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RELATIVE INTENSITIES OF SELECTED Si II MULTIPLETS IN THE SPECTRUM OF THE SUN AND ZETA

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ABSTRACT

The relative intensities of five multiplets of Si II are calculated by assuming that the excited levels are populated only by collisional excitation from the ground term; these are compared with the values observed in the spectrum of the Sun and ZETA. The observed intensity of the multiplet at 1195 Å, relative to that at 1309 Å, is an order of magnitude weaker than calculated, while the observed intensity of the multiplet at 1817 Å, relative to that at 1309 Å, is an order of magnitude stronger than calculated. It is suggested that the great strength of the latter multiplet is due to stepwise excitations via the metastable \( \text{3s3p}^2 \text{3P} \) levels and that the collision strength for the transition \( \text{4P}^{2} \rightarrow \text{3s3p}^2 \text{2D} \) is \( \Omega \simeq 10 \). A complete solution to these problems must await more accurate cross-sections.

I. INTRODUCTION

Six multiplets of Si II have been observed in emission in the solar spectrum between 1190 and 2350 Å (Hall, Damon, and Hinteregger 1963; Detwiler et al. 1961; Burton, Ridgeley, and Wilson 1967). Figure 1 shows a partial energy-level diagram of Si II and the observed transitions. The ion Si II is formed in the solar chromosphere, where the electron temperature, \( T_e \), is of the order of \( 10^5 \) °K, the electron density, \( N_e \), is of the order of \( 10^{11} \) cm\(^{-3} \), and the photospheric radiation field has a temperature \( T_r \leq 6000° \) K. Under these conditions collisional processes are the most important mechanism for populating the excited levels. However, if it is assumed that the excited levels are populated only by collisional excitation from the ground term, the calculated relative intensities of the multiplets discussed here do not agree with those observed. By taking the multiplet at 1309 Å as standard, the observed multiplet at 1195 Å is an order of magnitude weaker than calculated, while the observed multiplet at 1817 Å is an order of magnitude stronger than calculated.

With the exception of the intercombination lines at 2335 Å the same multiplets are observed in the spectrum of the plasma source ZETA, where \( N_e \sim 3 \times 10^{13} \) cm\(^{-3} \), \( T_e \sim 10^6 \) °K. Calculations of the relative intensities have been carried out for the above plasma conditions thus defined, including additional collisional processes which are important at the higher density. There are discrepancies between the observed and calculated values similar to those found from the Sun. Optical-depth effects are completely negligible in ZETA, so the similarity of the results from the Sun and ZETA makes it extremely unlikely that the discrepancies in the solar values are due to optical-depth effects.

The processes included in the calculations are discussed in §§ III and IV. It is suggested that the \( \text{3s3p}^2 \text{4D} \) levels are populated mainly by collisions from the metastable \( \text{3s3p}^2 \text{3P} \) levels. However, no satisfactory solution for the observed weakness of the lines from the \( \text{3s3p}^2 \text{3P} \) term has been found. Although the collision strength of the above \( \text{4P}^{2} \rightarrow \text{3s3p}^2 \text{4D} \) transition will be deduced, one of the purposes of the present paper is to draw attention to the need for reliable cross-sections in complex ions such as Si II.

II. DATA

Table 1 gives the observed intensities in the Sun and ZETA and the atomic data for all the transitions involved in the calculations. The observed solar intensities are taken
<table>
<thead>
<tr>
<th>( \lambda ) (Å)</th>
<th>Transition</th>
<th>( J )</th>
<th>( \xi )</th>
<th>( A_{\text{fit}} ) ( \left(10^{9} \text{ sec}^{-1}\right) )</th>
<th>(( \xi ))</th>
<th>Intensity</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Solar</td>
<td>ZETA</td>
<td>Disk ( \left(10^{-2} \text{ erg cm}^{-2} \text{ sec}^{-1}\right) )</td>
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<td>1816.92</td>
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*Blended with Ol.
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<th>TRANSITION</th>
<th>$J$</th>
<th>$\epsilon f$</th>
<th>$A_{\text{HI}}$ ($10^8$ sec$^{-1}$)</th>
<th>$\langle \epsilon \rangle$</th>
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<th>ZETA</th>
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<td>6347</td>
<td>$3s4s 3S-3s4p^1 3P^o$</td>
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<td>0.519</td>
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</table>
from Detwiler et al. (1961) and from Burton et al. (1967). The former data refer to integrated light from the whole disk, and the latter to a position off the solar limb. The intercombination lines are seen only in the limb spectrum. The observed relative intensities are expected to be accurate to within a factor of 2, with the exception of the intercombination line which is in a region where there is a high scattered-light background. The multiplet at 1195 Å is very faint in the limb spectrum, and only an upper limit can be placed on its intensity. The intensities from the ZETA spectrum are on an arbitrary scale. The relative intensities will have about the same accuracy as the solar data.

The oscillator strengths and transition probabilities have been taken from the calculations of Weiss (1966), Garstang and Shamey (1967), and Froese-Fischer (1968). The values given by Froese-Fischer have been used wherever possible as her method takes most account of configuration interaction, which is very important in computing the oscillator strength of the $3s^23p^2P^0-3s3p^2D^2$ transition.

\[ \text{The collisional excitation rate used is that given by Seaton (1964):} \]

\[ C_{12} = 1.7 \times 10^{-9} f_{12} \langle g \rangle W_{12}^{-1} T_e^{-1/2} e^{-W_{12}/kT_e} \text{ cm}^3 \text{ sec}^{-1}, \quad (1) \]

where $f_{12}$ is the absorption oscillator strength; $W_{12}$ is the excitation energy of the level, in electron volts; $\langle g \rangle$ is the Gaunt factor integrated over the Maxwellian distribution, as calculated from the tables of Burgess (1964) in his extension of Seaton's impact-parameter method. For forbidden transitions, $\langle g \rangle f_{12}/W_{12}$ is replaced by $5.1 \times 10^{-3} \Omega_{12}/\omega_1$, where $\omega_1$ is the statistical weight of the lower level and is the collision strength of the transition.

### III. THE SUN

#### a) Calculated Relative Intensities

The total flux, $E_{21}$, in an optically thin emission line is related to the population density, $N_2$, of the excited level, by the equation

\[ E_{21} = \frac{hc}{\lambda_{21}} \int N_2 A_{21} dV \text{ ergs sec}^{-1}, \quad (2) \]
where $A_{21}$ is the spontaneous transition probability, $V$ is the volume of the emitting material, and $\lambda_{21}$ is the wavelength of the transition.

The observed Si II lines will be formed in approximately the same region of the chromosphere, so that the relative intensity of two lines is given by the relation

$$\frac{E_{21}}{E_{24}} = \frac{\lambda_{21} N_2 A_{21}}{\lambda_{24} N_3 A_{24}},$$

where the subscripts 3 and 4 refer, respectively, to the excited and lower levels of a second transition.

Now consider the effect of a large optical depth on the relative intensities. The observed relative intensities of lines within the same multiplet do depart from the theoretical values for optically thin lines. However, if processes leading to the loss of photons from a given multiplet are negligible compared with the spontaneous transition probabilities, only the relative intensities of lines within the multiplet are changed. For the lines of Si II under consideration this will be true as long as they are formed in the region of the chromosphere where $T_e > 8000°$ K and the intensity of the leading line of each multiplet will not be changed by more than a factor of 2.25.

From equation (3), the relative intensity of two lines from different multiplets depends only on the populations of the excited levels and atomic constants. The problem is, therefore, to find the equilibrium population of each excited level and hence calculate the relative intensities as a function of temperature and density. Consider the populating and depopulating processes for the conditions $T_e \sim 10^4°$ K, $N_e \sim 10^{11}$ cm$^{-3}$, and $T_r < 6000°$ K, and ignore, for the present, processes involving radiatively forbidden transitions. The dominant populating process is electron collisions from the ground term and the dominant depopulating process is spontaneous radiative decay. Radiative excitation from the ground term and recombination into the excited levels are negligible. Radiative excitation from the excited levels to higher levels of visible-region radiation is the next most important depopulating mechanism but is a factor $\sim 10^{-3}$ less than the spontaneous decay rates. Photo-ionization from the excited states can be neglected and, at the above electron density, depopulation by collisional ionization, by collisions to higher levels or to the ground term, can also be neglected. Thus the relative intensities of the observed lines should be given by the relative collisional excitation rates from the ground term.

The optimum temperature for the formation of the Si II lines can be estimated in the following way. Equation (2), for the absolute intensity, can be rewritten in terms of the excitation rate, the ionization equilibrium $N(\text{ion})/N(\text{Si})$, the temperature gradient, and the electron density, to give

$$E_{21} \propto \frac{\int_{kT_1}^{kT_2} T_e^{-1/2} e^{-w/T_1/kT} N(\text{ion})}{N(\text{Si})} N_e^2 \left( \frac{dh}{d \log T} \right) d \log T.$$  

By using a model of the low chromosphere (based on Thomas and Athay 1961 and Jordan 1965), for the variation of $N_e$ and $dh/d \log T$ and the writer's (Jordan 1969) calculations of the ionization equilibrium of Si ions, it is found that the Si II lines will have their maximum emission at a temperature $T_e \sim 10^4°$ K. Table 2 gives the relative intensities calculated with $T_e = 10^4°$ K for the cases where $\tau < 1$ and $\tau > 1$ and also the observed relative intensities. Figure 2 shows the calculated intensities, relative to the line at 1309 Å as a function of temperature between 6300° and $2 \times 10^5°$ K.

b) Comparison of Calculated and Observed Relative Intensities

From Figure 2 it can be seen that the observed relative intensities of 1195 and 1817 Å agree with those calculated only if $T_e < 6300°$ K, which is an entirely unreasonable temperature.

From Table 2, the observed intensity of the line at 1195 Å, relative to that at 1309 Å,
is a factor of 9 weaker than calculated, while the intensity of the observed line at 1817 Å, relative to that at 1309 Å, is a factor of 9 stronger than calculated. Agreement within a factor of 2 could be considered as satisfactory. The weakness of the line at 1195 Å is extremely difficult to explain. If it is caused by a depopulating process other than spontaneous radiative decay, such a process would need a rate of $4 \times 10^{10}$ sec$^{-1}$. None of the processes considered earlier in this section has a rate greater than $\sim 10^{8}$ sec$^{-1}$.

There are two processes which could increase the intensity of the line at 1817 Å. Bely (1966) has found that transitions such as $2s^{-3s}$, $2s^{-3d}$ in the lithium-like ions, which are optically forbidden, can have large collision cross-sections. It is similarly possible that the $3s^23p^{-3s4p}$ cross-section is comparable in size to that of the $3p-4s$ transition. If so, such an excitation to $3s4p^2P^0$ would be followed by spontaneous radiative decay to the

<table>
<thead>
<tr>
<th>Intensity Ratio</th>
<th>Observed</th>
<th>Calculated</th>
</tr>
</thead>
</table>
| $E(1195 \AA)/E(1309 \AA)$ | Disk | Limb | $\tau < 1$ | $\tau > 1$
| $E(1195 \AA)/E(1309 \AA)$ | 0.27 | < 0.5 | 3.8 | 2.3
| $E(1265 \AA)/E(1309 \AA)$ | 3.3 | 1.0 | 5.5 | 7.3
| $E(1333 \AA)/E(1309 \AA)$ | 6.8 | 4.0 | 5.1 | 6.1
| $E(1817 \AA)/E(1309 \AA)$ | 58 | 125 | 6.7 | 6.7
| $E(2335 \AA)/E(1817 \AA)$ | Not obs. | 2.0 | 1.2 | 3.7

Fig. 2.—Variation of intensity ratios with $T_e$, for $N_e \lesssim 10^{13}$ cm$^{-3}$, excluding collisional processes involving radiatively forbidden transitions.
3s24s 3S and 3s3p2 2D levels, in a ratio of about 2:1. An upper limit to this cross-section can be found from the observed ratio \( E(1533 \text{ Å})/E(1309 \text{ Å}) \) and the equations for the populations of 3s24s 3S and 3s3p2 2P. The value found for the 3p 2 P0 2-3s24s 3S1/2 level would also increase the previously calculated rate to 3s3p2 3D5/2, but only by 11 per cent.

Now consider the possibility of collisional excitation from 3s3p2 4P to 3s3p2 2D. If this process is included in the equilibrium equation for the population of 3s3p2 3D5/2, the collision strength for the above transition can be calculated from equation (2) and the observed relative intensities of the lines at 1817 and 1309 Å, which gives

\[
\Omega (4P_{3/2} - 2D_{5/2}) = \frac{N(3p^2 2D_{5/2})}{N(4P_{3/2})} = 9.8 \times 10^4. \tag{5}
\]

(5)

It has been assumed that the levels within the 4P term are populated according to their statistical weights.

The value of \( N(3p^2 4P_{5/2})/N(3p^2 2D_{5/2}) \) can be found from the observed relative intensities of the lines at 2334 and 1817 Å, and equation (3), which gives

\[
\frac{N(3p^2 4P_{5/2})}{N(3p^2 2D_{5/2})} = 1.3 \times 10^4.
\]

By using this in equation (5), one finds

\[
\Omega (4P_{3/2} - 2D_{5/2}) = 7.7,
\]

which is a reasonable value for such a transition in a low ion.

The population of \( N(3p^2 4P_{5/2}) \) can be related to that of the ground term by applying equation (3) to the intensity of the lines at 1817 and 1309 Å and by assuming that the level 3p2 3S1/2 is populated only by collisions from the ground term. This gives the result

\[
\frac{N(3p^2 4P_{5/2})}{N(3p^2 3P_{0})} = 3.3 \times 10^{-3}.
\]

This is close to the Boltzmann population at \( T_e = 10^4 \text{ K} \), but the cross-sections for collisions from the ground to 3s3p2 4P are needed before it can be decided whether or not this fact is coincidental. Gailitis (1963) has investigated the resonant behavior of cross-sections due to the existence of auto-ionizing states in a lower ion. Auto-ionizing states of Si I below the 3s3p2 2P0 term of Si II may increase the cross-sections of all lower levels, since the transition 3s3p2 2P0-3s3p2 2P has the largest cross-section of the Si II levels. Such effects may be particularly important since \( kT_e < W_{12} \). Although this mechanism could resolve the discrepancy between the observed and calculated relative intensities of the lines at 1195 and 1309 Å, it would not entirely resolve the discrepancy between the observed and calculated relative intensities of the lines at 1817 and 1309 Å. It would still be necessary to invoke excitations from 3s3p2 4P to 3s3p2 2D.

Given accurate cross-sections and relative intensities, the temperature could be found from the relative intensities of the lines at 1195 and 2334 Å, and then the electron density from the relative intensity of the lines at 1817 and 2334 Å.

IV. ZETA

a) Calculated Relative Intensities

With the exception of the intercombination lines, the same Si II multiplets are observed in the spectrum of ZETA. As in the Sun the Si II lines will be formed in the same region of the plasma, and equation (3) can be used for the relative intensities. In ZETA,
optical-depth effects are certainly negligible. For the spectrum used in this analysis, the plasma conditions were

\[ N_e \simeq 3 \times 10^{13} \text{ cm}^{-3} \quad \text{and} \quad T_e \simeq 10^5 \text{ K} . \]

At this higher temperature the relative intensities are not very sensitive to the temperature (see Fig. 2).

The levels of the \( 3s3p^23S \) and \( 3s3p^22P \) terms are populated only by collisional excitation from the ground term. However, the higher density leads to additional terms in the equilibrium equations for the population of the \( 3s4d \; 2D \), \( 3s4p \; 2S \), and \( 3s3p \; 2D \) levels. The population of \( 3s4d \; 2D \) is coupled by collisions to that of \( 3d3p^22D \), via \( 3s4f^2P^0 \), and the population of \( 3s4p \; 2S \) is coupled to that of \( 3s3p^22D \), via \( 3s4p \; 2P^0 \). If \( 3s3p^22S \) is populated only by collisions from the ground term, the quantity \( N(3p^23S_{3/2})/N(3p^22P^0_{3/2}) \) can be calculated and hence the population of the other levels from the observed relative intensities and equation (3). These collisional processes are less important than collisional excitation from the ground term, or spontaneous radiative decay to the ground term, but they have been included in the calculations of the relative intensities, the results of which are given in Table 3.

| TABLE 3 |
|------------------|------------------|------------------|------------------|------------------|
| Intensity Ratio  | Observed         | Calculated       | Intensity Ratio  | Observed         | Calculated       |
| \( E(1195 \, \text{Å})/E(1309 \, \text{Å}) \) | 0.74             | 7.5              | \( E(1533 \, \text{Å})/E(1309 \, \text{Å}) \) | 2.2              | 9.0              |
| \( E(1265 \, \text{Å})/E(1309 \, \text{Å}) \) | 2.2              | 9.0              | \( E(1817 \, \text{Å})/E(1309 \, \text{Å}) \) | 7.8              | 0.36             |

b) Comparison of Calculated and Observed Relative Intensities

The results can be analyzed in the same way as the solar results. The observed line at 1195 Å is again an order of magnitude weaker than calculated, and the observed line at 1817 Å is more than an order of magnitude stronger than calculated. As in the Sun, no depopulation rate comparable in size to the spontaneous radiative decay rate can be found to explain the low population of the \( 3s3p^22P \) term. From the observed intensity of the lines at 1553 and 1309 Å an upper limit on the collision strength for the transition \( 3p^22P^0 \rightarrow 4p^22P^0 \) can be deduced. This is \( \Omega = 2.5 \), compared with the value of \( \Omega = 1.5 \) found from the solar results. Inclusion of this process increases the excitation rate to \( 3s3p^22D \) by a factor of 3. The population of the \( 3p^22P \) levels cannot be found, since the intercombination lines are not observed. As a first approximation, the population of \( 4P_{3/2} \) will be taken to be the Boltzmann value at \( T_e = 10^5 \text{ K} \), which is \( N(4P_{3/2}) = 0.81 \). Then from equations (6) and (7), \( \Omega(4P_{3/2})/N(2P_{3/2}) = 0.51 \). This is a factor of 3 larger than that found from the solar results, but the agreement is reasonably good considering the possible sources of error in the calculation.

In ZETA, \( kT_e \sim W_{13} \), so that the mechanism described by Gailitis for increasing the cross-sections of levels other than \( 3s3p^22P \) could still be valid.

V. CONCLUSIONS

There are large discrepancies between the calculated relative intensities of Si \( \Pi \) multiplets, based on the assumption of collisional excitation only from the ground term, and those observed in the spectrum of both the Sun and ZETA. But the high intensity of the lines at 1817 Å can be explained in terms of stepwise excitation of the \( 3s3p^22D \) levels via
the metastable 3s3p^2 4P levels. This would required a collision strength \( \Omega \sim 10 \) for the transitions 4P_{3/2,5/2} \rightarrow 3D_{5/2}. The source of the discrepancy between the calculated and observed relative intensities of the lines at 1195 and 1309 Å can only be the collision strengths used for the transitions 3s3p^2 2P_{0,1} \rightarrow 3s3p^2 4P and 3s3p^2 2P_{0,1} \rightarrow 3s3p^2 2S. Cascading following the optically forbidden transition 3s3p^2 2P_0 \rightarrow 3s4s 1S but is less important than collisional excitation from the ground term or, in the case of 3s3p^2 2D, than collisions from 3s3p^2 4P. The similarity of the results from the Sun and ZETA excludes optical-depth effects as the source of the discrepancies. It is emphasized that the observed Si II emission lines can be used in the interpretation of the solar chromosphere only when accurate cross-sections become available.

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