INTERPRETATION OF SOLAR HELIUM-LIKE ION LINE INTENSITIES

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SUMMARY

Recent identification of the $^2S \rightarrow ^1S$ line from helium-like ions in the solar soft X-ray spectrum, followed by calculation of its transition probability, enables an analysis of the observations to be carried out, based on intensities of the three lines $^2P \rightarrow ^1P$, $^2P \rightarrow ^1S$, and $^2S \rightarrow ^1S$. The relative collision rates to the excited levels and the electron densities in the emitting regions have been determined, subject to the limitation of available observations. Densities of $\approx 3 \times 10^8$ cm$^{-3}$ are found from lines formed over the quiet corona, but values of between $10^9$ and $10^{11}$ cm$^{-3}$ are found from lines emitted in active regions, and the highest electron densities occur in the hottest regions.

I. INTRODUCTION

In an earlier letter (1), we identified a sequence of intense lines in the solar soft X-ray spectrum as the forbidden magnetic dipole transition $1s^2 \, ^1S_0 \rightarrow 1s2s \, ^3S_1$ in helium-like ions. Owing to an underestimate of the single-photon decay rate, the $1s2s \, ^3S_1$ term had previously been assumed to decay by a two-photon process. From the observations, we were able to show that a single-photon decay rate $\gtrsim 10$ s$^{-1}$ is required for O VII. Using Dirac theory, in place of the Schrödinger wave mechanics with Pauli spin representation, Griem (2) has since carried out a new calculation of the single-photon rate. This now allows the solar interpretation to be extended to make use of the measured intensities of the forbidden lines. The present paper is an attempt to understand the existing observations in terms of the impact excitation rates and the electron densities in the quiet corona and active regions.

For each He-like ion we expect to find three lines, originating from the $1s2p \, ^1P_1$, $1s2p \, ^3P_1$ and $1s2s \, ^3S_1$ terms, in order of increasing wavelength. These will be referred to as the resonance, intercombination and forbidden lines. For ions with charge $\gtrsim 10$, the $1s2p \, ^3P_3 \rightarrow 1s^2 \, ^1S_0$ magnetic quadrupole transition (3), which will be unresolvable from the $1s2p \, ^3P_1 \rightarrow 1s^2 \, ^1S_0$ transition, will contribute significantly to the observed intercombination line. The total wavelength spread in one ion is typically $\approx 1$ Å or less, so that instrumental sensitivities can be assumed constant over this interval and the observed photon count rates used directly. A number of observations exist which enable the relative intensities of all three lines to be found. The present work makes use of crystal spectrometer traces by Fritz et al. (4) for O VII and Ne IX, by Rugge & Walker (5) for O VII, and by Evans & Pounds (private communication) for Ne IX and Mg XI, and photographic grazing-incidence records by Austin et al. (6) for C V and by Jones, Freeman & Wilson (7) for O VII. Since our earlier letter (1) the same three transitions have been identified in Si XIII from the spectrum of Evans & Pounds, giving the forbidden line at 6.74 Å. The Si XIII lines are also apparent on the spectra obtained during flares by Meekins et al. (8), from

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the satellite OSO-4, but have been mis-identified by them as a line of Al xii, the Si xiii resonance line and a blend of Mg xii and Si xii K, respectively. Their intensity data cannot be used because of the presence of the Si K edge, caused by the use of a mica window on their counter.

The present analysis is limited to the use of relative intensities, as these have a higher accuracy than the absolute values. However, if the absolute intensities and the volume of each active region were known, the abundances of the elements producing the lines could also be determined.

2. Theory

This analysis involves the assumption that the ratios of excitation rate coefficients to the four \( n = 2 \) terms have a temperature dependence which can be neglected. The temperature dependence of the ratio of singlet to triplet excitation rates has been calculated by Bely (9), who found a variation somewhat slower than linear with temperature. This is not however, supported by the experimental work of Kunze, Gabriel & Griem (10), who measure the same value of this ratio for two values of \( T_e/Z^2 \) (the reduced electron temperature) differing by a factor of 2, and it seems that the simple Coulomb–Born calculations may be overestimating the temperature dependence. Furthermore, ionization equilibrium calculations (11) show, as one might expect, that the temperatures at which the resonance lines of the various He-like ions have their maximum emission cover only a small range of \( T_e/Z^2 \).

The \( n = 2 \) terms are shown in Fig. 1, together with those excitation and decay mechanisms which are included in the analysis. The excitation rate coefficients all include contributions by cascade through higher levels. The \( 2^1P \) and \( 2^1S \) terms have a normal coronal-type equilibrium population, i.e. impact excitation balanced by radiative decay. However, the \( 2^3P \) and \( 2^3S \) terms, because of their longer lifetimes, interchange populations by means of additional processes between the excited states. These are collisional excitation of \( 2^3P \) from \( 2^3S \), radiative decay from \( 2^3P \) to \( 2^3S \) and we also include the possibility of photo-excitation of \( 2^3P \) from \( 2^3S \).

Fig. 1. The He-like ion, showing those terms and processes involved in the present analysis. The wavelengths indicated apply to the case of oxygen VII.
Corresponding processes for the singlet terms have a negligible effect. Collisional transfer from \(2^3S\) to \(2^1S\) can also be neglected. We assume that excitation rates to \(2^3P\) from both the ground and the \(2^3S\) terms are distributed between the \(J\)-levels in the ratio of their statistical weights. This general rule can be shown to be valid for LS coupling whenever the initial state has only one \(J\) component \((12)\). Collisional transfer between the \(J\)-levels of \(2^3P\) is estimated to be negligible compared with their radiative decay rates to \(2^3S\). Solution of the resulting coupled rate equations gives the following relation between the collisional rate coefficients \(C(i\rightarrow j)\), the spontaneous decay rates \(A(i\rightarrow j)\) and \(R\), the observed ratio of the forbidden line to the intercombination line intensities.

\[
R = \frac{A(2^3S\rightarrow 1^1S)}{[N_eC(2^3S\rightarrow 2^3P)+\Phi](1+F)+A(2^3S\rightarrow 1^1S)} \left(\frac{1+F}{B} - 1\right)
\]  

where we define

\[
F = \frac{C(1^1S\rightarrow 2^3S)}{C(1^1S\rightarrow 2^3P)},
\]

and the effective branching ratio

\[
B = \frac{1}{3} \frac{A(2^3P_1\rightarrow 1^1S)}{A(2^3P_1\rightarrow 1^1S)+A(2^3P\rightarrow 2^3S)} + \frac{5}{9} \frac{A(2^3P_2\rightarrow 1^1S)}{A(2^3P_2\rightarrow 1^1S)+A(2^3P\rightarrow 2^3S)}.
\]

\(N_e\) is the electron density, and \(\Phi\) \((\text{in } \text{s}^{-1})\) is the photo-excitation rate from \(2^3S\) to \(2^3P\). Values of \(A(2^3P\rightarrow 2^3S)\) are obtained from Wiese, Smith & Glennon \((13)\), \(A(2^3P_1\rightarrow 1^1S)\) from Drake & Dalgarno \((14)\), \(A(2^3P_2\rightarrow 1^1S)\) from Garstang \((3)\) and \(A(2^3S\rightarrow 1^1S)\) from Griem \((2)\). \(C(2^3S\rightarrow 2^3P)\) has been calculated using the formula of Van Regemorter \((15)\). The temperature used in each case is that at which the resonance line emission has its maximum intensity \((11)\). The actual temperatures may differ from these values, but the resulting densities are not very sensitive to temperature. Values of the atomic constants and rate coefficients used are listed in Table I.

The photo-excitation rate \(\Phi\) will have a negligible effect for all ions except C v (or lower), and we shall ignore it in our initial analysis. The variation of \(R\) with \(N_e\) is shown in Fig. 2 for three values of the rate coefficient ratio \(F\). In the limit of low density, we put \(N_e = 0\) in equation (1) and thus obtain the intensity ratio \(R\) as a function of the cross-section ratio \(F\). This is then the maximum observable value of \(R\). Again using equation (1) it is possible to find the value of \(N_e\) required to reduce the above value of \(R\) by say 10 per cent. This value, which we call \(N_e^*\), is then the smallest value of \(N_e\) which we can hope to detect because of changes in \(R\). Since \(N_e^*\) scales as \(1/(1+F)\), we have listed values of \((1+F)N_e^*\) in Table I. As shown later \((1+F)\) has a value between 1 and 2. We can now say without further computation that if the measured values of \(R\) for one ion, either from different records or from different active areas, vary by greater than 10 per cent, and if the variation is greater than the accuracy of measurement, then the densities in the sources must exceed the value of \(N_e^*\) listed.

3. INTERPRETATION AND DISCUSSION OF RESULTS

The observed data has been summarized in Table II. It is clearly not possible to carry out a rigorous analysis using equation (1), without knowing either the value of
### Table I

Atomic data used in the analysis. Values in parentheses are extrapolated.

<table>
<thead>
<tr>
<th>Ion</th>
<th>((2^3P\rightarrow2^3S))</th>
<th>((2^3P_1\rightarrow1^1S))</th>
<th>((2^3P_2\rightarrow1^1S))</th>
<th>((2^3S\rightarrow1^3S))</th>
<th>(A)</th>
<th>(B)</th>
<th>(C(2^3S\rightarrow2^3P)) at (T_e)</th>
<th>((1+F)N_e^*)</th>
<th>((1+F)N_e^*C)</th>
<th>(\Phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C v</td>
<td>5.65</td>
<td>0.284</td>
<td>2.54</td>
<td>0.112</td>
<td>28.0</td>
<td>1.0</td>
<td>1.0 (\times 10^7)</td>
<td>0.28</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>O vii</td>
<td>7.94</td>
<td>5.53</td>
<td>0.3</td>
<td>0.292</td>
<td>11.6</td>
<td>1.8</td>
<td>3.1 (\times 10^8)</td>
<td>3.6</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Ne ix</td>
<td>9.80</td>
<td>54.3</td>
<td>[2.2]</td>
<td>222</td>
<td>0.340</td>
<td>5.82</td>
<td>3.5 (\times 10^9)</td>
<td>4.3 (\times 10^9)</td>
<td>25</td>
<td>0.003</td>
</tr>
<tr>
<td>Mg xi</td>
<td>[12.6]</td>
<td>[11.5]</td>
<td>1044</td>
<td>0.380</td>
<td>3.28</td>
<td>5.8</td>
<td>3.5 (\times 10^{10})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si xii</td>
<td>[14.9]</td>
<td>[42.4]</td>
<td>3930</td>
<td>0.456</td>
<td>2.16</td>
<td>8.9</td>
<td>2.0 (\times 10^{11})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table II

Summary of observations and derived densities.

<table>
<thead>
<tr>
<th>Wavelength (2^3S→1^1S)</th>
<th>Intensity relative to (2^3P→2^3S)</th>
<th>Ratios (G)</th>
<th>(N_e(\pm 10%) except where indicated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>Reference</td>
<td>((2^3P\rightarrow1^1S))</td>
<td>((2^3S\rightarrow1^1S))</td>
</tr>
<tr>
<td>C v</td>
<td>41.47</td>
<td>(6) 0.26</td>
<td>0.51</td>
</tr>
<tr>
<td>O vii</td>
<td>22.10</td>
<td>(4) 0.41</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5) 0.48</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(7) 0.22</td>
<td>0.81</td>
</tr>
<tr>
<td>Ne ix</td>
<td>13.70</td>
<td>(4) 0.24</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) 0.38</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) 0.42</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) 0.15</td>
<td>0.85</td>
</tr>
<tr>
<td>Mg xi</td>
<td>9.32</td>
<td>E 0.43</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E 0.37</td>
<td>0.89</td>
</tr>
<tr>
<td>Si xii</td>
<td>6.74</td>
<td>E 0.62</td>
<td>1.0</td>
</tr>
</tbody>
</table>

E—Evans and Pounds (private communication).
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$F$ to use, or one of the densities to start with. However, if we can confidently claim that the density for one ion must be below the value of $N_e^*$ given in Table I, then we can apply equation (1) in the low density limit and thereby derive a value for $F$. Spectroheliogram observations (6) show that highly charged ions (i.e. ions formed where $T_e \approx 3 - 4 \times 10^6 \text{K}$) are formed predominantly in active regions, where the density is most uncertain. Observations of short term variations in intensity (i.e. during a month) made by Neupert (16) show that lines from ions formed at temperatures less than $1.6 \times 10^6 \text{K}$ vary with the presence of active regions by less than a factor of 1.4, indicating that most of the emission comes from a large volume of the corona and not from the active regions. On the other hand, lines from ions formed at temperatures greater than $1.6 \times 10^6 \text{K}$ show variations which are as large as a factor of 4 for ions formed almost entirely in active regions. The ion C v has its maximum abundance at $3 \times 10^5 \text{K}$, but when the excitation rate and density gradient of the corona are included, the resonance line has its maximum intensity at $\approx 1 \times 10^6 \text{K}$, and should, therefore, be formed over the whole quiet corona. However, for C v, $N_e^*$ is $\approx 10^7 \text{cm}^{-3}$ which is certainly lower than the coronal density of $\approx 2 \times 10^8 \text{cm}^{-3}$. The resonance line of O vii has its maximum intensity at a temperature of $2 \times 10^6 \text{K}$. In the absence of active regions the line should be found over the whole quiet corona ($T_e \approx 1.6 \times 10^6 \text{K}$), but its intensity will be sensitive to the presence of material at higher temperatures. We, therefore, start by assuming that in O vii for the highest observed ratio $R$, the lines are produced at the density of the quiet corona, and also that this density is $\leq N_e^*$. Putting $N_e = 0$ in equation (1) then gives $F = 0.35$. We now use this value of $F$ for all ions. Values of $N_e$ determined for each of the observations are listed in Table II. Values for $F = 0.11$
and \( F = 1.0 \) are also listed to illustrate the way in which changes in \( F \) influence the calculated densities.

The densities obtained for \( \text{C v} \) are found to be almost independent of the value of \( F \); these densities are close to \( 3 \times 10^8 \) cm\(^{-3}\) which is an acceptable value for the quiet corona at \( 1.0 \times 10^6 \) K. However, at this stage, we must go back and examine the effect of the photo-excitation rate \( \Phi \) from \( 2^3S \) to \( 2^3P \). This has been calculated for a black body source with a dilution factor of 0.5 and a temperature of 5000 K for \( \text{C v} \) and 4500 K for \( \text{O vii} \) and \( \text{Ne ix} \). The values are included in Table I. For photo-excitation to have a negligible effect, \( \Phi \) must be much less than \( N_e C(2^3S \rightarrow 2^3P) \). Values of \((1 + F)N_e^* C(2^3S \rightarrow 2^3P) \) have been tabulated alongside for comparison. Clearly the effect will be negligible for \( \text{Ne ix} \) and higher ions, and will introduce only a 10 per cent contribution in \( \text{O vii} \). However, the figures predict a serious effect in \( \text{C v} \). With \( \Phi \) at 260 s\(^{-1}\), the maximum value of \( R \) attainable for zero density would be 0.08. This is clearly inconsistent with the observations. Although equation (1) is correctly formulated in terms of the photo-excitation \( \Phi \) to the total \( 2^3P \) term, it should be realized that only excitation to the \( 2^3P_1 \) level is effective in depopulating the \( 2^3S \) term, since the other two levels \( 2^3P_{0,2} \) decay back to \( 2^3S \). This is accounted for by the effective branching ratio \( B \) in equation (1). The effect of photo-excitation, therefore, depends entirely on the background continuum intensity at one wavelength, \( 2^3S \rightarrow 2^3P_1 \), or 2278.6 Å in \( \text{C v} \). It is known that there is a large number of absorption lines in the spectrum in this region (17), in particular an \( \text{Fe} \) line at precisely this wavelength. Data at present available does not give the actual strength of these absorptions, but we are forced to conclude that they are sufficient to reduce \( \Phi \) to the point at which its effect is small.

For \( \text{O vii} \) we now find significant density variations through the four observed ratios. For the Rugge & Walker data at \( F = 0.35 \) we obtain of course the low density limit \( \leq 2.3 \times 10^8 \) cm\(^{-3}\), since this was the starting assumption in the analysis. This is then consistent with the quiet coronal density, which is about \( 2 \times 10^8 \) cm\(^{-3}\). The observations giving higher densities must therefore contain important contributions from active regions. In particular, the Culham observation (7) gives \( 3.0 \times 10^9 \) cm\(^{-3}\), an increase of an order of magnitude. It is of interest that the absolute flux in the \( \text{O vii} \) lines on this flight was significantly higher than recorded previously by Blake et al. (18), and Evans & Pounds (19), which again supports a strong contribution from active regions.

In the case of \( \text{Ne ix} \) and \( \text{Mg xi} \), which are formed predominantly in active regions, the observations are made with crystal spectrometers, and as these are non-focusing instruments, it has been possible in each case to isolate spectra from two active regions on each flight. The two regions show a significant difference in the ratio \( R \), implying a difference in density between them. We find densities of \( < 3.0 \times 10^9 \) to \( > 10^{10} \) cm\(^{-3}\) in \( \text{Ne ix} \), and for \( \text{Mg xi} \), densities of \( < 3 \times 10^{10} \) to \( \approx 10^{11} \) cm\(^{-3}\). In the case of \( \text{Si xiii} \), since \( R \) does not depart significantly from its value at the low density limit, it is only possible to give an upper limit of \( 1.5 \times 10^{11} \) cm\(^{-3}\) for \( N_e \).

The density in the quiet corona and chromosphere increases as the temperature decreases inwards towards the photosphere. It is apparent from Table II that in an active region the density increases systematically as the temperature increases. Other observations (20) show that the radiation from the highest temperature regions comes from the smallest volume of material.

So far we have used only the relative intensity of the forbidden to intercombination
lines. Also listed in Table I is the ratio $G$, which is defined as the ratio of the sum of the intensities of the intercombination and forbidden lines to that of the resonance line. Since all the density dependent processes, together with photo-excitation, serve only to transfer populations between the $2^3S$ and $2^3P$ levels, the sum of intensities from these two terms is independent of such processes, and is equal to the sum of the excitation rates to these terms. We, therefore, expect $G$ to be independent of $N_e$. This is supported by the observations in Table I. Where two sets of intensities arise from two active regions, although $R$ varies by significant factors, $G$ remains constant as predicted by the model. In the case of C v, it could be argued that the forbidden line is in fact only $0.08$ of the intensity of the intercombination line as predicted from the above photo-excitation rate and that the observed line is a wrong identification. However, the observations in other ions indicate that $G$, the ratio of the sum of the forbidden line and intercombination line intensities to that of the resonance line should be $\approx 1.1$. If $R$ were indeed $0.08$, the ratio of the intercombination line to the resonance line would be $\approx 1.0$, instead of $0.26$ as observed.

The conclusions regarding excitation rate ratios can now be summarized in combination with a previous experimental results. Measurements on laboratory plasmas at similar values of reduced temperature (10) show that

$$\frac{C(1^1S \rightarrow 2^1P) + C(1^1S \rightarrow 2^1S)}{C(1^1S \rightarrow 2^3P) + C(1^1S \rightarrow 2^3S)} = 1.8 \pm 0.2. \quad (2)$$

This leads to the final ratios listed in Table III. Of these four rates, the value for $C(1^1S \rightarrow 2^1S)$ makes use of the laboratory data whereas the other three are derived solely from the solar analysis. All these values include a contribution by cascade from higher levels. According to Bely (9), this is small for the singlets, but $\sim 30$ per cent for the triplets.

### Table III

<table>
<thead>
<tr>
<th>Relative excitation rates, for $F = 0.35$ and $G = 1.1$, including contributions from cascades.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate coefficient</td>
</tr>
<tr>
<td>$C(1^1S \rightarrow 2^1P)$</td>
</tr>
<tr>
<td>$C(1^1S \rightarrow 2^1S)$</td>
</tr>
<tr>
<td>$C(1^1S \rightarrow 2^3P)$</td>
</tr>
<tr>
<td>$C(1^1S \rightarrow 2^3S)$</td>
</tr>
</tbody>
</table>

### 4. CONCLUSIONS

We find that a study of the relative intensities of the resonance, intercombination and forbidden lines of helium-like ions, can give values of electron densities and excitation rate ratios. At present, the method is limited by the accuracy of the data available. Improved observations and reliable values for the excitation rate ratios could lead to very accurate density measurements. The present results show that in active regions the highest electron densities occur in the regions where the temperature is highest, e.g. at $2 \times 10^6$ K the density is $10^9$ cm$^{-3}$, and where $T_e \approx 5 \times 10^6$ K the density is $10^{11}$ cm$^{-3}$.

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**REFERENCES**


**NOTE ADDED IN PROOF**

The theory presented here applies to a plasma in ionization equilibrium, or to an ionizing plasma. Recent observation of these spectra from solar flares raises the possibility that in such transient plasmas the spectra may be produced primarily in the recombining phase through radiative recombination. In these conditions we would expect that there would be little change in the interpretation of the intensity ratio $R$, although the ratio $G$ would tend to 3.0, rather than 1.1.