-3}$</td>
<td>0.971</td>
<td>2.52 x 10$^{-3}$</td>
</tr>
<tr>
<td>0.5</td>
<td>16.0</td>
<td>1.56 x 10$^{-3}$</td>
<td>0.973</td>
<td>2.53 x 10$^{-3}$</td>
</tr>
<tr>
<td>0.5</td>
<td>24.0</td>
<td>1.37 x 10$^{-3}$</td>
<td>0.973</td>
<td>2.53 x 10$^{-3}$</td>
</tr>
</tbody>
</table>

**Note:** The electron density is 10$^{10}$ cm$^{-3}$. The quantities $k_n T_{eq}$ and $k_n T_{ex}$ are the quiescent and excitation temperatures, respectively.

### Table 3

**Level Population Matrix for $k_n T_{eq} = 8$ eV, $k_n T_{ex} = 2$ eV, and Electron Density = 10$^{10}$ cm$^{-3}$**

<table>
<thead>
<tr>
<th>$1s^22s$</th>
<th>$1s2s2S$</th>
<th>$1s2s2S$</th>
<th>$1s2p^2P$</th>
<th>$1s2p^1P$</th>
<th>$1s^22S$</th>
<th>$2s^2S$</th>
<th>$2p^2P$</th>
<th>He$^{++}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.58</td>
<td>-1.97 x 10$^6$</td>
<td>2.16 x 10$^3$</td>
<td>1.02 x 10$^{-4}$</td>
<td>428</td>
<td>3.01 x 10$^{-4}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.12</td>
<td>652</td>
<td>-2.63 x 10$^6$</td>
<td>61.6</td>
<td>1.99 x 10$^4$</td>
<td>1.00 x 10$^{-4}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.00</td>
<td>1.96 x 10$^6$</td>
<td>531</td>
<td>-1.04 x 10$^4$</td>
<td>4.55 x 10$^3$</td>
<td>9.03 x 10$^{-4}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.62</td>
<td>358</td>
<td>2.56 x 10$^6$</td>
<td>1.47 x 10$^{-3}$</td>
<td>-1.80 x 10$^3$</td>
<td>3.01 x 10$^{-4}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8.17 x 10$^{-3}$</td>
<td>1.12 x 10$^6$</td>
<td>6.52 x 10$^3$</td>
<td>1.43 x 10$^{-3}$</td>
<td>2.56 x 10$^3$</td>
<td>-0.527</td>
<td>5.27$^a$</td>
<td>1.00 x 10$^{10a}$</td>
<td>8.08 x 10$^{-3}$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.79 x 10$^{-2}$</td>
<td>-4.55 x 10$^3$</td>
<td>1.52 x 10$^3$</td>
<td>1.01 x 10$^3$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.493</td>
<td>4.55 x 10$^3$</td>
<td>-1.00 x 10$^{10a}$</td>
<td>3.03 x 10$^{-3}$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8.00 x 10$^{-4b}$</td>
<td>0.243</td>
<td>0.308</td>
<td>-1.21 x 10$^{-2}$</td>
</tr>
</tbody>
</table>

**Note:** The matrix element $a_{ij}$ is the total rate of population transfer from level $i$ to level $j$, except for those in the first row, where the elements are replaced by 1 to give nine linearly independent equations. For convenience, the states referred to are given at the top, the first five being in He, the next three in He$^+$, and the last being He$^{++}$.

$^a$ Dominated by radiative decay.

$^b$ Dominated by photoionization or photoexcitation.
The line emission is calculated assuming collisional excitation from the ground level. Cross sections for He ii $1s$--$np$ excitations are taken from Golden & Sampson (1971), with Bethe coefficients for their formula for $n > 3$ from Vriens & Smeets (1980). Rates for the He i ($1s^2 1S_0$--$1sn^p P_j$) excitations come from the tabulation of Janev et al. (1987), with the $n = 3$ cross sections scaled to match the excitation rate for $n = 3$ at 30,000 K calculated by Berrington & Kingston (1987). The same scaling factor is applied to the cross sections for excitations to higher levels. Only collisional excitations from the ground state are important. The effect of the metastable states in excitation of lines in He i is less important than for ionization, discussed below. Since the electron temperature used to calculate the excitation rates is higher than the one for ionization rates, the difference in the Boltzmann factors for excitations from the ground and excited states is much smaller than for ionizations from the ground and excited states. Hence the relative increase in the excitation rate in including excitations from the metastable levels is smaller than in the case of the ionization rate. Photoexcitation by the solar continuum has been neglected for levels with $n > 2$.

The line intensities in He ii are also affected by collisions with protons which redistribute population in a given $n$ level among the almost degenerate angular momentum sublevels. In the limit of complete redistribution, the emission rate in the Lyman series is modified by a factor $3A_{np-1s}/n^2\langle A\rangle n$, where $A_{np-1s}$ is the decay rate for the Lyman transition, and $\langle A\rangle n$ is the average decay rate for the level $n$. The proton collision rate is taken from the calculation of Zygelman & Dalgarño (1987), scaled by $n^4$. In cases where the proton collision rate is greater than or equal to the Lyman decay rate, complete redistribution is assumed and the modification factor is applied. Where the Lyman decay rate is greater, the factor is left out of the emission rate expression. This makes the choice of electron (and hence proton) density in fitting the spectra not altogether straightforward since one would expect a steep drop in intensity somewhere in the Lyman series at the $n$ level where the redistribution becomes important. We discuss this further below.

Following the burst, the plasma will recombine back to its quiescent state. Further line emission may occur during this recombination phase. This is accounted for in the following manner. The total number of recombinations taking place is evaluated from the difference between the helium ionization fraction corresponding to the maximum temperature (estimated analytically) reached in the burst and that in the quiescent state. The fraction of these recombinations going to a particular $1sn^p P$ level in He i or a particular $n$ or $np$ level (depending on the effect of proton collisions) in He ii is taken from calculations for individual levels by Burgess & Seaton (1960) for He i and from Pengelly (1964) for He ii, and divided by the total recombination rate, taken from the same references. In each case, the fraction is taken at a temperature of $10^4$ K, and assumed for our purposes to be temperature-independent. The effects of proton collisions as described above are also included.

Optical depth in the He i ($1s^2 1S$--$1sx^p P$) and the Lyman series in He ii is dealt with following the analysis in Osterbrock (1989), the burst region being assumed spherical. The escape probability for a photon emitted in a Doppler-broadened line, averaged over the region, is

$$
\epsilon(t_0) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} p(t_\alpha) \exp \left(-x^2\right) dx,
$$

where $t_\alpha$ is the optical radius at the center of the line, $t_\alpha$ is the optical radius at the normalized frequency $x$, and $p(t_\alpha)$ is the escape probability for a photon with this normalized frequency. For $t_\alpha < 20$ we use the approximation $\epsilon(t_\alpha) = 1.72/(t_\alpha + 1.72)$, and for higher values the integral is evaluated numerically. The intensity of a Lyman line is then given by the geometric progression

$$
b_t \epsilon + b_t^2 \epsilon(1 - e) + b_t^3 \epsilon(1 - e)^2 + \cdots = \frac{b_t \epsilon}{1 - b_t(1 - e)},
$$

multiplied by the excitation rate, the burst rate, and the ion lifetime within the burst, and for He ii, the factor in terms of $A$-coefficients accounting for proton $i$-changing collisions, where $b_t$ is the probability that the particular $np$ level decays emitting a Lyman photon. The optical radius during the burst is taken to be half the emitting column density multiplied by the ionization fraction for the particular charge state. During the recombination phase, the optical radius for He ii is assumed to be given by the column density times the ionization fraction for the final charge state plus half of the ionization fraction for the initial charge state, thus approximating the optical radius halfway through the recombination. In He i, radiative transfer effects may occur in quiescent solar atmosphere outside the burst region where neutral He is the dominant charge state. This complicates the calculation, but for our purposes here we take the optical radius to be given by the column density of He in the quiescent state.

Significant optical depths in the Lyman lines also make population following cascading transitions more likely, since Lyman photons are recycled into Balmer and other series photons. For the $n = 3$ levels in He ii, during the collisional excitation phase in the case of no proton collisional redistribution, estimates including radiative transfer effects showed that in our cases, population via cascades amounts to up to a 10% correction, with correspondingly less in higher levels. This is at the level of the uncertainty in the theoretical cross sections, and so is ignored. Under collisional excitation when proton collisions are important, the cascades give an approximate 20% correction to all levels of interest, which is included in the calculations. During the recombination phase, following Seaton (1959b), assuming complete redistribution, a 50% correction arises from cascades. This contribution will be reduced in the absence of proton collisions, though by not as large a factor as for collisional excitation.

3. COMPARISON WITH DATA

Spectra consisting of the $1s^2 1S$--$1nx^p P$ transitions in He i and the Lyman series in He ii have been observed from Skylab during the 1973 December 2 flare. Model spectra have been fitted to these data to try and determine some of the parameters relevant to a burst model. Considering He ii first, model spectra are calculated assuming collisional excitation and recombination as described above. The data consist of the Lyman lines from $1s$--$4p$ upward, with the omission of $1s$--$6p$. Lyman $\alpha$ ($1s$--$2p$) is generally overexposed on these plates; Lyman $\beta$ ($1s$--$3p$) at 256.317 Â is blended with a line at 256.39 Â, and Lyman $\epsilon$ ($1s$--$6p$) at 234.34 Â is also blended, presumably with the $S$ XII 234.48 line. The electron density for this flare has been determined from three diagnostic line intensity ratios in Ne vi, Ne vii, and Mg ix, formed at temperatures $4.3 \times 10^5$ K, $5.3 \times 10^5$ K, and $9.5 \times 10^5$ K, respectively (Feldman & Widing 1990). Assuming a constant density within the flare we take the value here to be $2.6 \times 10^{12}$ cm$^{-3}$ for the
The relative intensities of lines multiplied by the He II collisional excitation occurs is taken to be the burst rate multiplied by the abundance of Mg relative to H as recombination radiation becomes more important in forming the spectrum. The differential emission measure of a column as defined by Feldman & Widing (1990) (including the duty cycle of the collisional excitation) multiplied by the abundance of Mg relative to H is tabulated in Table 5 for comparison with Figure 4 of Feldman & Widing (1990). In a straightforward comparison, we find the best agreement with their results at burst temperatures of 12–15 eV. However, we believe this to be an underestimate for the following reason. Using an equilibrium model to deduce emission measures as in Feldman & Widing (1990) will usually give higher values compared to those deduced from a burst model, for the range of emission measures considered by these authors. We estimate that these values are larger by factors of 2–5, with the larger corrections being required for those lines formed at lower quiescent temperatures. With such a correction being taken into account, burst temperatures of 15–18 eV are more plausible.

This temperature agrees well as far as one can tell with that given by an analysis of the He II continuum. The number of photons in this structure is determined to be \( \sim 10^{16} \, \text{s}^{-1} \, \text{cm}^{-2} \). The number of recombinations from He II to He I is approximately twice this, when recombinations into excited states are accounted for. The number of recombinations deduced from the fits given by the number of recombinations per atom times emission lines of He. At such a density, proton l-changing collisions are important for all levels with \( n \geq 4 \). Following the suggestion of these authors that the flare origin was the lower chromosphere, consistent with the electron density, small size, and impulsiveness of the event, and the observed abundances which were close to a photospheric distribution, we take \( k_B \, T_{\text{eff}} = 0.6 \, \text{eV} \), consistent with the chromosphere models of Vernazza, Avrett, & Loeser (1981). Least-squares minimizations were performed to determine the emitting column density and the rate at which these events occur within the observed compact flaring region, for various assumed values of \( k_B \, T_{\text{eff}} \) between 6 and 21 eV. The “duty cycle” in which collisional excitation occurs is taken to be the burst rate multiplied by the \( \text{He}^+ \) ion lifetime within the burst, and that for the recombination radiation to be merely the burst rate, since this contribution is already integrated over time. The \( \chi^2 \) is calculated assuming that observational and theoretical errors are each at the 10% level. This theoretical uncertainty is probably reasonable for the He II lines. The relative intensities of lines within the Lyman series for excitation temperatures of more than a few eV are mainly determined by radiative transfer effects, which are most sensitive to the column density, and also to a certain extent to the excitation temperature, which determines the Doppler line width. The observed very large line widths of 120 km s\(^{-1}\) (Feldman & Widing 1990) are presumably dominated by nonthermal motions, which we assume to be motions of the entire burst region, and therefore not affecting the otherwise Doppler absorption profile within the burst. Similar nonthermal broadenings are discussed by Brueckner et al. (1988) in the case of C IV for bursts observed in the HRTS data.

Values for the fitted parameters for the three plates showing He II lines are given in Table 5 for varying assumed values for \( k_B \, T_{\text{eff}} \). The data and fitted line intensities are given in Table 6. From these fits we can determine a size and an emission measure for the bursting regions, if an assumption is made concerning the abundance of helium relative to hydrogen. We take this value to be 0.1. The diameter of the emitting region is then about 5 km at \( k_B \, T_{\text{eff}} = 6 \, \text{eV} \), increasing to 15 km at 21 eV, as recombination radiation becomes more important in forming the spectrum. The differential emission measure of a column as defined by Feldman & Widing (1990) (including the duty cycle of the collisional excitation) multiplied by the abundance of Mg relative to H is tabulated in Table 5 for comparison with Figure 4 of Feldman & Widing (1990). In a straightforward comparison, we find the best agreement with their results at burst temperatures of 12–15 eV. However, we believe this to be an underestimate for the following reason. Using an equilibrium model to deduce emission measures as in Feldman & Widing (1990) will usually give higher values compared to those deduced from a burst model, for the range of emission measures considered by these authors. We estimate that these values are larger by factors of 2–5, with the larger corrections being required for those lines formed at lower quiescent temperatures. With such a correction being taken into account, burst temperatures of 15–18 eV are more plausible.

This temperature agrees well as far as one can tell with that given by an analysis of the He II continuum. The number of photons in this structure is determined to be \( \sim 10^{16} \, \text{s}^{-1} \, \text{cm}^{-2} \). The number of recombinations from He II to He I is approximately twice this, when recombinations into excited states are accounted for. The number of recombinations deduced from the fits given by the number of recombinations per atom times
the column density times the burst rate varies between \(10^{16}\) and \(4 \times \times 10^{16} \text{s}^{-1} \text{cm}^{-2}\) for \(k_B T_{ex} = 15 \text{eV}\) or more. A similar number of photons are determined to be present in the He i continuum. This is also consistent with our fits for excitation temperatures greater than \(\sim 15 \text{eV}\).

Arguments can be made to rule out other values for \(k_B T_{ex}\). We find that for \(k_B T_{ex} = 5\), the parameters fitted to the He II spectrum predict more intensity than is observed in the He i spectrum, with the discrepancy worsening as one goes to lower temperatures. This is principally due to the ionization fraction of He increasing as the burst temperature decreases, leading to more collisional excitation of lines in this spectrum. The contribution due to recombination to He does not change very much in this temperature range. The burst will also be constrained by the fact that its size/lifetime ratio must be suitably smaller than the speed of light, giving a maximum \(k_B T_{ex}\) of order 100 eV.

The value we choose for \(k_B T_{ex}\) really represents some sort of average over the temperatures through which the plasma will travel during the course of an event. In view of the looseness of its definition here, we cannot really claim to have determined the solar abundance of He; we have merely found a model for the He emission, which is consistent with the observational data and an He abundance of 0.1 relative to H.

A steady state isothermal model to explain these data can give reasonable fits for the He II transitions, but fails for He I. In these fits, the duty cycle becomes a filling factor, and the electron density is assumed to be 7.5 eV for He. The value we choose for \(k_B T_{ex}\) is not possible to constrain the minimum excitation temperature as was done for the 1973 December 2 flare. The emission measures derived from our fits agrees less well with the data of Widing (1982) and Widing & Hiei (1984) for a helium abundance of 0.1 relative to hydrogen, even when the overestimated emission measure from the ionization equilibrium analysis is considered. Our emission measures are still in general lower, although it is plausible that our results at 12–15 eV are consistent with theirs. Further underestimates of the emission measure may occur if the helium abundance is too high, or the electron density too low in our calculations. The data and fitted line intensities for these flares are given in Table 8 for a temperature of 15 eV. The variation and order of magnitude of the fitted parameters is very similar in all cases. It is harder to be so clear about the size of the burst region in the last two cases due to the uncertainty in the electron density, but sizes ranging from a few km to a few tens of km seem likely. Quiescent models for these flares have the same problem as for the 1973 December 2 event, in that the emission measure predicted for a helium abundance of 0.1 is far in excess of that reported for other lines by Widing (1982) and Widing & Hiei (1984), by an order of magnitude or more.

TABLE 7

<table>
<thead>
<tr>
<th>Flare</th>
<th>Exp (s)</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 22</td>
<td>19</td>
<td>(4.3 \times 10^{17})</td>
<td>(3.9 \times 10^{17})</td>
<td>(5.7 \times 10^{17})</td>
<td>(6.3 \times 10^{17})</td>
<td>(6.2 \times 10^{17})</td>
<td>(6.3 \times 10^{17})</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>0.44</td>
<td>0.19</td>
<td>0.16</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>3.4</td>
<td>3.1</td>
<td>3.1</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.0 (\times 10^{29})</td>
<td>1.1 (\times 10^{29})</td>
<td>3.6 (\times 10^{28})</td>
<td>1.5 (\times 10^{28})</td>
<td>7.9 (\times 10^{27})</td>
<td>4.9 (\times 10^{26})</td>
<td></td>
</tr>
<tr>
<td>Jan 21</td>
<td>18.5</td>
<td>(2.2 \times 10^{17})</td>
<td>(2.5 \times 10^{17})</td>
<td>(3.8 \times 10^{17})</td>
<td>(4.3 \times 10^{17})</td>
<td>(4.1 \times 10^{17})</td>
<td>(4.1 \times 10^{17})</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>0.22</td>
<td>0.092</td>
<td>0.079</td>
<td>0.079</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>3.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.4</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0 (\times 10^{29})</td>
<td>3.5 (\times 10^{28})</td>
<td>1.2 (\times 10^{28})</td>
<td>5.0 (\times 10^{27})</td>
<td>2.6 (\times 10^{27})</td>
<td>1.6 (\times 10^{27})</td>
<td></td>
</tr>
</tbody>
</table>

* For each flare, the entries for each \(k_B T_{ex}\) are in order; fitted column density in cm\(^{-2}\), fitted burst incidence in cm\(^{-2}\) s\(^{-1}\), \(\chi^2\), and derived column emission measure, \(j n_e^2 ds\), in cm\(^{-3}\). The \(k_B T_{ex}\) values in the first line are eV.
ratio. He II is excited by electron collisions and self-absorption, with recombination being more important in the decay phase of the burst. Choosing a value for the quiescent temperature in the 1973 December 2 flare consistent with its known origin in the lower chromosphere leads to values of the emitting column density of $\sim 1 - 4 \times 10^{17}$ cm$^{-2}$, depending on the excitation temperature. Comparing the differential emission measure of such structures with that observed in other lines formed at 100,000-300,000 K shows that such a model is consistent with abundance for helium of 0.1 relative to hydrogen for burst temperatures of 15-18 eV. The diameter of the emitting region was thus deduced to be 5-15 km, from the fitted density of helium atoms, the electron density, and the derived abundance. Similar conclusions result from our analysis of the other two flares.

We would like to thank J. F. Seely, R. G. Athay, J. C. Raymond, & E. H. Avrett for their comments on an earlier draft of this paper.

REFERENCES


Cook, J. W. 1991, preprint

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