SVI LINE RATIOS IN THE SUN

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Abstract. R-matrix calculations of electron impact excitation rates in SVI are used to determine the theoretical temperature sensitive emission line ratios

\[ R_1 = \frac{I(3d^2D_{3/2},5/2 - 3p^2P_{3/2})}{I(3p^2P_{1/2} - 3s^2S_{1/2})} = \frac{I(712.8 \text{ Å})}{I(944.5 \text{ Å})} \]

and

\[ R_2 = \frac{I(3d^2D_{3/2},5/2 - 3p^2P_{3/2})}{I(3p^2P_{3/2} - 3s^2S_{1/2})} = \frac{I(712.8 \text{ Å})}{I(933.4 \text{ Å})}, \]

which are found to be up to 30% larger than the earlier results of Flower and Nussbaumer. A comparison of the present data with solar observations from the Harvard S-055 spectrometer on board Skylab implies that the 944.5 Å transition may be blended with lines from species with relatively low ionization potentials, in contrast to the findings of Flower and Nussbaumer. The 712.8 Å transition may also be similarly blended.

1. Introduction

It has long been known that the intensity ratios of emission lines arising from 3d – 3p and 3p – 3s transitions in sodium-like ions are very sensitive to the electron temperature of the emitting plasma, due to the relatively large separation of the ionic levels involved (Flower and Nussbaumer, 1975; Feldman and Doschek, 1977). However, the reliable calculation of such ratios is dependent on the availability of accurate atomic physics data, especially for the electron impact excitation rates from the 3s 2S ground state to the 3p 2P and 3d 2D levels (see, for example, Dufton and Kingston, 1981).

Flower and Nussbaumer (1975) have determined T_e-sensitive line ratios for Na-like SiIV, SVI and FeXVI using atomic data calculated in the distorted wave approximation (Eissner et al., 1974), and compared these with observed ratios measured from low resolution solar spectra. They found large discrepancies between theory and observation, which they attributed to blends in the observational data. More recently, Dufton and Kingston (1987) have used the R-matrix code (Burke and Robb, 1975; Berrington et al., 1978) to estimate electron excitation rates for AlIII, SiIV, and SVI, and found significantly different results from those of Flower and Nussbaumer. Keenan, Dufton, and Kingston (1986) and Keenan and Doyle (1988) subsequently employed the Dufton and Kingston results in the analysis of solar data for AlIII and SiIV obtained with the Naval Research Laboratory’s S082-B and the Harvard S-055 instruments on board Skylab, and found, in some cases, good agreement between theory and observation, thereby providing support for the atomic data adopted in their analyses (see also Doschek and Feldman, 1987).

In this paper we use the Dufton and Kingston (1987) data for SVI to recalculate line ratios for this ion, and investigate if the agreement between theory and observation may be improved.


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2. Atomic Data

The model ion adopted for S VI consisted of the five energetically lowest LS states, namely 3s\(^2\)S, 3p\(^2\)P, 3d\(^2\)D, 4s\(^2\)S, and 4p\(^2\)P, making a total of eight levels when the fine structure splitting in the \(^2\)P and \(^2\)D levels was included. Energies of all the ionic levels were taken from Bashkin and Stoner (1975).

Electron impact excitation rates for transitions among the five lowest LS states in S VI have been calculated by Dufton and Kingston (1987) using the R-matrix code. These data, which include the effects of resonance structure in the collision strengths, are probably the most accurate currently available and, hence, have been adopted in the present analysis.

Einstein A-coefficients for allowed transitions in S VI were obtained from Ganas (1987) and Lindgaard and Nielsen (1977). Radiative rates for the forbidden 3s\(^2\)S  3d\(^2\)D transitions from Godefroid et al. (1985) were also included in the model ion, although we note that inclusion of these data does not have a significant effect on the derived emission line ratios.

As has been discussed by, for example, Seaton (1964), proton excitation may be important for transitions with small excitation energies, i.e. fine structure transitions such as that in the 2s\(^2\)2p\(^4\)\(^2\)P ground term of Fe XVIII (Keenan and Reid, 1987). However, test calculations for S VI setting the proton rates for \(^2\)P\(_{1/2}\)  \(^2\)P\(_{3/2}\) and \(^2\)D\(_{3/2}\)  \(^2\)D\(_{5/2}\) equal to the equivalent electron excitation rates or 100 times these values had a negligible effect on the level populations, showing this atomic process to be unimportant, as found by Keenan, Dufton, and Kingston (1986) for Al III and Si IV.

3. Results and Discussion

Using the atomic data discussed in Section 2 in conjunction with the statistical equilibrium code of Dufton (1977), relative S VI level populations and hence emission line strengths were derived for a range of electron temperatures about that of maximum S VI fractional abundance in ionization equilibrium, log \(T_{\text{max}}\) = 5.3 (Arnaud and Rothenflug, 1985). The following assumptions were made in the calculations: (i) that ionization to and recombination from other ionic levels is slow compared with bound-bound rates, (ii) that photoexcitation and de-excitation rates are negligible in comparison with the corresponding collision rates, (iii) that all transitions are optically thin. Further details of the procedures involved may be found in Dufton (1977) and Dufton et al. (1978).

In Figure 1 the theoretical emission line ratios \(R_1 = I(3d\(^2\)D\(_{3/2}\), 5/2) - 3p\(^2\)P\(_{3/2}\))/I(3p\(^2\)P\(_{1/2}\) - 3s\(^2\)S\(_{1/2}\)) = I(712.8 Å)/I(944.5 Å) \) and \(R_2 = I(3d\(^2\)D\(_{3/2}\), 5/2) - 3p\(^2\)P\(_{3/2}\))/I(3p\(^2\)P\(_{3/2}\) - 3s\(^2\)S\(_{1/2}\)) = I(712.8 Å)/I(933.4 Å) \) are plotted as a function of electron temperature. The ratios \(R_3 = I(3d\(^2\)D\(_{3/2}\) - 3p\(^2\)P\(_{1/2}\))/I(3p\(^2\)P\(_{1/2}\) - 3s\(^2\)S\(_{1/2}\)) = I(706.5 Å)/I(944.5 Å) \) and \(R_4 = I(3d\(^2\)D\(_{3/2}\) - 3p\(^2\)P\(_{1/2}\))/I(3p\(^2\)P\(_{3/2}\) - 3s\(^2\)S\(_{1/2}\)) = I(706.5 Å)/I(933.4 Å) \) may be deduced from those in the figures by using the
Fig. 1. The theoretical emission line ratios \( R_1 = I(3d^2D_{3/2, 5/2} - 3p^2P_{3/2})/I(3p^2P_{1/2} - 3s^2S_{1/2}) = I(712.8 \, \text{Å})/I(944.5 \, \text{Å}) \) and \( R_2 = I(3d^2D_{3/2, 5/2} - 3p^2P_{3/2})/I(3p^2P_{3/2} - 3s^2S_{1/2}) = I(712.8 \, \text{Å})/I(933.4 \, \text{Å}) \) plotted as a function of electron temperature.

expressions:

\[
R_3 = R_2, \quad (1)
\]

\[
R_4 = 0.5R_2. \quad (2)
\]

We note that the \( R_2 \) and \( R_4 \) ratios have been derived by Flower and Nussbaumer (1975) using electron excitation rates calculated in the distorted wave approximation (Eissner, Jones, and Nussbaumer, 1974). The present results are approximately 30\% larger than those of Flower and Nussbaumer at \( T_e = 60000 \, \text{K} \), while at \( T_e = 300000 \, \text{K} \) the discrepancy is about 10\%. These differences are due to the adoption of improved electron excitation rates in our analysis (see Section 2).

Emission lines arising from \( 3d^2D - 3p^2P \) and \( 3p^2P - 3s^2S \) transitions in S vi have
been extensively observed in solar spectra obtained with the Harvard S-055 EUV spectrometer on board Skylab. This instrument covered the wavelength region 280–1350 Å and observed a spatial area of 5 × 5 arc sec with a spectral resolution of approximately 1.6 Å (FWHM) using an integration time of 0.04 s and a step length of 0.2112 Å. A full description of the instrument and its calibration may be found in Reeves, Huber, and Timothy (1977) and Reeves et al. (1977).

**TABLE I**

<table>
<thead>
<tr>
<th>Solar feature</th>
<th>$R$</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>Source</th>
<th>log $T_e(R_1)$</th>
<th>log $T_e(R_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiet Sun</td>
<td>0.75</td>
<td>0.17</td>
<td>0.13</td>
<td>Vernazza and Reeves (1978)</td>
<td>5.53</td>
<td>$H^a$</td>
</tr>
<tr>
<td>Coronal hole</td>
<td>0.70</td>
<td>0.20</td>
<td>0.14</td>
<td>Vernazza and Reeves (1978)</td>
<td>5.70</td>
<td>$H$</td>
</tr>
<tr>
<td>Sunspot</td>
<td>0.54</td>
<td>0.16</td>
<td>0.086</td>
<td>Noyes et al. (1985)</td>
<td>5.50</td>
<td>5.55</td>
</tr>
<tr>
<td>Active region</td>
<td>0.49</td>
<td>0.12</td>
<td>0.061</td>
<td>Vernazza and Reeves (1978)</td>
<td>5.32</td>
<td>5.32</td>
</tr>
<tr>
<td>Flare</td>
<td>0.50</td>
<td>0.11</td>
<td>0.053</td>
<td>Doyle (1983)</td>
<td>5.28</td>
<td>5.25</td>
</tr>
</tbody>
</table>

$a$ $H$ indicates that the observed line ratio is greater than the high temperature limit.

In Table I we summarize observed values of $R_1$ and $R_2$ for the average quiet Sun and coronal hole discussed by Vernazza and Reeves (1978), a sunspot plume (Noyes et al., 1985), an average active region (Vernazza and Reeves, 1978) and the 1973, September 7 flare at 14:03 UT (Doyle, 1983). Unfortunately no measurements are available for $R_3$ and $R_4$ as the S\textsc{vi} 706.5 Å line is blended with the strong Mg\textsc{ix} $2s2p\ ^3P_1 - 2s^2\ ^1S$ transition at 706.1 Å (Keenan et al., 1984).

Also shown in Table I is the ratio $R = I(944.5\ \text{Å})/I(933.4\ \text{Å})$, which theoretically should equal 0.5 irrespective of the electron density and temperature. However, for the quiet Sun and coronal hole observations $R = 0.75$ and 0.70, respectively, which suggest that there is blending in the 944.5 Å line in these cases. The fact that the blending occurs in the quiet Sun and coronal hole data, rather than in the flare and active region, implies that species with relatively low ionization potentials are probably responsible for any blend. This is in contrast to the results of Flower and Nussbaumer (1975), who found that the discrepancy between theory and observation in the $R$ ratio was worse for an active region than for the quiet Sun using the satellite and rocket observations of Dupree et al. (1973) and Heroux, Cohen, and Higgins (1974), respectively. We should also point out that Doyle (1987) notes that the 944.5 Å transition is blended with a line from a high ionization species, namely Si\textsc{viii} 944.2 Å. In the light of the above, the present results are difficult to understand, unless the Si\textsc{viii} line contributes little to the 944.5 Å blend. Low ionization species that may make a significant contribution include, for example, an Fe\textsc{ii} line at 945.1 Å (Wiese, 1985). We note that the disagreement between theory and observation for the $R$ ratio in the sunspot is much smaller than for the coronal hole and quiet Sun. This is probably due to the fact that, for this sunspot, the intensities...
of lines formed near log $T_e = 5.0$ are up to $\sim 40$ times larger than the average quiet Sun values, while lines formed near log $T_e = 4.3$ and 6.0 are only enhanced by a factor of two (Doyle et al., 1985). Hence, the blending species in the 944.5 Å line probably contribute a smaller amount to the total flux in this case.

The logarithmic electron temperatures derived from the observed $R_1$ and $R_2$ ratios are summarized in Table I. It may be seen from the table that for the active region and flare the values of $T_e$ deduced from the two line ratios are similar and, furthermore, are in excellent agreement with the temperature of maximum S vi abundance in ionization equilibrium, log $T_{\text{max}} = 5.3$ (Arnaud and Rothenflug, 1985). However, for the other solar features the observed ratios are up to 2.5 times greater than one would expect ($R_1 = 0.116$, $R_2 = 0.058$ for log $T_{\text{max}} = 5.3$ from Figure 1). Optical depth effects in the 933.4 and 944.5 Å lines could explain this, so we have calculated line strengths for the solar model of Gabriel (1976), which is appropriate to the network centres of quiet solar regions. The atomic data discussed in Section 2 were again adopted, along with a solar sulphur abundance of $S/H = 1.62 \times 10^{-5}$ (Grevesse, 1984), a helium to hydrogen ratio of 0.1 by number, the ionization equilibrium calculations of Arnaud and Rothenflug (1985) and a mass motion in the transition region of approximately 20 km s$^{-1}$ (Doschek et al., 1976). Line centre optical depths of $\tau = 1.0 \times 10^{-3}$ and $5.1 \times 10^{-4}$ were derived for the 933.4 and 944.5 Å transitions, respectively, at the solar limb, decreasing to $1.1 \times 10^{-4}$ and $5.5 \times 10^{-5}$ at disk centre. Not only are these not great enough to explain the observed discrepancies, but they are smaller than the values deduced for Na-like Al III (see Keenan, Dufton, and Keenan, 1986), for which agreement between theory and observation is satisfactory (Keenan, Dufton, and Keenan, 1986; Doschek and Feldman, 1987).

It would, therefore, appear that blends in the 712.8 Å line are probably the cause of the above discrepancy. However, as agreement between theory and observation for the solar flare and active region data is excellent, we may probably conclude that any blending is due to species with relatively small ionization potentials. One possible candidate is a Si III transition at 711.8 Å (Kelly, 1982).

4. Conclusions

The principal conclusions are:

1. Theoretical temperature sensitive emission line ratios $R_1 = I(712.8 \, \text{Å})/I(944.5 \, \text{Å})$ and $R_2 = I(712.8 \, \text{Å})/I(933.4 \, \text{Å})$ in S vi, calculated using $R$-matrix electron excitation rates, are up to 30% larger than those estimated by Flower and Nussbaumer (1975). These differences are principally due to the adoption of improved atomic data in the present analysis.

2. The observed values of $R = I(944.5 \, \text{Å})/I(933.4 \, \text{Å})$ for an active region and flare obtained with the S-055 EUV spectrometer on board Skylab are in much better agreement with theory ($R = 0.5$) than are the observational data for a coronal hole and the quiet Sun. This is in contrast to the results of Flower and Nussbaumer (1975), who found smaller discrepancies between theory and observation for the quiet Sun than for an active region using rocket and satellite observations.

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(3) Electron temperatures for the flare and active region deduced from $R_1$ and $R_2$ are similar, and are also in excellent agreement with the temperature of maximum $\text{Si} \text{VI}$ fractional abundance in ionization equilibrium, $\log T_{\text{max}} = 5.3$ (Arnaud and Rothenflug, 1985). However, for the other solar features the discrepancies between theory and observation are large (up to a factor of 2.5), which is probably due to the blending of the 712.8 Å transition with lines arising from species with relatively low ionization potentials.

Acknowledgement

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References