SOLAR Si III LINE RATIOS FROM THE HIGH-RESOLUTION TELESCOPE AND SPECTROGRAPH ON BOARD SPACELAB 2: THE EFFECTS OF NON-MAXWELLIAN ELECTRON DISTRIBUTION FUNCTIONS

F. P. KEENAN, J. W. COOK, P. L. DUFTON, and A. E. KINGSTON

ABSTRACT

Electron impact excitation rates for transitions in Si III, incorporating the effects of non-Maxwellian electron velocity distribution functions (EVDFs), are presented for a range of electron temperatures appropriate to the solar transition region. A comparison of theoretical line ratios with observational data for a quiet solar region, a sunspot, and an active region obtained with the high-resolution telescope and spectrograph (HRTS) on board Spacelab 2 indicates that non-Maxwellian EVDFs may exist in the transition region. Non-Maxwellian effects appear to be larger for the sunspot than for the quiet Sun, implying that the temperature gradient may be greater in the former.

Subject headings: atomic processes — Sun: spectra — Sun: sunspots — Sun: transition region — ultraviolet: spectra

I. INTRODUCTION

The solar spectrum from 1200 to 2000 Å contains many emission lines due to Si III, which are formed in the transition region (see, for example, the line list of Sandlin et al. 1986). Dufton et al. (1983) have calculated line ratios involving several of these transitions; they found generally good agreement with observational data obtained with the Naval Research Laboratory’s slit spectrograph (S082B) on board Skylab, although electron densities derived from \( R_1 \) \( \equiv \frac{I(1296 \, \text{Å})}{I(1892 \, \text{Å})} \) and \( R_2 \) \( \equiv \frac{I(1301 \, \text{Å})}{I(1313 \, \text{Å})} \) were incompatible. Dufton, Kingston, and Keenan (1984) suggested that these discrepancies might be due to the presence of non-Maxwellian electron energy distribution functions (EVDFs) in the transition region caused by the steep temperature gradient. The high-energy tail to the EVDF would significantly increase the collisional rate from the ground state to the 3s4s \( ^1 \)S level of the 1313 Å line. This in turn would decrease both the theoretical values for \( R_3 \) and the discrepancy between the plasma parameters implied by the observed values of \( R_1 \) and \( R_2 \).

One problem with the observational data discussed by Dufton et al. (1983) is that they were recorded on separate spectrograms, making any comparison of different solar regions difficult. However in this paper we present Si III line ratios for a quiet solar region, a sunspot, and an active region, whose spectra were exposed on a single photographic plate obtained with the high-resolution telescope and spectrograph (HRTS) on board Spacelab 2 (see § III).

II. ATOMIC DATA AND THEORETICAL LINE RATIOS

The atomic data adopted in the present analysis are those discussed by Dufton et al. (1983), with the exception of spontaneous radiative rates among the 3s2 \( ^1 \)S and 3s3p \( ^3 \)P levels. Dufton et al. used the CIV3 code (Hibbert 1975) to calculate an A-value for the 3s2 \( ^1 \)S–3s3p \( ^3 \)P1 intercombination line of 1.46 \( \times \) 10\(^4 \) s\(^{-1} \), which lies outside the 6% error bars of the experimental result of 1.67 \( \times \) 10\(^4 \) s\(^{-1} \) derived by Kwong et al. (1983). Recently however, Ojha, Keenan, and Hibbert (1988) have reevaluated decay rates among 3s2 \( ^1 \)S and 3s3p \( ^3 \)P levels in Si III using an improved version of CIV3, and found an intercombination line A-value of 1.67 \( \times \) 10\(^4 \) s\(^{-1} \), in excellent agreement with observation. These data have therefore been adopted here, although we note that they lead to only a small change in the Si III relative populations and hence emission-line strengths given in Dufton et al. (1983).

We have calculated non-Maxwellian collision rates for transitions in Si III using the non-Maxwellian EVDFs of Shoub (1982, 1983). In the second of these papers, Shoub (1983) gives results for the quiet Sun, which are derived from direct numerical solution of the Landau-Fokker-Planck equation assuming constant pressure atmospheres. Data are given for two electron pressures \( P_e \) \( \equiv (N_e T_e) \), namely \( P_e = P_0 = 6 \times 10^{14} \) cm\(^{-3} \) K (Dupree 1972), and \( P_e = P_{0/2} \) (Withbroe 1977). For other solar regions, Shoub (1982) has deduced analytical expressions which depend on the pressure in the transition region (assumed to be constant), the electron temperature at the top of the region \( T_e \), and the temperature and density profile of the thermal electron background gas. In Table 1 we summarize Maxwellian effective collision strengths for selected transitions in Si III [based on R-matrix calculations similar to those discussed by Baluja, Burke, and Kingston (1980, 1981), but incorporating improvements in the method of calculation—see Dufton et al. (1983) for details], as well as non-Maxwellian results calculated by convolving the R-matrix collision strengths with the EVDF of Shoub (1983) for \( P_e = P_0 \). As can be seen from the table, the effect of the non-Maxwellian is largest at low values of \( T_e \) (due to the greater enhancement in the high-energy tail of the EVDF), and for those transitions with the greatest excitation energies \( E_{\text{ex}} \). For example, at \( \log T_e = 4.5 \), the temperature of maximum ionization fraction of Si III from the calculations of Arnaud and Rothenflug (1985), the non-Maxwellian distribution increases the collision rate by 32% for the 3s2 \( ^1 \)S–3s3p \( ^3 \)P transition \( E_{\text{ex}} = 19.7 \) eV, compared with only 1% for 3s2 \( ^1 \)S–3s3p \( ^1 \)P \( E_{\text{ex}} = 10.3 \) eV.

In Table 2 we compare the Maxwellian effective collision
Effective Collision Strengths at $P_e = P_0$ for Selected Transitions in Si III

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\log T_e = 4.3$</th>
<th>$\log T_e = 4.5$</th>
<th>$\log T_e = 4.7$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>NM</td>
<td>M</td>
</tr>
<tr>
<td>$3s^2^1S-3s3p^1P$</td>
<td>4.40</td>
<td>4.36</td>
<td>3.78</td>
</tr>
<tr>
<td>$3s^2^1S-3s3p^1P$</td>
<td>6.20</td>
<td>7.81</td>
<td>6.76</td>
</tr>
<tr>
<td>$3s^2^1S-3s4s^1S$</td>
<td>0.525</td>
<td>8.696</td>
<td>0.525</td>
</tr>
<tr>
<td>$3s3p^1P-3s3p^1P$</td>
<td>2.00</td>
<td>21.8</td>
<td>21.2</td>
</tr>
<tr>
<td>$3s3p^1P-3s3p^1P$</td>
<td>0.769</td>
<td>1.16</td>
<td>0.669</td>
</tr>
</tbody>
</table>

Jitter in the Spacelab 2 pointing system typically limited $\sigma_{\theta_{\text{ASA}}} = 0.5^\circ$ to $1^\circ$, and $\sigma_{\theta_{\text{ASA}}} = 0.8^\circ$ for the flare curve with the $P_e = P_0$ and $P_e/2$ curves. Also shown in the table are the non-Maxwellian rates derived from Shoub's (1983) analytical expressions, where we have taken a pressure of $\log N_e^p = 10.5$ with strengths for selected Si III transitions at $\log T_e = 4.5$, with Maxwellian electron excitation rates of $\log T_e = 4.5$, with Maxwellian electron excitation rates of $\log T_e = 10^7$ K, in order to simulate typical conditions in a solar flare (Pneuman 1982). The non-Maxwellian effects for the $P_e/2$ case are larger than for $P_e$, due to the increase in the thermalization length with decreasing density for electrons diffusing down through the transition region. Under flare conditions, the non-Maxwellian rates are greatly enhanced by the steeper temperature gradient than is present in the quiet Sun (reflected by the high value of $T_e$), but this is offset to some extent by the increased electron pressure in the flare.

In Dufton et al. (1983), four line ratios were considered, namely $R_1 = I(1296 \AA)/I(1292 \AA)$, $R_2 = I(1301 \AA)/I(1313 \AA)$, $R_3 = I(1301 \AA)/I(1296 \AA)$ and $R_4 = I(1301 \AA)/I(1303 \AA)$. The $R_2$ ratio contains the $3s3p^1P-3s4s^1S$ transition at 1313 Å, and the upper state of this line is principally excited by electron impact from the $3s^2^1S$ ground state. As was noted earlier, the $3s^2^1S-3s4s^1S$ transition is the one significantly affected by non-Maxwellian EVDFs, and hence the $R_2$ ratio may be expected to show non-Maxwellian effects. In Figure 1 we therefore plot the $R_2$ ratio as a function of $\log N_e$ at a temperature of $\log T_e = 4.5$, with Maxwellian electron excitation rates employed in the calculations, as well as non-Maxwellian rates for $P_e = P_0$, $P_e/2$ and “flare” conditions summarized in Table 2. We note that non-Maxwellian effects on $R_1$, $R_3$, and $R_4$ are negligible, unless the temperature is very low, while for $\log T_e = 4.7$ even the non-Maxwellian rate for $3s^2^1S-3s4s^1S$ is close to the Maxwellian value (Table 1). For these cases the results in Dufton et al. (1983) for these diagnostics may be used. However it is clear from Figure 1 that at $\log T_e = 4.5$ the values of $R_2$ do depend on the EVDF and will hence lead to significantly different electron density estimates. For example, the $R_2$ value which corresponds to $\log N_e = 10.5$ with the Maxwellian curve corresponds to a density 1.5 times larger with the $P_e = P_0$ quiet Sun curve, while the Maxwellian value of $R_2$ for $\log N_e = 11.0$ implies an electron density approximately a factor of 10 greater when used with the flare curve.

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FIG. 1.—Theoretical values of the emission line ratio $R_2$ plotted as a function of electron density at $\log T_e = 4.5$. Curves are given for each set of effective collision strengths listed in Table 2 and discussed in § II, with solid line: Maxwellian atomic data; long dashed line: non-Maxwellian for $P_e = P_0$; dashed-dotted line: non-Maxwellian for $P_e = P_0/2$; short-dashed line: non-Maxwellian for flare conditions.

III. OBSERVATIONAL DATA

The HRTS experiment from the Naval Research Laboratory was flown aboard the Spacelab 2 mission from 1985 July 29 to August 6. HRTS consists of a 30 cm Gregorian telescope, a broadband spectroheliograph which was tuned to a wavelength region around 1550 Å, a slit spectrograph which covered a wavelength range from 1190 to 1680 Å with 0.05 Å spectral resolution, and an Ha system. Slit spectra were recorded by film exposures using Kodak type 101 emulsion.

The spectrograph slit was 920”, or approximately a solar radius, in length. In previous sounding rocket flights spatial resolutions of up to 0.8 along the slit had been achieved, but jitter in the Spacelab 2 pointing system typically limited resolution to 1”–2” in practice. The instrument and general results are described in Brueckner et al. (1986).

For this project we have used a 60 s spectrograph exposure from the first orbit of HRTS observations (1985 August 1 1400 UT). During the course of the Spacelab 2 mission the spectrograph progressively lost instrumental sensitivity below 1400 Å, and observations at 1300 Å were the most sensitively recorded during the orbit we have used. The slit pointing covered the largest sunspot present during the mission (in NOAA Active Region 4682), as well as some surrounding weak plage, and quiet solar regions. The 60 s exposure time is the longest exposure made of the sunspot during this orbit of optimal instrumental efficiency.
The spectrum was digitized and converted to relative intensities using a film characteristic curve constructed from exposures with differing exposure times from a somewhat later observing sequence during the same orbit (see Cook, Ewing, and Sutton [1988] for further discussion of the method employed). It was then put on an absolute intensity scale by comparison of intensities with those from a previous careful calibration of an earlier rocket flight of the HRTS instrument. The present calibration is less than ideal, but because all the spectral lines studied in this paper are within the range 1296–1313 Å, the ratios of line intensities reported are not very dependent on the instrumental absolute calibration. For lines this close together in wavelength we would estimate the errors as approximately 20% in the relative intensity of each line (from errors in the conversion to intensity using the film characteristic curve and from determining the integrated line intensity, but not including an estimate for the absolute intensity calibration error), and 30% for a line ratio.

We show in Figure 2a a section of the 60 s exposure after conversion to intensity and removal of geometric distortions to produce a flat field spectrum. The wavelength range from just below 1296 Å to just above 1313 Å is shown in two parts, with a spatial coverage along the slit of approximately 200". The slit covers an area of active region plage surrounding the sunspot, and quiet areas.

After the conversion from film density to absolute intensity, areas along the slit of 10", 10", and 5" were averaged to form representative active region, quiet region, and sunspot spectra.

**Fig. 2(a).—**HRTS spectrum in the 1300 Å wavelength region, showing the Si III lines 1296 Å, 1301 Å, 1303 Å, and 1313 Å and their variation along the spectrograph slit. The spatial coverage along the slit is approximately 200" and it covers quiet regions, a sunspot, and some weak plage regions. The areas used to determine average AR, QR, and SS spectra are marked. They are average intensities over 10", 10", and 5", respectively.

**Fig. 2(b).—**Logarithmic plots of the absolute intensities of the AR, QR, and SS average spectra. The spectra have been displaced so that the actual plots are of log (AR) + 1, log (QR), and log (SS) – 1. Line intensities used to calculate line ratios listed in Table 3 were determined from a numerical integration over each line profile, with the background level subtracted.
These areas are indicated on Figure 2a, while Figure 2b shows plots of log intensity versus wavelength of the three average feature spectra. Line intensities for Si \( \lambda \) 1296 Å, 1301 Å, 1303 Å, and 1313 Å were then determined for each of the average feature spectra by numerically integrating over the line profile, with the background intensity level subtracted.

The sunspot was small (less than 10" in diameter) and the surrounding active region area was not of great intensity. The electron density later estimated from the average active region spectrum is a little on the low side of typical previous determinations for rather brighter active regions (typically 5 times the average quiet Sun electron density; see Cook and Nicolas 1979). The sunspot and active region we have used is however the best available over the entire Spacelab 2 time period.

In Table 3 the values of the observed \( \text{Si} \( \lambda \) 1301 Å) divided by \( \iota \) (1313 Å), \( R_3 = l(1301 \text{ Å}) / l(1296 \text{ Å}) \), and \( R_4 = l(1301 \text{ Å}) / l(1303 \text{ Å}) \) for the average quiet region, active region, and sunspot spectra are tabulated. The ratio \( R_2/R_3 \) should have the constant value 0.81, the ratio of the \( A \)-values of the 1303 Å and 1296 Å transitions, because of their common upper level. In Table 3, we also show rescaled values for the \( R_3 \) and \( R_4 \) ratios. These are formed from the sum of the observed values of \( R_3 \) and \( R_4 \) by requiring that the rescaled \( R_2/R_3 = 0.81 \). There is no significant difference except for the active region, which gives an observed value \( R_2/R_3 = 1.1 \). We have used the rescaled values of \( R_3 \) and \( R_4 \) throughout since these should redistribute the errors in observed values of the individual ratios in a better way.

### IV. Discussion

In Table 4 the electron densities derived from the values listed in Table 3 of the ratios \( R_2 \), \( R_3 \), and \( R_4 \) for the quiet Sun, active region, and sunspot are summarized for values of log \( T_e = 4.5 \) and 4.7. Only one electron density is given for \( R_3 \) and \( R_4 \) as we have rescaled the observational data to ensure that \( R_4 = 0.81R_3 \) (see § III). An inspection of the table shows that there is reasonable agreement between the electron densities derived from \( R_3 \) and \( R_4 \) in the case of the quiet Sun, but that there is a significant discrepancy for the active region for log \( T_e = 4.5 \), although this is removed if log \( T_e = 4.7 \) is adopted. Recent ionization balance calculations favor log \( T_e = 4.5 \) as the temperature of maximum fractional abundance of Si \( \text{in} \) in ionization equilibrium (Arnaud and Rothenflug 1985), which is also supported by the Si \( \text{in} \) line ratio measurements in the quiet Sun, as for log \( T_e = 4.7 \) the observed values of this diagnostic lie below the theoretical low-density limit (Dufton et al. 1983). For the sunspot observations there is a large discrepancy between log \( N_e(R_3) \) and log \( N_e(R_3-R_4) \) whichever temperature is adopted. The electron densities estimated from \( R_3-R_4 \) in the quiet Sun and active region are in excellent agreement with those determined using other methods (Dufton et al.), although the value of \( N_e \) derived for the sunspot from \( R_3-R_4 \) (log \( N_e = 10.9 \)) is somewhat larger than those typically found for this type of solar feature, log \( N_e \approx 10.5 \) (Cheng, Doschek, and Feldman 1976; Cheng and Kjeldseth-Moe 1977; Gurman et al. 1982; Kingston et al. 1982; Doyle et al. 1985). However, the diagnostics available to these authors were somewhat limited, and in some cases their line ratios included resonance transitions (for example, Si \( \lambda \) 1206 Å), which may have optical depth problems (Doyle and McWhirter 1980; Dufton et al. 1983; Keenan and Kingston 1986). In the present case the 1296, 1301, and 1303 Å lines in the \( R_3 \) and \( R_4 \) ratios have been well determined (see Fig. 1), are optically thin (Keenan and Kingston 1986), and have been shown to give reliable results for laboratory plasmas, where the electron density has been independently measured (Yu, Finkenthal, and Moos 1986).

A possible explanation for the above discrepancies between log \( N_e(R_3) \) and log \( N_e(R_3-R_4) \) are non-Maxwellian contributions to the \( R_3 \) ratios. For the quiet Sun, the non-Maxwellian for \( P_x = P_y \) in Figure 1 would increase log \( N_e(R_3) \) from 10.2 to 10.4, placing it in better agreement with log \( N_e(R_3-R_4) \). For the active region and sunspot, it is difficult to estimate what the non-Maxwellian \( R_3 \) ratios should be, as no explicit calculations have been performed for these types of solar features. However it is worth pointing out that the flare non-Maxwellian graph in Figure 1 implies log \( N_e(R_2) = 11.2 \) for the active region, which is in reasonable agreement with the value of log \( N_e = 10.9 \) from \( R_3-R_4 \), and a non-Maxwellian EVDF for his solar feature may not be too far removed from that adopted for the flare. In addition, we note that any non-Maxwellian EVDF would need to increase the Maxwellian 3s2 1S–3s4 1S effective collision strength by factors of approximately 2.3 and 5.5 for the active region and sunspot respectively in order to remove the observed discrepancies between log \( N_e(R_3) \) and log \( N_e(R_3-R_4) \) at log \( T_e = 4.5 \). These factors have been calculated on the assumption that the EVDFs produce a negligible change on other collision rates. Inspection of Table 1 indicates that this assumption should be valid.

Another possible cause for the disagreement in the sunspot observations could be the presence of heating flows. These would have a similar effect as a non-Maxwellian as they would push \( \text{Si} \) ions into the upper part of the transition region where log \( T_e > 4.5 \), so that the 3s2 1S–3s4 1S collisional rate would become enhanced due to the increased number of high-energy electrons. Lites (1980) has found that transition region lines in many sunspots show upward motions of \( \sim 20 \text{ km s}^{-1} \), although Foukal (1976), Bruner et al. (1976), and Nicolas et al. (1982) have all observed large downflow velocities in sunspots, while Gurman and Athay (1983) have determined flow velocities ranging from 4.5 km s\(^{-1}\) upward to 7.2 km s\(^{-1}\) down-
ward. The HRTS sunspot spectrum in the present analysis does show a small, redshifted component with a downflow velocity of approximately 30–60 km s\(^{-1}\) (see Fig. 2 also). The main sunspot line also seems to have a general smaller blue-shift of the center of the profile, corresponding to approximately 5–20 km s\(^{-1}\) (see Kjeldseth-Moe et al. 1988). Our analysis refers to measurements of the main component of the line profile.

Estimates for the temperature gradient \(dT/dh\) in the quiet Sun for \(T_e \leq 10^5\) K are 0.04 K cm\(^{-1}\) (Raymond and Doyle 1981) and 0.07 K cm\(^{-1}\) (Dupree 1972), while for a sunspot it is believed to be smaller (\(0.014–0.03\) K cm\(^{-1}\); Doyle et al. 1985), although Lites and Skumanich (1982) have derived \(dT/dh = 0.2\) K cm\(^{-1}\) for this solar feature. However if the current discrepancies between theory and observation for the \(R_T\) ratios are due to the presence of non-Maxwellian EVDFs, the higher electron pressure in the sunspot compared to the quiet Sun (as reflected by the \(N_e\) measurements) implies that the temperature gradient in the former must be significantly larger, in order to produce a greater non-Maxwellian effect.

Finally, we note that observations of the \(3s3p^1P–3s4s^1S\) line in other Mg-sequence ions would be useful, in order that the possible existence of non-Maxwellian EVDFs in the solar transition region may be further investigated. Of particular interest would be the 2816.2 Å line of Al \(\alpha\) (Bashkin and Stoner 1975), as for this species any non-Maxwellian enhancement of collision rates will be larger than for Si \(\alpha\), due to the fact that the magnitude of these effects is inversely correlated with atomic number along an isoelectronic sequence (see, for example, Keenan [1984] for more details).

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REFERENCES

