S v LINE RATIOS IN THE SUN


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ABSTRACT

New atomic data for S v have been used to predict level populations and emission-line intensity ratios for electron densities and temperatures appropriate to the Sun. The electron impact collision rates for spin-forbidden transitions and the intercombination transition spontaneous radiative rate are substantially larger than those previously published. The calculated intensity ratios show correspondingly significant changes.

The S v intensity ratio, \( \frac{I(3s^2 \;^1S \rightarrow 3s3p \;^3P^0; \;1199 \;\AA) - I(3s3p \;^1P \rightarrow 3p^2 \;^1D^0; \;1502 \;\AA)}{I(3s3p \;^1P \rightarrow 3p^2 \;^1P^0; \;1502 \;\AA)} \), is shown to be a useful electron density diagnostic for log \( N_e > 11.5 \). Generally ratios deduced from observations obtained with the NRL slit spectrograph aboard Skylab are in good agreement with our theoretical values.

Subject headings: atomic processes — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

Previously we have discussed the solar ultraviolet emission-line spectra for three ions in the third row of the periodic table, namely S iv: Dufton et al. (1982); Si iii: Dufton et al. (1983); and Si ii: Dufton and Kingston (1985). Generally good agreement was found between theory and observation, provided reliable atomic data were used. In particular, it was important to include resonance effects when calculating the electron impact excitation cross sections as resonances can increase the corresponding collision rates by factors of up to 5 at the temperatures appropriate to the solar transition region.

Another ion in the third row of the periodic table which has observable ultraviolet emission lines is S v and its spectrum has been discussed previously by Feldman, Doschek, and Bhatia (1982). These authors calculated Einstein A-coefficients and electron excitation rates. A comparison between theoretical and observed solar line strengths implied that their collision rates were too low (by about a factor of 5 for the \( 3^2 \;^1S^0 \rightarrow 3s3p \;^3P^0 \) transition) and Feldman et al. suggested that this could be due to the resonance structure which could not be calculated using their distorted wave approach.

Recently we have published electron impact collision strength for S v (Dufton and Kingston 1984) using the R-matrix method (Burke and Robb 1975). For spin-forbidden transitions, the cross sections at low electron impact energies are again dominated by resonances. Here we use these atomic data together with a new value for the Einstein A-coefficient of the \( 3s^2 \;^1S^0 \rightarrow 3s3p \;^3P^0 \) intercombination line to reanalyze the solar observations. Additionally we identify an emission line at approximately 1501.8 Å as due to the \( 3s3p \;^1P^0 \rightarrow 3p^2 \;^1D^0 \) transition in S v and use it together with the intercombination transition as an electron density diagnostic in solar flares.

II. ATOMIC DATA

a) Radiative Deexcitation Rates

Oscillator strengths for optically allowed transitions in S v have been published by Feldman, Doschek, and Bhatia (1982), van Wyngaarden and Henry (1981), and Baluja and Hibbert (1985). All these calculations use configuration interaction (CI) wave functions and normally yield oscillator strengths which agree to 10% or better. Here we adopt the results of Baluja and Hibbert since they are based on the most extensive CI expansion.

Their calculations have been extended by Brage and Hibbert (1985) to discuss the J-dependent energy levels for a substantial number of states in S v, including the \( 3s3p \;^3P^0 \) states. Their intermediate coupled wave functions can be used to evaluate the \( 3s3p \;^3P^0 \rightarrow 3s \;^2 \;^1S^0 \) intercombination line transition probability. In our earlier work on the corresponding transition in Si iii (Dufton et al. 1983), ab initio calculations were modified to correct errors in the calculated energy splittings between the states \( 3s3p \;^3P_1 \) and \( 3s^2 \;^1S_0 \), \( 3s^3 \;^1S_0 \), \( 3p^3 \;^1S_0 \), and \( 3p^3 \;^3P_0 \). The resulting oscillator strength was in quite close agreement with an experimentally determined value.

For S v, no experimental value has, as yet, been published, but we have again performed the empirical adjustment of the wave functions to correct the energy splittings. The CI wave functions are expressed as sums of single configuration functions \( I_j \):

\[
\Phi(LSJ) = \sum_{i=1}^{M} a_i(LSJ) \Phi_i(LS)
\]

and the \( \{a_i\} \) are the eigenvector components of the Hamiltonian matrix \( H_{ij} = \langle f_i | H | f_j \rangle \), where \( H \) is J-dependent because of, for example, spin-orbit interactions. The \( ^3P_1 \rightarrow ^1P_1 \) mixing, which is the most important reason for a nonzero intercombination transition probability, is refined by adjusting the diagonal matrix elements by small amounts in order to bring the calculated energy splitting \( ^3P_1 \rightarrow ^1P_1 \) into agreement with experiment.

The mixing between the \( ^3P_1 \) and \( ^1P_1 \) states is also proportional to the off-diagonal matrix element \( \langle H | P_1 \rangle | P_1 \rangle \) which is, in turn, approximately proportional to the fine-
structure splitting of the \(3P\) state. The ab initio splittings of \(P_0-3P\) and \(P_1-3P\) are 331.6 cm\(^{-1}\) and 671.0 cm\(^{-1}\), respectively, compared with the experimental values of 369.5 cm\(^{-1}\) and 761.7 cm\(^{-1}\). The calculated values are therefore too small by the factors 1.114 and 1.135, respectively. When the off-diagonal element is scaled by these factors, and when the empirical adjustments to the diagonal elements are also made, the \(P_1-3S\) transition probability has the values 1.680 \(\times\) 10\(^5\) s\(^{-1}\) and 1.744 \(\times\) 10\(^5\) s\(^{-1}\), respectively, for these two scaling factors.

Laughlin and Victor (1979), applying a model potential approach to several lowly ionized Mg-like systems, obtain the intercombination \(A\)-value of 1.63 \(\times\) 10\(^5\) s\(^{-1}\). Cheng and Johnson (1977) also consider this transition in Mg-like ions, but not for ions as low as \(S\) \(v\). An extrapolation of their \(A\)-values for higher ions gives a value of approximately 1.8 \(\times\) 10\(^5\) s\(^{-1}\).

Hence for the intercombination line, we adopt a value of 1.7 \(\times\) 10\(^5\) s\(^{-1}\) with an estimated uncertainty of less than 10%. We note that this is a factor more than 2 larger than that found by Feldman, Doschek, and Bhatia (1982) from wave functions based on a more limited CI expansion, the principal reason for the difference being the correction of the \(3P_1-1\) \(P_1\) energy splitting.

### b) Collision Rates for Electron Impacts

Collision strengths for the electron impact excitation of \(S\) \(v\) have been calculated using the \(R\)-matrix method (Burke and Robb 1975). The calculation was limited to the eight lowest \(LS\) states, viz \(3s^2\ 1S^0, 3s3p\ 3P^0, 3p\ 1D^0, 3s3p\ 3P^1, 3s3d\ 3P^0\) and \(1P\). The \(R\)-matrix results gave a collision rate larger by a factor of 4.2 than that of Feldman et al. and of 2.9 than that of van Wyngaarden and Henry (1981), who have undertaken a close coupling calculation which also excluded any resonance contribution.

For transitions between the two triplet levels, the \(LS\) results given by Dufton and Kingston are not suitable. Therefore we have used the program of Saraph (1978) to transform to a \(J\) coupling scheme. Collision rates for transition between individual fine-structure levels have then been calculated by integrating over a Maxwellian electron energy distribution. For the most important transitions, viz, \(3s3p\ 3P_1\rightarrow 3s3p\ 3P_0\), and \(3s3p\ 3P_1\rightarrow 3P_0\), we list in Table 1 the effective collision strengths (which can be related to the corresponding collision rates, see for example, Dufton and Kingston 1981) for a range of electron temperatures, \(T_e\). These, together with the effective collision strengths given in Dufton and Kingston (1984) should provide rates for all transitions which will be important in solar transition region or flare plasmas.

### Table 1

<table>
<thead>
<tr>
<th>Transition</th>
<th>(\log T_e)</th>
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<tbody>
<tr>
<td></td>
<td>4.7</td>
</tr>
<tr>
<td>(3s3p\ 3P_0\rightarrow 3s3p\ 3P_0)</td>
<td>1.98</td>
</tr>
<tr>
<td>(3s3p\ 3P_1\rightarrow 3s3p\ 3P_1)</td>
<td>2.26</td>
</tr>
<tr>
<td>(3s3p\ 3P_0\rightarrow 3P_0)</td>
<td>7.59</td>
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<tr>
<td>(3s3p\ 3P_1\rightarrow 3P_1)</td>
<td>0.034</td>
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<tr>
<td>(3s3p\ 3P_0\rightarrow 3P_0)</td>
<td>3.51</td>
</tr>
<tr>
<td>(3s3p\ 3P_1\rightarrow 3P_1)</td>
<td>0.096</td>
</tr>
<tr>
<td>(3s3p\ 3P_0\rightarrow 3P_0)</td>
<td>3.52</td>
</tr>
<tr>
<td>(3s3p\ 3P_1\rightarrow 3P_1)</td>
<td>2.79</td>
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<tr>
<td>(3s3p\ 3P_0\rightarrow 3P_0)</td>
<td>4.58</td>
</tr>
<tr>
<td>(3s3p\ 3P_1\rightarrow 3P_1)</td>
<td>0.096</td>
</tr>
<tr>
<td>(3s3p\ 3P_0\rightarrow 3P_0)</td>
<td>4.65</td>
</tr>
<tr>
<td>(3s3p\ 3P_1\rightarrow 3P_1)</td>
<td>13.5</td>
</tr>
</tbody>
</table>

### c) Collision Rates for Proton Impacts

For the plasma conditions considered here, proton impact excitation will be significant only for transition between states with similar energies. Feldman, Doschek, and Bhatia (1982) have calculated rates for a number of transitions, the largest values being for those between the triplet fine-structure levels, for example \(3s3p\ 3P_0\rightarrow 3s3p\ 3P_2\). Here we adopt these values but note that in all cases at the electron temperature, \(T_e\), corresponding to the maximum ionization fraction of \(S\) \(v\) (\(\log T_e = 5.1\)), the proton rates are smaller than the corresponding electron rates by a factor of 10 or more. Hence uncertainties in these rates are unlikely to be a serious source of error in predicting theoretical line strengths.

### III. Theoretical Level Populations and Line Strengths

With the atomic data discussed in § II, theoretical \(S\) \(v\) level populations have been calculated for the six \(LS\) states (corresponding to 10 levels when the \(3s3p\ 3P^0\) and \(3s3p\ 3P^2\) fine-structure splitting is included). The two additional states \(3s3d\ 1D^0\) and \(1P\), for which \(R\)-matrix collision rates are available, were not included as emission lines originating from these states have not been observed in the Sun. The statistical equilibrium calculations assumed that the plasma was optically thin, and that transitions between different ionization stages together with stimulated radiative processes could be neglected.

The populations of the \(S\) \(v\) ionic levels are listed in Table 2 with their sums being normalized to unity. They are tabulated for three electron temperatures (\(\log T_e = 4.8\), 5.1, and 5.4) and a range of electron densities (\(N_e = 10^{9}\) to \(10^{14}\) cm\(^{-3}\)) which should cover those normally found in the solar atmosphere. The middle temperature corresponds to that of the maximum ionization fraction of \(S\) \(v\) (Jordan 1969; Summers 1974), while for the other two temperatures the \(S\) \(v\) abundance has fallen by approximately two orders of magnitude.

These populations can be used in conjunction with the Einstein \(A\)-coefficients to derive the ratios of emission line intensities. Here we concentrate on one ratio, viz.,

\[
R = I(3s3p\ 1S^0\rightarrow 3s3p\ 3P^0, 1199.18 \text{ Å})/I(3s3p\ 1P^0\rightarrow 3p^2\ 1D^0, 1501.76 \text{ Å})
\]
This ratio (in energy units) is plotted in Figure 1 against electron density for various electron temperatures. For electron densities above \( N_e \approx 10^{11} \text{ cm}^{-3} \), the ratio is density sensitive as the upper levels of the transitions are in Boltzmann statistics relative to \( P° \) or the coronal approximation \( (3p^3 \, 3P) \) or \( (3p^1 \, 1D) \) to \( (3p^1 \, 3P) \), \( (3p^3 \, 3P) \) or \( (3p^3 \, 3P) \) to \( (3p^1 \, 3P) \), \( (3p^3 \, 3P) \) or \( (3p^1 \, 1D) \) relative to the ground state. Hence this ratio is potentially an excellent density diagnostic for solar flares.

IV. OBSERVATIONAL DATA

Feldman, Doschek, and Bhatia (1982) normalized the strength of the \( S \) \& \( V \) intercombination line to that of a nearby allowed \( N \) \& \( V \) transition. Here we prefer to consider the ratio \( R \) (defined in § III) in order to eliminate possible errors due to different ionization equilibria of \( S \) \& \( V \) and \( N \) \& \( V \). The \( S \) \& \( V \) transition \( 3p^3 \, 1P \rightarrow 3p^3 \, 3P \) with a transition energy of 1501.8 Å at the wavelength of 1501.76 Å.

We have measured the ratio \( R \) from spectrograms taken with the NRL slit spectrograph on SkyLab (SO82-B). The spectra had a resolution of approximately 0.06 Å and further details of the solar features were given in Bartoe et al. (1977). A variety of solar features were chosen and these may be summarized as follows: (a) two quiet regions at +2° to +8° above the white-light solar limb observed on 1973 August 27 (see Doschek et al. 1976) and at +2° to +6° above the limb on 1973 December 6 (Mariska, Feldman, and Doschek 1978); (b) a coronal hole at +2° to +6° above the limb on 1973 August 14 (Feldman and Doschek 1978b); (c) an active region at +2° to +6° above the limb on 1973 August 11 (designated region B by Feldman and Doschek 1978a); and (d) three large flares observed at approximately 1831 UT on 1973 September 5 (Cheng 1978), 0040 UT on 1973 December 17 (Widing and Spicer 1980), and 2328 UT on 1974 January 21 (Feldman and Doschek 1978b). A number of other disk flare spectra were also considered but rejected due to the lack of reliable fluxes particularly for the 1502 Å line, which was severely blended with a strong chromospheric \( N \) \& \( II \) line at 1502.15 Å (Doschek et al. 1976).

The observed ratios (in energy units) are listed in Table 3 and are based on the instrumental calibration of Nicolas et al. (1977). It should be noted that there is some uncertainty in the calibration below 1400 Å with, for example, the values of Nicolas et al. (1977) differing by a factor of approximately 3 at 1190 Å from the preliminary calibration tabulated in Doschek et al. (1976). Hence the absolute values in Table 3 should be treated with caution although variations in the ratio between different regions should be reliable. For the quiet, coronal hole, and active regions, the observed ratios are the mean of several measurements from regions of apparently similar density and both the number of measurements (\( n \)) and the standard error of the sample are quoted in Table 3. The actual
random errors appropriate to these mean values should therefore be considerably smaller.

V. RESULTS AND DISCUSSION

From Figure 1, it can be seen that for electron densities, \( N_e < 3 \times 10^{11} \text{ cm}^{-3} \), the ratio \( R \) should be in its low-density limit. Therefore, the observed values for the quiet, coronal hole, and active regions should all be in this limit, and this is confirmed by the very similar values deduced for all three regions. Adopting an observed low-density limit of 0.25, a logarithmic electron temperature between 5.1 and 5.4 is deduced from Figure 1. Separate calculations at intermediate temperatures leads to a value \( \log T_e = 5.22 \). This is in reasonable agreement with the ionization equilibrium calculations of both Jordan (1968) and Summers (1974) and therefore provides indirect support for the instrumental calibration of Nicolas et al. (1977).

For the three flares, values of \( R \) significantly larger than the low-density limit were observed. These ratios have been analyzed to yield electron densities for three electron temperatures, viz. \( \log T_e = 4.8, 5.1, \) and 5.4. For each temperature, the observed ratios were scaled so that the low-density regions corresponded to the appropriate theoretical limit (e.g., for \( \log T_e = 5.1 \), the observed values were multiplied by 0.16/0.25). This procedure should eliminate uncertainties due to the instrumental calibration and is analogous to that used by Feldman et al. (1982) in their analysis of the S v to N v line ratio. The derived electron densities are listed in Table 4 together with independent estimates from O iv and O v lines (1973 September 5: Cheng (1978); 1973 December 17: Feldman and Doschek (1978b); Widing and Spicer (1980); Widing and Cook (1985); 1974 January 21: Feldman and Doschek (1978b)).

The electron densities deduced from the S v lines depend slightly on the adopted electron temperature. This is principally due to changes in the intercombination collision rate which determines the electron density at which the 3s3p \(^1P_0\) levels moves into Boltzmann statistics relative to the ground state. Adopting an electron temperature, \( \log T_e = 5.1 \), the density estimates are in good agreement for both the September 5 and December 17 flares. For the former, the lower limit from Si iii lines is based on the observational data of Cheng (1978) but reanalyzed using the atomic data discussed by Dufton et al. (1983). For the latter, the lower value of \( \log N_e = 11.7 \) is from an O v line ratio. This ion is formed at a higher temperature (\( \log T_e \approx 5.4 \)), and hence the corresponding pressure is in excellent agreement with that deduced from the S v ratio. By contrast, the S v electron density is significantly larger than the O iv estimate for the January 21 flare, and the reason for this is unclear. To reduce the electron density to \( \log N_e = 12.0 \) would require a change in \( R \) of approximately 50%, which is considerably larger than the estimated observational error. The O iv electron density is based on an estimate of the emission measure at the temperature of maximum O iv ionization fraction. This emission measure was interpolated from values deduced from optically allowed lines of C iv and N v. However, again it would seem unlikely that this value is in error by the factor of 3-4 needed to remove this discrepancy.

Our main conclusions can be summarized as follows:

1. New atomic data are presented for S v. These are different from those of Feldman et al. (1982) and van Wyngaarden and Henry (1981), particularly for the spin-forbidden collision rates and the intercombination transition A-value and are more accurate.

2. The S v emission-line intensity ratio \( R \) is a useful electron density diagnostic for \( \log N_e > 11.5 \) and hence may be suitable for solar flares.

3. In general the electron densities from the S v ratio are in good agreement with independent estimates, although there is a discrepancy for the January 21 flare.

4. For quiet solar regions, our theoretical line strengths support the Skylab instrumental calibration of Nicolas et al. (1977) rather than the preliminary calibration of Doschek et al. (1976).
We wish to thank Professors P. G. Burke, FRS, and H. B. Gilbody for their interest and encouragement. Most of the calculations presented here were carried out using an SERC-funded data link to the SERC Cray-I computer at the Daresbury Laboratory. Two of us (F. P. K. and G. A. D.) are supported by grants from SERC and NASA, respectively.

REFERENCES

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