A COMPARISON OF THEORETICAL Mg VI EMISSION LINE STRENGTHS WITH ACTIVE-REGION OBSERVATIONS FROM SERTS

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Abstract. R-matrix calculations of electron impact excitation rates in N-like Mg VI are used to derive theoretical electron-density-sensitive emission line ratios involving $2s^22p^3 - 2s2p^4$ transitions in the 269–403 Å wavelength range. A comparison of these with observations of a solar active region, obtained during the 1989 flight of the Solar EUV Rocket Telescope and Spectrograph (SERTS), reveals good agreement between theory and observation for the $2s^22p^3\ {}^4S - 2s2p^4\ {}^4P$ transitions at 399.28, 400.67, and 403.30 Å, and the $2s^22p^3\ {}^2P - 2s2p^4\ {}^2D$ lines at 387.77 and 387.97 Å. However, intensities for the other lines attributed to Mg VI in this spectrum by various authors do not match the present theoretical predictions. We argue that these discrepancies are not due to errors in the adopted atomic data, as previously suggested, but rather to observational uncertainties or misidentifications. Some of the features previously identified as Mg VI lines in the SERTS spectrum, such as 291.36 and 293.15 Å, are judged to be noise, while others (including 349.16 Å) appear to be blended.

1. Introduction

Emission lines arising from transitions in ions of the nitrogen isoelectronic sequence are frequently observed in the spectra of astrophysical sources, including the solar transition region and corona (see, for example, Thomas and Neupert, 1994, and references therein). The diagnostic potential of these emission lines was first noted by Aller, Ufford, and Van Vleck (1949), who suggested using optical line ratios in O II to determine electron densities in gaseous nebulae. Feldman *et al.* (1978) subsequently showed that N-like ions also provide very useful density diagnostics for solar plasmas.

Many authors have produced theoretical line ratios for N-like Mg VI applicable to solar spectra (see, for example, Dwivedi and Raju, 1988; Raju and Dwivedi, 1990), which have been calculated using electron impact excitation rates produced in the distorted-wave approximation (see Bhatia and Young, 1998; Keenan, 1996 and references therein). In this paper we present Mg VI line ratios determined with

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TABLE I

Mg VI transitions in the 1989 SERTS active-region spectrum.

Wavelength (Å)	Transition	Line intensity (erg cm^{-2} s^{-1} sr^{-1})	Line FWHM (mÅ)
269.04	$2s^2 2p^3\ ^2D_{3/2} - 2s2p^4\ ^2P_{1/2}$	40.1 ± 16.3	74 ± 16
270.40	$2s^2 2p^3\ ^2D_{3/2,5/2} - 2s2p^4\ ^2P_{3/2}$	66.0 ± 15.0	74 ± 3
291.36	$2s^2 2p^3\ ^2P_{1/2,3/2} - 2s2p^4\ ^2P_{1/2}$	–	–
293.15	$2s^2 2p^3\ ^2P_{1/2,3/2} - 2s2p^4\ ^2P_{3/2}$	–	–
314.56	$2s^2 2p^3\ ^2P_{1/2} - 2s2p^4\ ^2S_{1/2}$	–	–
314.67	$2s^2 2p^3\ ^2P_{3/2} - 2s2p^4\ ^2S_{1/2}$	–	–
314.59	Unidentified feature[a]	24.0 ± 3.4	80 ± 9
349.16	$2s^2 2p^3\ ^2D_{3/2,5/2} - 2s2p^4\ ^2D_{3/2,5/2}$	66.0 ± 8.3	175 ± 10
387.77	$2s^2 2p^3\ ^2P_{1/2} - 2s2p^4\ ^2D_{3/2}$	4.0 ± 2.0	60 ± 13
387.97	$2s^2 2p^3\ ^2P_{3/2} - 2s2p^4\ ^2D_{3/2,5/2}$	5.0 ± 2.4	90 ± 18
399.28	$2s^2 2p^3\ ^4S_{3/2} - 2s2p^4\ ^4P_{1/2}$	9.0 ± 0.9	80 ± 10
400.67	$2s^2 2p^3\ ^4S_{3/2} - 2s2p^4\ ^4P_{3/2}$	17.0 ± 2.0	100 ± 7
403.30	$2s^2 2p^3\ ^4S_{3/2} - 2s2p^4\ ^4P_{5/2}$	46.0 ± 5.2	130 ± 4

[a]See discussion in Section 4.

R-matrix electron excitation rates, and subsequently compare these with other recent theoretical results, and also with active-region observations obtained with the Solar EUV Rocket Telescope and Spectrograph (SERTS).

2. Observational Data

The solar spectrum analysed in the present paper is that of active region NOAA 5464, recorded on Eastman Kodak 101-07 emulsion by SERTS during a rocket flight on 5 May 1989 at 17:50 UT (Neupert *et al.*, 1992). The observations cover the wavelength regions 235.46–448.76 Å in first order and 170–224.38 Å in second order (the short wavelength cutoff in the latter being due to an absorption edge in the thin aluminium filter installed to reduce stray light), with a spatial resolution of about 7 arc sec (FWHM) and a spectral resolution of 50–80 mÅ (FWHM) in first order and ≤ 40 mÅ in second. The active region measurements used here were spatially averaged over the central 4.60 arc min of the spectrograph slit, and wavelength calibrated and converted to absolute intensities using procedures described by Thomas and Neupert (1994). A more recent re-evaluation of the absolute calibration scale for the 1989 SERTS observations increases all active region intensities by a factor of 1.24 over the values reported by Thomas and Neupert, and has been incorporated in the present work.

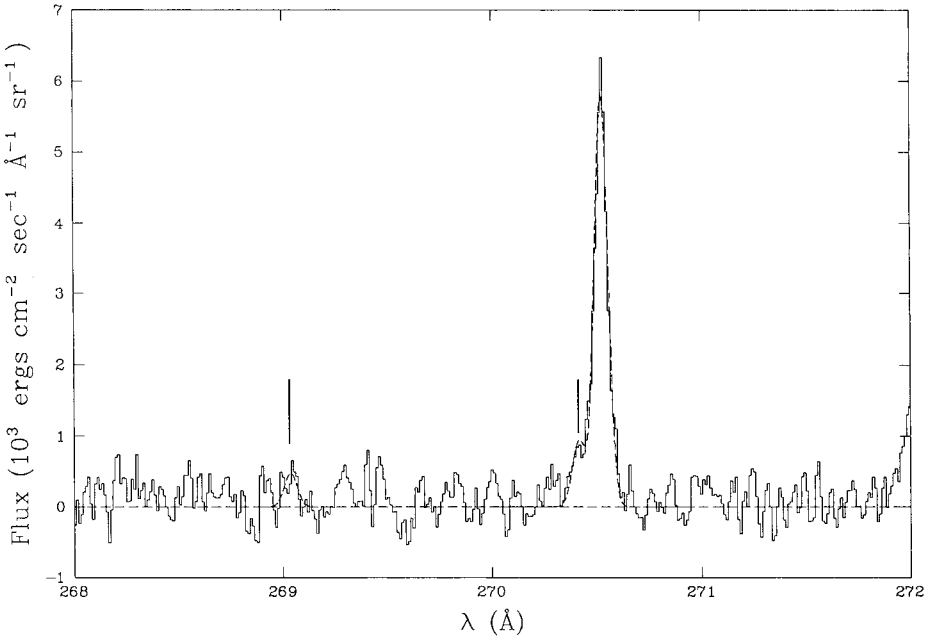

Figure 1. Portion of the 1989 SERTS active-region spectrum, where the Mg VI features at 269.04 and 270.40 Å are indicated by *solid lines*, and the profile fits by a *dashed line*. Also clearly visible in the figure is the Fe XIV 270.52 Å emission line.

We have searched for Mg VI emission lines in the SERTS spectrum, using the original line identifications by Thomas and Neupert (1994), as well as some additional identifications suggested by Dwivedi, Mohan, and Thomas (1998), or those made by Young, Landi, and Thomas (1998) based on predictions from the CHIANTI database (Dere *et al.*, 1997). In Table I we list the Mg VI transitions found in the active region spectrum by these authors, along with the measured wavelengths. Also given in the table are the intensities and line widths (FWHM) of these features, newly re-measured using the spectrum synthesis package DIPSO (Howarth, Murray, and Mills, 1994) by fitting gaussian profiles to the observations. Uncertainties in these measurements have been determined using methods discussed in detail by Thomas and Neupert. In Figures 1 to 6 we plot portions of the SERTS spectrum containing the Mg VI features, to show the quality of the observational data.

We note that the 1989 SERTS rocket flight also recorded the EUV spectrum of a small subflare, which has provided a rich source of emission lines for some species, such as Fe XII and Si X, useful for testing the accuracy of line ratio calculations (Keenan *et al.*, 1996, 2000a). Unfortunately, however, the Mg VI lines in the subflare spectrum are too weak to be reliably identified and measured.

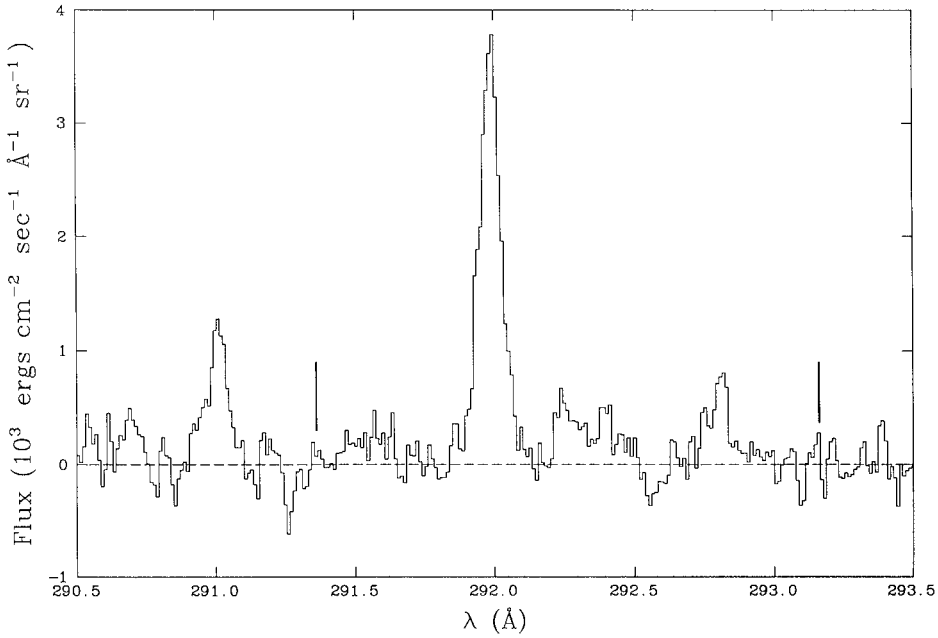

Figure 2. Portion of the 1989 SERTS active-region spectrum, where the expected positions of the Mg VI features at 291.36 and 293.15 Å are indicated by *solid lines*. Also clearly visible in the figure are the Fe XII 291.01 and Ni XVIII 291.99 Å emission lines.

3. Theoretical Line Ratios

The model ion for Mg VI consisted of the 12 energetically lowest LS states, namely $2s^22p^3\ ^4S$, ^2D and ^2P, $2s2p^4\ ^4P$, ^2D, ^2S and ^2P, $2p^5\ ^2P$ and $2s^22p^23s\ ^4P$, ^2P, ^2D and ^2S, making a total of 23 fine-structure levels. Energies for these levels were taken from Edlén (1984) and Martin *et al.* (1995). Test calculations including higher-lying states, such as $2s^22p^23p$, were found to have a negligible effect on the theoretical line ratios considered in the present paper.

Electron impact excitation rates for transitions among the Mg VI levels discussed above have been calculated by Ramsbottom and Bell (1997) using the R-matrix code as adapted for the Opacity Project (Berrington *et al.*, 1997; Seaton, 1987). These data, which include the effects of resonance structure on the collision strengths (in contrast to distorted-wave results), are probably the most accurate currently available, and have therefore been adopted in the present analysis.

Einstein A-coefficients for Mg VI were obtained from Bhatia and Young (1998), which is also the source of proton impact excitation rates for transitions among the $2s^22p^3$ levels. As discussed by, for example, Seaton (1964), proton excitation may be important for transitions with small excitation energies. However, Feldman *et al.* (1978) point out that inclusion of proton rates has a small effect on line ratio calculations for N-like ions.

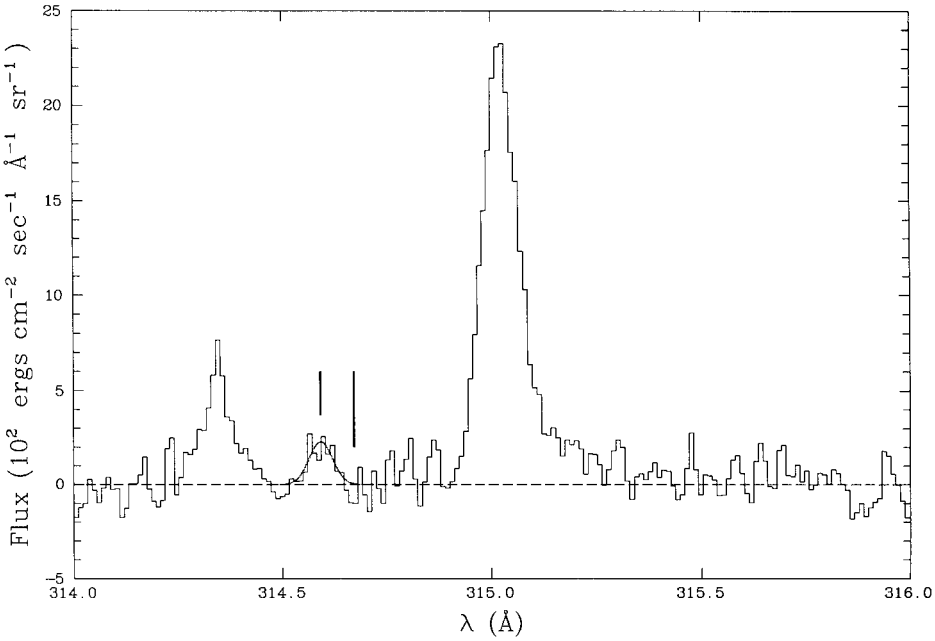

Figure 3. Portion of the 1989 SERTS active-region spectrum, where the expected position of the Mg VI 314.67 Å feature is indicated by a *solid line*. No Mg VI transition is present at the predicted wavelength of 314.56 Å. However, there is an unidentified feature at 314.59 Å, indicated by another *solid line*, with a profile fit shown by a *dashed line*. Also clearly visible in the figure are the Si VIII 314.35 and Mg VIII 315.02 Å emission lines.

Using the atomic data discussed above in conjunction with the statistical equilibrium code of Dufton (1977), relative Mg VI level populations and hence emission line strengths were calculated as a function of electron temperature (T_e) and density (N_e). Details of the procedures involved and approximations made may be found in Dufton (1977) and Dufton *et al.* (1978).

In Figures 7 and 8 we plot the theoretical emission line ratios

$$R_1 = I(269.04\ \text{Å})/I(399.28\ \text{Å}), \quad R_2 = I(270.40\ \text{Å})/I(399.28\ \text{Å}),$$

$$R_3 = I(314.56\ \text{Å})/I(399.28\ \text{Å}), \quad R_4 = I(349.16\ \text{Å})/I(399.28\ \text{Å}),$$

$$R_5 = I(387.77\ \text{Å})/I(399.28\ \text{Å}),$$

and

$$R_6 = I(387.97\ \text{Å})/I(399.28\ \text{Å})$$

as a function of electron density at the temperature of maximum Mg VI fractional abundance in ionization equilibrium, $T_e = 4 \times 10^5$ K (Mazzotta *et al.*, 1998), where the transitions corresponding to these wavelengths are listed in Table I. Given errors in the adopted atomic data of typically $\pm 10\%$ (see above references), we would expect the theoretical ratios to be accurate to better than $\pm 15\%$.

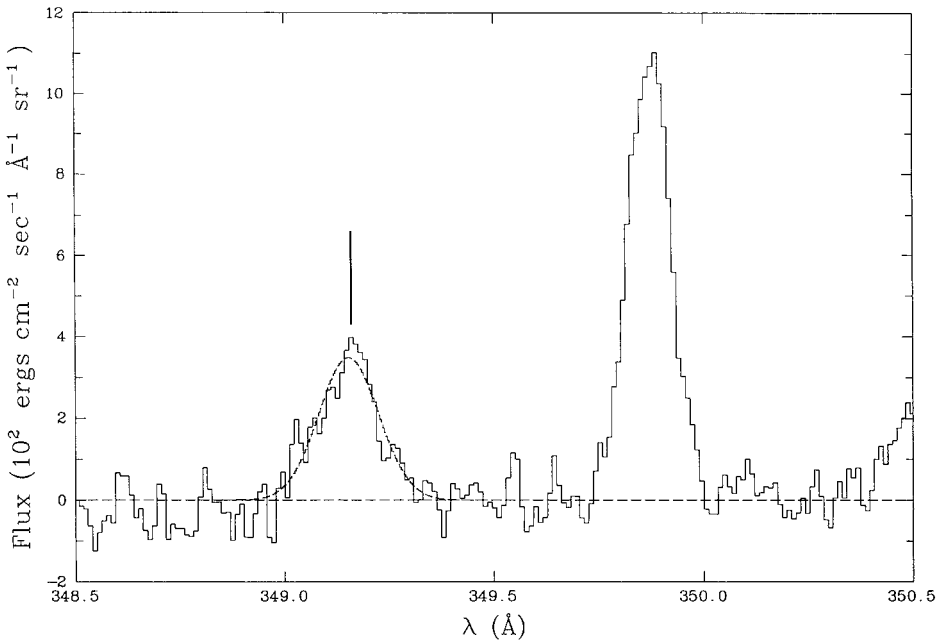

Figure 4. Portion of the 1989 SERTS active-region spectrum, where the Mg VI feature at 349.16 Å is indicated by a *solid line*, and the profile fit by a *dashed line*. Also clearly visible in the figure is the Si IX 349.87 Å emission line.

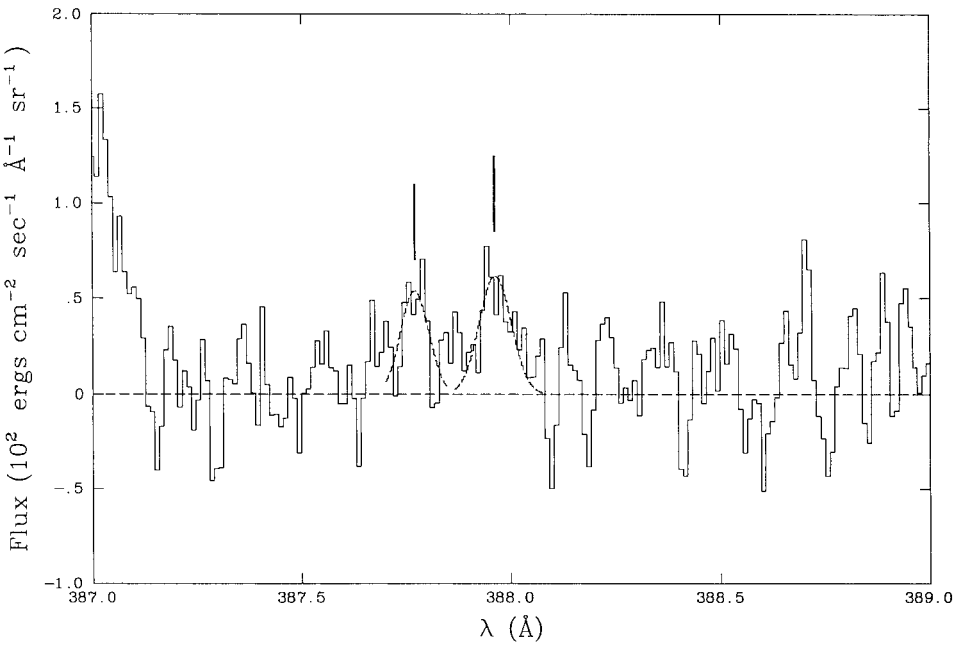

Figure 5. Portion of the 1989 SERTS active-region spectrum, where the Mg VI features at 387.77 and 387.97 Å are indicated by *solid lines*, and the profile fits by a *dashed line*.

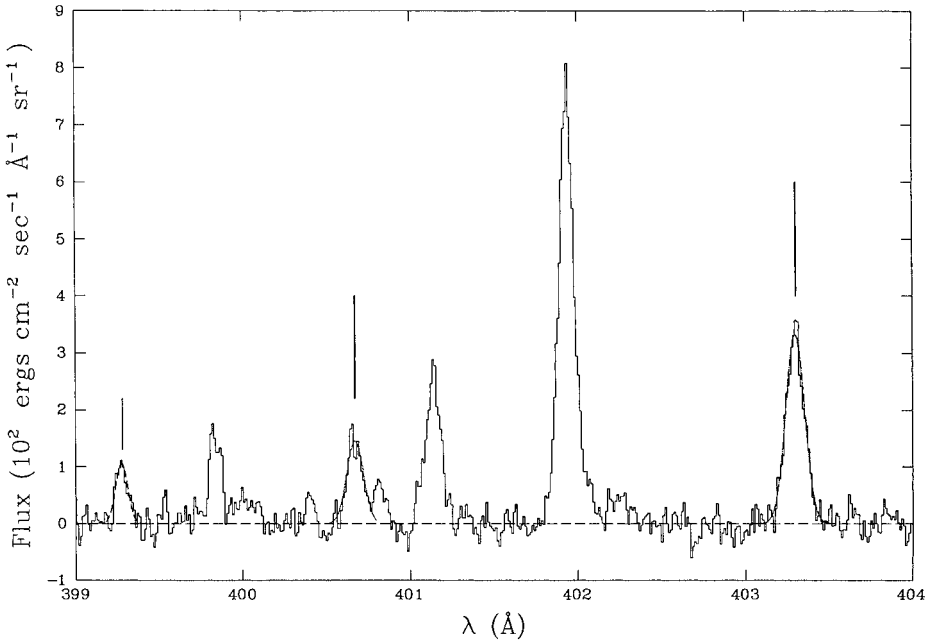

Figure 6. Portion of the 1989 SERTS active-region spectrum, where the Mg VI features at 399.28, 400.67, and 403.30 Å are indicated by *solid lines*, and the profile fits by a *dashed line*. Also clearly visible in the figure are the Ne VI 399.84, 401.14 and 401.94 Å emission lines.

The ratios in Figures 7 and 8 are given relative to the 399.28 Å transition, as this feature is the most reliably measured Mg VI emission line in the SERTS spectrum (see Figures 1–6). However, we note that theoretical results involving any line pair are available from one of the authors (*F.Keenan@qub.ac.uk*) on request.

An inspection of the figures reveals that R_1 through R_6 are sensitive to variations in the electron density, with for example R_1 varying by a factor of 2.9 between $N_e = 10^8$ and 10^{12} cm^{-3}, while R_3 changes by a factor of 36 over the same density interval. However we note that the ratios are relatively T_e-insensitive. For example, at $N_e = 10^8$ cm^{-3}, changing T_e from 4×10^5 K to 2.5×10^5 K (i.e., by a factor of 1.6) leads to a reduction in R_1 from 0.428 to 0.326, and R_2 from 0.877 to 0.662, corresponding to variations of $< 25\%$. Similarly, at $N_e = 10^{10}$ cm^{-3}, R_1 and R_2 change by $< 26\%$, while the other ratios vary by $<10\%$ over the $T_e = 2.5 \times 10^5$–4×10^5 K temperature interval. The N_e-sensitivity of the line ratios, combined with their relative insensitivity to changes in T_e, make them potentially useful density diagnostics for the Mg VI emitting region of a plasma.

Also shown in Figures 7 and 8 are the results of Bhatia and Young (1998), who presented theoretical ratios at $N_e = 10^8$, 10^{10} and 10^{12} cm^{-3}, determined using electron impact excitation rates calculated in the distorted-wave approximation. The present line ratios differ by up to 16% from those of Bhatia and Young, due

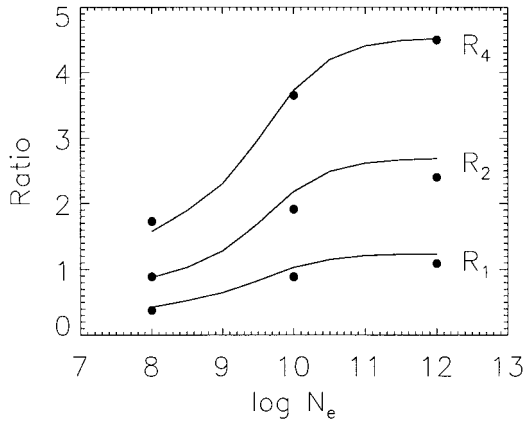

Figure 7. The theoretical Mg VI emission line ratios $R_1 = I(269.04\ \text{Å})/I(399.28\ \text{Å})$, $R_2 = I(270.40\ \text{Å})/I(399.28\ \text{Å})$, and $R_4 = I(349.16\ \text{Å})/I(399.28\ \text{Å})$, where I is in energy units, plotted as a function of logarithmic electron density (N_e in cm^{-3}) at the temperature of maximum Mg VI fractional abundance in ionization equilibrium, $T_e = 4 \times 10^5$ K (Mazzotta *et al.*, 1998). The present calculations are shown as *solid lines*, while the *filled circles* are the results of Bhatia and Young (1998).

to the adoption of the electron rates of Ramsbottom and Bell (1997) in the current work.

We note that the ratios

$$R_7 = I(291.36\ \text{Å})/I(399.28\ \text{Å}), \qquad R_8 = I(293.15\ \text{Å})/I(399.28\ \text{Å})$$

and

$$R_9 = I(314.67\ \text{Å})/I(399.28\ \text{Å})$$

have the same temperature and density dependence as R_1, R_2 and R_3, respectively, owing to common upper levels, but with

$$R_7 = 0.320 \times R_1,\ R_8 = 0.219 \times R_2, \quad \text{and} \quad R_9 = 1.77 \times R_3.$$

Similarly, the ratios

$$R_{10} = I(400.67\ \text{Å})/I(399.28\ \text{Å})$$

and

$$R_{11} = I(403.30\ \text{Å})/I(399.28\ \text{Å})$$

have common upper levels and so are independent of both T_e and N_e, with constant values of

$$R_{10} = 1.99, \quad \text{and} \quad R_{11} = 2.94.$$

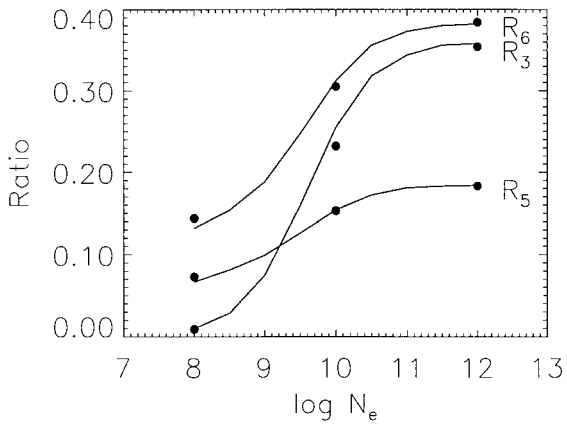

Figure 8. Same as Figure 7 except for $R_3 = I(314.56\ \text{Å})/I(399.28\ \text{Å})$, $R_5 = I(387.77\ \text{Å})/I(399.28\ \text{Å})$, and $R_6 = I(387.97\ \text{Å})/I(399.28\ \text{Å})$.

4. Results and Discussion

Dwivedi, Mohan, and Thomas (1998) reported marginal detections in the 1989 SERTS active-region spectrum for two features that matched predicted wavelengths of Mg VI transitions at 291.36 and 293.15 Å, but were not present in the original line list of Thomas and Neupert (1994), while Young, Landi, and Thomas (1998) give line intensities and widths for these features. However, our calculations show that theoretical intensities for these Mg VI transitions are more than an order of magnitude below the reported observational values, a result that even Dwivedi, Mohan, and Tomas gave in their Table II. Therefore, these features are unlikely to be due to Mg VI, and may simply be noise spikes (see Figure 2). This is supported by the fact that the line widths for both features are only ~37 mÅ. Thomas and Neupert note that the line widths in the SERTS spectrum have a normal distribution in the range ~ 70–140 mÅ, with some of the features with larger widths being unresolved blends, while those that are narrower may not be real. We also point out that although the $I(291.36\ \text{Å})/I(293.15\ \text{Å})$ intensity ratio measured by Young, Landi, and Thomas ($= 0.74 \pm 0.62$) is in good agreement with theory ($= 0.71$), the error bar on the experimental value is very large, so little weight can be attached to this result.

The CHIANTI database predicts that the Mg VI $2s^2 2p^3\ {}^2P_{1/2} - 2s2p^4\ {}^2S$ and $2s^2 2p^3\ {}^2P_{3/2} - 2s2p^4\ {}^2S$ lines should be at wavelengths of 314.56 and 314.67 Å, respectively. However as noted by Young, Landi, and Thomas (1998) and may be seen from Figure 3, there are no lines at these wavelengths, although there appears to be a feature at 314.59 Å. Dwivedi, Mohan, and Thomas (1998) identified this as the Mg VI 314.67 Å line, while Young, Landi, and Thomas suggest the possibility that it could be a blend of the $2s^2 2p^3\ {}^2P_{1/2} - 2s2p^4\ {}^2S$ and $2s^2 2p^3\ {}^2P_{3/2} - 2s2p^4\ {}^2S$ transitions. However, Young, Landi, and Thomas also note the wavelength separa-

TABLE II

Mg VI emission line ratios in the 1989 SERTS active-region spectrum.

Ratio designation	Observed ratio	Theoretical ratio[a]
$R_1 = I(269.04\ \text{Å})/I(399.28\ \text{Å})$	4.5 ± 1.9	1.0
$R_2 = I(270.40\ \text{Å})/I(399.28\ \text{Å})$	7.3 ± 1.8	2.2
$R_3 = I(314.56\ \text{Å})/I(399.28\ \text{Å})$	2.7 ± 0.5[b]	0.26
$R_9 = I(314.67\ \text{Å})/I(399.28\ \text{Å})$	2.7 ± 0.5[c]	0.46
$R_4 = I(349.16\ \text{Å})/I(399.28\ \text{Å})$	7.3 ± 1.2	3.7
$R_5 = I(387.77\ \text{Å})/I(399.28\ \text{Å})$	0.44 ± 0.23	0.15
$R_6 = I(387.97\ \text{Å})/I(399.28\ \text{Å})$	0.56 ± 0.27	0.31
$R_{10} = I(400.67\ \text{Å})/I(399.28\ \text{Å})$	1.9 ± 0.3	2.0
$R_{11} = I(403.30\ \text{Å})/I(399.28\ \text{Å})$	5.1 ± 0.8	2.9

[a]Determined from Figures 7 and 8 at $N_e = 10^{10}$ cm^{-3}.
[b]Observed line ratio on the assumption that the unidentified feature at 314.59 Å listed in Table I is the 314.56 Å transition.
[c]Observed line ratio on the assumption that the unidentified feature at 314.59 Å listed in Table I is the 314.67 Å transition.

tion of these two lines is constrained to be 0.11 Å from observations of other Mg VI features in the solar spectrum, which should be resolvable by SERTS. Additionally, we note that the line width of ~ 80 mÅ is consistent with a single transition, while a blended line would be expected to be broader. To investigate if the 314.59 Å line might be the $2s^2 2p^3\ {}^2P_{1/2} - 2s2p^4\ {}^2S$ or $2s^2 2p^3\ {}^2P_{3/2} - 2s2p^4\ {}^2S$ transition, below we analyse the feature for both of these possibilities.

In Table II we list observed Mg VI line ratios, where we have used the 399.28 Å feature as the reference transition as this is the most reliably detected Mg VI line in the SERTS spectrum (see Figures 1–6). Also listed in the table are the theoretical ratios from Figures 7 and 8 at an electron density of $N_e = 10^{10}$ cm^{-3}, derived from other species in the SERTS spectrum formed at electron temperatures similar to Mg VI (Young, Landi, and Thomas, 1998). However, we note that the discussion and conclusions presented below would not be affected if this adopted electron density were changed by even an order of magnitude.

An inspection of Table II reveals that many of the line ratios, with the exception of R_5, R_6 and R_{10}, are much greater than the theoretical predictions, even considering measurement uncertainties. However some of these discrepancies are clearly due to blending. Young, Landi, and Thomas (1998) note that the Mg VI 403.30 Å line is blended with Ne VI 403.30 Å, and have used an Ne VI branching ratio to estimate the Mg VI contribution as 27 erg cm^{-2} s^{-1} sr^{-1}. Adopting this value for the 403.30 Å line intensity gives us a revised value of $R_{11} = 3.0$, in excellent agreement with the theoretical result of 2.94.

The very large width of the 349.16 Å line ($\sim$ 175 mÅ) would appear to indicate blending, but this feature consists of four Mg VI transitions at wavelengths of 349.12, 349.14, 349.17, and 349.19 Å (Dere *et al.*, 1997). However, the line may be blended with other species, especially given its large width, with possible candidates including S IV 349.10 Å and O IV 349.21 Å (Kelly, 1987). We note that the CHIANTI database lists an Fe XXII transition at 349.26 Å, but this high-temperature ion is unlikely to be responsible for the blending, as the Mg VI feature is also detected in quiet-Sun observations (Brosius *et al.*, 1996).

In the case of the R_1 and R_2 ratios, we believe the discrepancies are due to the fact that the 269.04 and 270.40 Å lines are actually below the sensitivity limits of the 1989 SERTS measurements. An inspection of Figure 1 reveals that the feature identified as Mg VI 270.40 Å is only detected as a blip on the wing of the strong Fe XIV 270.52 Å line, and could be a noise spike. Similarly, the 269.04 Å line is at the noise level of the spectrum, and it is not evident that there is even an emission feature present at this wavelength. As with the 291.36 and 293.15 Å lines discussed above, the fact that the measured I(269.04 Å)/I(270.40 Å) intensity ratio ($= 0.61 \pm 0.28$) agrees with theory ($= 0.47$) is fortuitous, and no great weight should be attached to this.

A comparison of theory and observation for the R_3 and R_4 ratios indicate that the intensity of the 314.59 Å line is inconsistent with it being the $2s^2 2p^3\ {}^2P_{1/2} - 2s2p^4\ {}^2S$ or $2s^2 2p^3\ {}^2P_{3/2} - 2s2p^4\ {}^2S$ transition. Indeed, the feature is too strong to be a blend of the lines, already ruled out on wavelength separation and line width considerations (see above). The CHIANTI database reveals no suitable alternative identifications, although Kelly (1987) lists a possible Ca VII transition at 314.61 Å, and other Ca VII lines have been tentatively identified in the SERTS spectrum (Thomas and Neupert, 1994). In addition, Brosius *et al.* (2000) point out that the 314.59 Å feature may correspond to one of the highly uncertain He I wavelengths (314.6 Å) listed by Kelly (1987).

Analyses of the Mg VI lines in the SERTS spectrum by Bhatia and Young (1998) and Young, Landi, and Thomas (1998) led these authors to conclude that there are inaccuracies in the Mg VI atomic data. For example, they found good agreement between theory and observation for I(269.04 Å)/I(270.40 Å), but the ratio of these lines to the 349.16 Å feature then implied that the latter is too weak by 30–40%. On the other hand, a comparison between theory and experiment for I(349.16 Å)/I(400.67 Å) indicated that that the 349.16 Å line is too strong.

However, we believe the results presented here show that the discrepancies between theory and observation for Mg VI can be explained by errors in the observational data, with many of the lines previously identified in the SERTS spectrum being in fact noise features. For the few lines where intensities can be reliably measured or inferred, namely those in the ratios R_5, R_6, R_{10}, and R_{11}, agreement between theory and experiment is reasonably good. There is therefore no need to invoke inaccuracies in the atomic data, and hence no reason to believe that the line ratio calculations adopted here or by previous authors are in error.

Clearly, further observations of Mg VI in the solar spectrum would be highly desirable, to properly assess the reliability of the line ratio calculations in Figures 7 and 8, and hence the atomic data adopted in their derivation. Unfortunately, as noted by Bhatia and Young (1998), the Coronal Diagnostic Spectrometer on the Solar and Heliospheric Observatory cannot be used for such work, as the Mg VI lines lie primarily in spectral regions covered by the Grazing Incidence Spectrometer (GIS). The GIS spectra suffer from ghosting and other calibration problems, and as a result the weak Mg VI lines cannot be reliably measured (Landi *et al.*, 1999). However, another possibility would be to search for the lines in laboratory spectra, in particular those of magnetically-confined tokamak plasmas. The physical conditions in such plasmas are quite similar to those of the solar transition region and corona, and tokamak observations have frequently been employed to test astrophysical diagnostic calculations, and also to help in the identification of emission lines in solar spectra (see, for example, Keenan *et al.*, 1998, 2000b).

Acknowledgements

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