SiIII ELECTRON TEMPERATURE DIAGNOSTICS FOR THE SOLAR TRANSITION REGION

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Abstract. R-matrix calculations of electron impact excitation rates for transitions in SiIII are used to derive the electron-density-sensitive emission line ratios

\[ R_1 = \frac{I(1113.2\ \text{Å})}{I(1206.3\ \text{Å})}, \quad R_2 = \frac{I(1298.9\ \text{Å})}{I(1206.3\ \text{Å})}, \quad \text{and} \quad R_3 = \frac{I(1296.7\ \text{Å})}{I(1206.3\ \text{Å})}. \]

A comparison of these with observational data for several solar features obtained with the Harvard S-055 spectrometer on board Skylab reveals that theory and experiment are compatible if the electron temperature of the SiIII emitting region of the solar atmosphere is \( \log T_e = 4.5 \), but not if \( \log T_e = 4.7 \). The implication of the choice of a lower temperature on the electron energy distribution function is also briefly discussed.

1. Introduction

In a previous paper, Dufton et al. (1983) calculated the electron-density-sensitive SiIII emission line ratios \( R_1 = \frac{I(1296\ \text{Å})}{I(1892\ \text{Å})}, \quad R_2 = \frac{I(1301\ \text{Å})}{I(1313\ \text{Å})}, \quad R_3 = \frac{I(1301\ \text{Å})}{I(1296\ \text{Å})}, \quad \text{and} \quad R_4 = \frac{I(1301\ \text{Å})}{I(1303\ \text{Å})} \), and compared these with solar observational data obtained with the Naval Research Laboratory’s S082B spectrograph on board Skylab. In general, there was good agreement between theory and experiment, except in the case of \( R_1 \) and \( R_2 \). It was found that if an electron temperature \( \log T_e = 4.5 \) were adopted in the analysis, \( R_1, R_3, \) and \( R_4 \) gave similar electron density estimates, but the values of \( \log N_e \) derived from \( R_2 \) were systematically too small by \( \sim 0.8 \) dex. In contrast, the adoption of \( \log T_e = 4.7 \) led to excellent agreement among \( R_2, R_3, \) and \( R_4 \), but most observations of \( R_1 \) then layed below the theoretical low-density limit.

One possible explanation for the above discrepancies, noted by Dufton et al. (1983), was observational uncertainties in \( R_1 \) caused by intensity calibration errors, as the two components in this ratio are well separated in wavelength, unlike transitions in the other diagnostics. More recently Dufton, Kingston, and Keenan (1984) and Keenan et al. (1989) have suggested that the discrepancies may be due to the presence of non-Maxwellian electron energy distribution functions (EEDFs) in the transition region, caused by the steep temperature gradient. The high-energy tail of the EEDF would
significantly increase the collisional rate from the ground state to the 3s4s $^1S$ upper level of the 1313 Å line. This in turn would decrease both the theoretical values for $R_2$ and the discrepancies between the plasma parameters implied by the observed values of $R_1$ and $R_2$.

From the above discussion it is clear that the electron temperature of the Si III emitting region must be reliably determined. If $\log T_e(\text{Si III}) = 4.5$, a discrepancy occurs for the ratio $R_2$; on the other hand, if $\log T_e(\text{Si III}) = 4.7$, the disagreement between theory and observation must be explained for $R_1$. Unfortunately, different ionisation equilibrium calculations imply temperatures for the maximum Si III ionisation fraction ranging from approximately $\log T_e = 4.5$ to 4.7 (see Arnaud and Rothenflug, 1985, and references therein). Additionally, Balunas and Butler (1980) have shown that charge exchange reactions may significantly affect the silicon ionisation structure. Hence, in this paper we compare theoretical Si III line strengths with solar spectra from the Harvard S-055 instrument on board Skylab, and investigate if the electron temperature of Si III in the solar atmosphere may be properly evaluated.

2. Atomic Data

The model ion was chosen so as to provide reliable theoretical emission line strengths for transitions observed in the solar ultraviolet spectrum (see Section 3). It consisted of the following 14 levels; $3s^2\, ^1S$, $3s3p\, ^3P_{0,1,2}$, $^1P$; $3p^2\, ^1D$, $^3P_{0,1,2}$; $3s3d\, ^3D_{1,2,3}$; $3s4s\, ^1S$; $3s3d\, ^1D$, whose energies were obtained from Martin and Zalubas (1983). It should be noted that these are not the energetically lowest 14 levels – for example, $3s4s\, ^3S$ and $3p^2\, ^1S$ both lie below $3s4s\, ^1S$ (Martin and Zalubas, 1983). However, because the excluded levels have only a negligible interaction with those in the model ion, this should not be a significant source of error.

Electron impact excitation rates for transitions in Si III were based on those calculated by Baluja, Burke, and Kingston (1980, 1981) with the $R$-matrix code (Burke and Robb, 1975; Berrington et al., 1978), but incorporating improvements in the method of calculation as discussed by Dufton et al. (1983). Einstein $A$-coefficients were obtained from Baluja and Hibbert (1980), apart from those among the $3s^2\, ^1S$ and $3s3p\, ^3P$ levels, where the results of Ojha, Keenan, and Hibbert (1988) were adopted. As pointed out by Dufton et al., the proton impact excitation rates among $3s3p\, ^3P$ determined by Nicolas (1977) are more than a factor of 5 smaller than the corresponding electron rates and, hence, the former were not included in the present analysis.

3. Results and Discussion

Using the atomic data discussed in Section 2 in conjunction with the statistical equilibrium code of Dufton (1977), relative level populations and hence emission line strengths in Si III were determined for a range of electron temperatures and densities. Details of the procedures involved and approximations made may be found in Dufton (1977) and Dufton et al. (1978).
Fig. 1. The theoretical Si III emission line ratio

\[ R_1 = \frac{I(3s3p^3P_2 - 3s3d^3D_{1,2,3})/I(3s^2^1S - 3s3p^1P)}{I(1113.2 \text{ Å})/I(1206.3 \text{ Å})}, \]

plotted as a function of electron density at electron temperatures of \( \log T_e = 4.5 \) (solid line) and \( \log T_e = 4.7 \) (dashed line).

Fig. 2. The theoretical Si III emission line ratio

\[ R_2 = \frac{I(3s3p^3P_1 - 3p^2^3P_1 + 3s3p^3P_2 - 3p^2^3P_2)/I(3s^2^1S - 3s3p^1P)}{I(1298.9 \text{ Å})/I(1206.3 \text{ Å})}, \]

plotted as a function of electron density at electron temperatures of \( \log T_e = 4.5 \) (solid line) and \( \log T_e = 4.7 \) (dashed line).
In Figures 1 to 3 we plot the emission line ratios

\[ R_1 = I(3s3p^3 P_2 - 3s3d^3 D_{1,2,3})/I(3s^2^1 S - 3s3p^1 P), \]

\[ R_2 = I([1 - 1] + [2 - 2])/I(3s^2^1 S - 3s3p^1 P), \]

and

\[ R_3 = I([1 - 2] + [0 - 1])/I(3s^2^1 S - 3s3p^1 P), \]

respectively, as a function of electron density, where we have used \([J - J']\) for conciseness to denote the transition \(3s3p^3 P_J - 3p^2^3 P_{J'}\). As the electron temperature of the \(\text{Si}^{III}\) emitting region of the solar atmosphere is uncertain (see Section 1 and Dufton et al., 1983), theoretical line ratios are given for two values of \(T_e\), namely \(T_e = 4.5\) and 4.7. An inspection of the figures shows that the density sensitivity of the ratios is reasonable for values of \(N_e\) between \(\sim 10^{10.5}\) and \(10^{12}\) \(\text{cm}^{-3}\), with \(R_1, R_2,\) and \(R_3\) varying by factors of approximately 2.1, 2.5, and 2.6, respectively. Hence, they may be useful as diagnostics for high density solar features, such as flares and active regions.

The \(3s3p^3 P_2 - 3s3d^3 D_{1,2,3}\) transition in \(\text{Si}^{III}\) at 1113.2 \(\text{Å}\), \(3s^2^1 S - 3s3p^1 P\) at 1206.3 \(\text{Å}\), \([1 - 2] + [0 - 1]\) at 1296.7 \(\text{Å}\) and \([1 - 1] + [2 - 2]\) at 1298.9 \(\text{Å}\), have been
observed in solar spectra obtained with the Harvard S-055 EUV spectrometer on board Skylab (Vernazza and Reeves, 1978). 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. It is discussed in detail by Reeves, Huber, and Timothy (1977) and Reeves et al. (1977).

In Table I we summarize observed values of \( R_1 = I(1113.2 \, \text{Å})/I(1206.3 \, \text{Å}) \), \( R_2 = I(1298.9 \, \text{Å})/I(1206.3 \, \text{Å}) \), and \( R_3 = I(1296.7 \, \text{Å})/I(1206.3 \, \text{Å}) \) for the average active region discussed by Vernazza and Reeves (1978), a sunspot (Noyes et al., 1985) and the solar flare of September 7, 1973 (Doyle, 1983). Unfortunately, no measurement of \( R_3 \) is available for the sunspot, which is compatible with this transition being weak in sunspot spectra (see, for example, Keenan et al., 1989).

In Table II we list the logarithmic electron densities derived from the observed line ratios at electron temperatures of \( \log T_e = 4.5 \) and 4.7. Also listed in the table are the

**TABLE I**

<table>
<thead>
<tr>
<th>Solar feature</th>
<th>( R_1/10^{-2} )</th>
<th>( R_2/10^{-2} )</th>
<th>( R_3/10^{-2} )</th>
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<td>2.9</td>
<td>1.3</td>
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<td>–</td>
</tr>
<tr>
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<td>5.3</td>
<td>3.2</td>
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<tr>
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<td>4.6</td>
<td>3.2</td>
<td>2.0</td>
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**TABLE II**

<table>
<thead>
<tr>
<th>Solar feature</th>
<th>( \log T_e )</th>
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<th>( R_2 )</th>
<th>( R_3 )</th>
<th>Other methods</th>
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<td>Active region</td>
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<td>10.0</td>
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<td>4.7</td>
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<td>Sunspot</td>
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<td>10.5</td>
<td>10.6</td>
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<td></td>
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<td>L</td>
<td>L</td>
<td>–</td>
<td>10.3</td>
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<tr>
<td>7 September, 1973</td>
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<td>10.2</td>
<td>11.2</td>
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<td>&gt;11.0</td>
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<tr>
<td>7 September, 1973</td>
<td>L</td>
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<td>11.5</td>
<td>11.0</td>
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<td>7 September, 1973</td>
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</tbody>
</table>

\( ^a \) Observed ratio lies below the theoretical low-density limit.

\( ^b \) Observed ratio lies above the theoretical high-density limit.
values of log $N_e$ estimated for those solar features from ions formed at similar electron temperatures to SiIII. These have been obtained from the references given above for the different solar features.

An inspection of Table II shows that, if an electron temperature of log $T_e = 4.5$ is adopted, the values of log $N_e$ deduced from $R_1$, $R_2$, and $R_3$ are generally in reasonable agreement with electron densities derived from other methods, typical discrepancies being 0.4 dex. Such an error in the electron density corresponds to only a 25% error in the line ratios, which is well within the uncertainties in the observations (typically ± 50%, Noyes et al., 1985) and the calculations (± 20%, Dufton et al., 1983). However, if an electron temperature of log $T_e = 4.7$ is assumed, then the observed ratios either lie below the theoretical low-density limit (by factors of 2 in the cases of $R_1$ and $R_3$ in the sunspot and active region, respectively), or imply values of log $N_e$ that differ by typically an order of magnitude from those deduced from other methods.

The above results indicate that the electron temperature of the SiIII emitting region of the solar atmosphere is closer to log $T_e = 4.5$ than 4.7. This in turn implies that significant non-Maxwellian electron energy distributions may exist in the transition region: if log $T_e$(SiIII) = 4.5, poor agreement is found for the $I(1301 \ \text{Å})/I(1313 \ \text{Å})$ line ratio when compared with theoretical results deduced using Maxwellian EEDFs, yet the discrepancies are removed if non-Maxwellian excitation rates for the 1313 Å transition are included in the line ratio calculations (see Dufton et al., 1984; Keenan et al., 1989).

Finally, Dufton et al. (1983) had noted that the SiIII 3s$^2$ 1S - 3s3p 1P resonance line is unsuitable for use in diagnostic line ratios due to its large optical depth, but, later, Keenan and Kingston (1986) pointed out that the optical depth of this transition is not as large as Dufton et al. had suggested. The good agreement found between theory and observation for $R_1$, $R_2$, and $R_3$ in the present analysis would appear to indicate that the resonance line is, after all, suitable for use as a diagnostic. It is possible that this line is similar to the CII 2s$^2$2p$^2$2P - 2s2p$^2$2D resonance transition at ~ 1335 Å, which although optically thick yields line fluxes indistinguishable from the optically thin case (Brown and Carpenter, 1984).

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References