THEORETICAL Si IV LINE RATIOS COMPARED TO EXTREME ULTRAVIOLET SOLAR OBSERVATIONS

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Abstract. New theoretical electron temperature sensitive emission line ratios in Si IV involving the $3d\,^2D - 3p\,^2P$ and $4s\,^2S - 3p\,^2P$ multiplets at ~ 1125 and 816 Å, respectively, are derived using recent *R*-matrix electron excitation rate calculations. A comparison of these with observational data for a solar active region at the limb obtained with the Harvard S-055 spectrometer on board *Skylab* reveals that there is good agreement between theory and observation for ratios that include the $^2D_{3/2,\,5/2} - {}^2P_{3/2}$ transition at 1128.3 Å. This is in contrast to the findings of Keenan, Dufton, and Kingston (1986) and provides support for the atomic data adopted in the calculations. However, the $^2D_{3/2} - {}^2P_{1/2}$ line at 1122.5 Å appears to be severely blended, as suggested previously by Burton and Ridgeley (1970) and Feldman and Doschek (1977), as it leads to electron temperature estimates that differ significantly from that expected in ionisation equilibrium. The fact that the $I(1122.5\ \text{Å})/I(1128.3\ \text{Å})$ intensity ratios determined from several flare spectra are closer to theory than that for the active region indicates that the blending is probably due to species with relatively low ionization potentials, as noted by Flower and Nussbaumer (1975). Electron temperatures deduced for a sunspot are much lower than that predicted from ionisation balance calculations, in agreement with earlier results, and imply that a cooling flow may be present.

1. Introduction

In a recent paper Keenan, Dufton, and Kingston (1986) used electron excitation rates calculated with the *R*-matrix code (Burke and Robb, 1975) by Dufton and Kingston (1987) to derive the theoretical electron temperature sensitive emission line ratios

$$R_1 = I(3d\,^2D_{3/2,\,5/2} - 3p\,^2P_{3/2})/I(3p\,^2P_{1/2} - 3s\,^2S_{1/2})$$

and

$$R_2 = I(3d\,^2D_{3/2,\,5/2} - 3p\,^2P_{3/2})/I(3p\,^2P_{3/2} - 3s\,^2S_{1/2})$$

for the sodium-like ions Al III and Si IV . A comparison of the Al III results with high resolution (~ 0.06 Å) solar data obtained with the Naval Research Laboratory's S082-B spectrograph on board *Skylab* showed reasonable agreement between theory and observation (see also Doschek and Feldman, 1987), but a similar analysis for Si IV using low-resolution (~ 2 Å) EUV satellite spectra for the quiet Sun and an active region revealed that the calculations and observational data were incompatible. Keenan *et al.* (1984) came to the conclusion that blending of the $^2D_{3/2,\,5/2} - {}^2P_{3/2}$ transition at

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1128.3 Å with lines arising from ions with relatively low ionization potentials was probably responsible for this discrepancy.

In this paper we determine Si IV line strengths from somewhat higher resolution EUV spectrometer solar observations obtained with the Harvard instrument on board *Skylab*, and investigate if the disagreement between theory and observation found by Keenan *et al.* (1986) may be removed.

2. Theoretical Ratios

The atomic data adopted in the present calculations have been discussed by Keenan *et al.* (1986). Briefly, the model ion consisted of the four lowest LS states, namely $3s\ ^2S$,

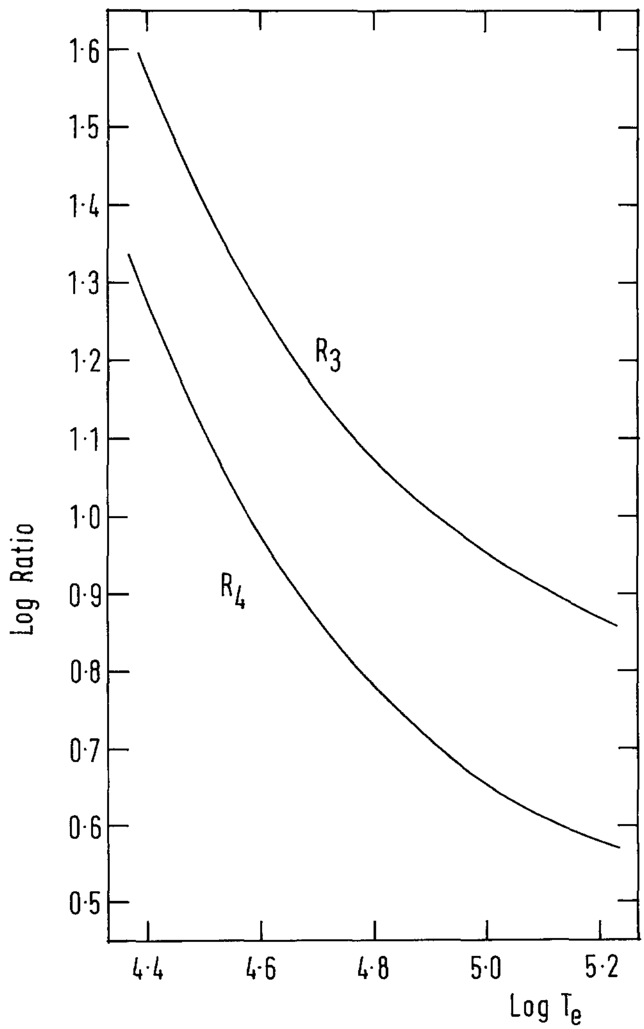

Fig. 1. The theoretical Si IV emission line ratios $R_3 = I(^2D_{3/2,5/2} - {}^2P_{3/2})/I(^2S_U - {}^2P_{1/2}) = I(1128.3\ \text{Å})/I(815.0\ \text{Å})$ and $R_4 = I(^2D_{3/2,5/2} - {}^2P_{3/2})/I(^2S_U - {}^2P_{3/2}) = I(1128.3\ \text{Å})/I(818.1\ \text{Å})$ plotted as a function of electron temperature.

$3p\,^2P$, $3d\,^2D$, and $4s\,^2S$, making a total of six levels when the fine structure splitting is included. (Henceforth, the two ^2S terms will be denoted by the subscripts L (for lower) and U (for upper), respectively, to avoid confusion.) The only atomic processes considered were collisional excitation and de-excitation by electrons and spontaneous radiative decay, and the plasma was assumed to be optically thin. Further details may be found in Keenan *et al.* (1986).

In Figure 1 the theoretical emission line ratios

$$R_3 = I(^2D_{3/2,\,5/2} - {}^2P_{3/2})/I(^2S_U - {}^2P_{1/2}) = I(1128.3\ \text{Å})/I(815.0\ \text{Å})$$

and

$$R_4 = I(^2D_{3/2,\,5/2} - {}^2P_{3/2})/I(^2S_U - {}^2P_{3/2}) = I(1128.3\ \text{Å})/I(818.1\ \text{Å})$$

are plotted as a function of electron temperature for a range of values of $\log T_e$ about that of maximum Si IV fractional abundance in ionisation equilibrium, $\log T_{\max} = 4.8$ (Arnaud and Rothenflug, 1985). We note that the ratios

$$R_5 = I(^2D_{3/2} - {}^2P_{1/2})/I(^2S_U - {}^2P_{1/2}) = I(1122.5\ \text{Å})/I(815.0\ \text{Å})$$

and

$$R_6 = I(^2D_{3/2} - {}^2P_{1/2})/I(^2S_U - {}^2P_{3/2}) = I(1122.5\ \text{Å})/I(818.1\ \text{Å})$$

are related to those in Figure 1 by the expressions:

$$R_5 = R_4\,, \qquad (1)$$

$$R_6/R_4 = 0.5\,. \qquad (2)$$

3. Observational Data

The $^2D - {}^2P$ and $^2S_U - {}^2P$ multiplets in Si IV have been observed in solar spectra obtained with the Harvard S-055 EUV spectrometer flown on *Skylab* during 1973–1974. This instrument could either operate in a raster mode or spectral scanning mode covering the wavelength range 280–1350 Å. Operating in the spectrometer mode, the instrument observed a spatial area of 5 × 5 arc sec with a spectral resolution of approximately 1.6 Å, 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 *et al.* (1977) and Reeves, Huber, and Timothy (1977).

In Table I we summarize Si IV line fluxes observed in several solar features. These include (a) the large two-ribbon flare of 7 September, 1973 (discussed by Doyle, 1983), (b) an active region at the limb observed on 16 December, 1973 (Doyle, Mason, and Vernazza, 1985), and (c) a sunspot plume near disc centre recorded on 29 August, 1973 (Noyes *et al.*, 1985). Due the strong Lyman continuum in the flare observations, no measurements of the $^2S_U - {}^2P$ multiplet at ~816 Å are available for these features. Only the $^2S_U - {}^2P_{3/2}$ component of this multiplet at 818.1 Å could be resolved in the sunspot and active region observations, as the $^2S_U - {}^2P_{1/2}$ line at 815.0 Å is severely blended

TABLE I

Observed Si IV line fluxes (erg cm^{-2} s^{-1})

Solar feature	I(1122.5 Å)	I(1128.3 Å)	I(818.1 Å)	$R = I$(1122.5 Å)/I(1128.3 Å)
7 September, 1973 Flare 12:55 UT	37110	53480	–	0.69
7 September, 1973 Flare 14:03 UT	18260	25060	–	0.73
7 September, 1973 Flare 15:52 UT	10995	15040	–	0.73
16 December, 1973 Active region	500	477	60	1.05
29 August, 1973 Sunspot	1760	2130	205	0.83

with the strong $3s^2 3p\ ^2P_{3/2} - 3s3p^2\ ^2S_{1/2}$ S IV line at 816.0 Å. Furthermore, we note that the $^2D_{3/2} - {}^2P_{1/2}$ line at 1122.5 Å is blended with the second order Ne VII $2s2p\ ^3P_1 - 2p^2\ ^3P_1$ and $2s2p\ ^3P_2 - 2p^2\ ^3P_2$ transitions at 561.4 and 561.7 Å, respectively. It was possible to remove the contribution of these lines to the blend in two ways, the first by using the intensity of the second order Ne VII $2s2p\ ^3P_2 - 2p^2\ ^3P_1$ line at 564.5 Å and the theoretical Ne VII intensity ratio calculations of Keenan *et al.* (1984). The second involved measuring the ratio of the Ne VII 561 Å complex to the Ne VI $2s^2 2p\ ^2P_{3/2} - 2s2p^2\ ^2D_{3/2,\,5/2}$ line at 562.8 Å in first order, which was then used in conjunction with the Ne VI line in second order to estimate the Ne VII contribution to the blend. Both these methods lead to essentially the same Si IV 1122.5 Å fluxes, thereby providing support for their use.

4. Results and Discussion

In Table II the observed Si IV line ratios are summarized along with the derived logarithmic electron temperatures. An inspection of the table reveals that the value of $\log T_e$ estimated for the active region from R_4 is close to the temperature of maximum

TABLE II

Observed Si IV line ratios and derived logarithmic electron temperatures

	Active region	Sunspot
R_4	8.0	10.4
R_6	8.3	8.6
$\log T_e$ (R_4)	4.64	4.56
$\log T_e$ (R_6)	4.43	4.42

Si IV fractional abundance in ionisation equilibrium, $\log T_{max} = 4.8$ (Arnaud and Rothenflug, 1985). This provides support for the atomic data adopted in the calculations and, furthermore, implies that the Si IV 1128.3 Å line is relatively unblended, in contrast to the findings of Keenan, Dufton, and Kingston (1986) who suggested blending to explain a discrepancy between theory and observation for the ratio $R_2 = I(1128.3\ \text{Å})/I(1393.8\ \text{Å})$. A more likely cause of this is an error in the 1393.8 Å line flux. We have already ruled out optical depth effects in the 1393.8 Å transition (see Keenan, Dufton, and Kingston, 1986, and also Roussel-Dupré, Francis, and Billings, 1979). However, the R_2 ratio analyzed by Keenan *et al.* was determined by Dupree and Reeves (1971) from a low resolution EUV spectrum covering the wavelength range 300–1400 Å, obtained by a spectrometer on board the Orbiting Astronomical Observatory (OSO) IV satellite. As the 1393.8 Å line occurred near the edge of the instrumental spectral coverage (see Figure 2(a) of Dupree and Reeves, 1971) it is possible that its intensity was not well determined.

The temperature deduced for the active region from R_6 in Table II is approximately 0.4 dex less than $\log T_{max}$. A probable cause of this disagreement is blending in the 1122.5 Å feature, as suggested previously by Flower and Nussbaumer (1975). To support this, we note that the theoretical ratio $R = I(1122.5\ \text{Å})/I(1128.3\ \text{Å})$ is 0.5, which is independent of electron temperature and density. However, an inspection of Table I shows that for the solar features analysed $R > 0.69$. The fact that the R ratios determined from flare spectra are closer to theory than that for the active region indicates that any blending is probably due to lines of species with relatively low ionization potentials. Both Burton and Ridgeley (1970) and Feldman and Doschek (1977) have noted that the 1122.5 Å line is blended with an unresolved Fe III transition only 0.04 Å away. The 1128.3 Å line will also be blended with Fe III transitions at 1128.0 Å and 1128.7 Å in low resolution spectra, although the high resolution (0.06 Å) *Skylab* observations of Feldman and Doschek show that the contribution of the Fe III lines to the total flux is small, at least in solar limb spectra, such as the present active region data. However, we should point out that this may not be true with disc observations, where the Fe III lines may be much stronger relative to Si IV.

In the case of the sunspot observations the electron temperatures derived from R_4 and R_6 are in slightly better agreement than those for the active region, although they are about a factor of two smaller than T_{max}. Noyes *et al.* (1985) note that for this sunspot the intensities of the lines formed near $\log T_e = 5.0$ are up to ~ 40 times larger than the average quiet-Sun values of Vernazza and Reeves (1978), although lines formed near $\log T_e = 4.3$ and 6.0 are only enhanced by a factor of two. Hence, the Fe III line in the 1122.5 Å blend should contribute a smaller amount to the total flux in this case as $\log T_{max}(\text{Fe III}) = 4.4$ (Arnaud and Rothenflug, 1985). Furthermore, Doyle *et al.* (1985) point out that temperature diagnostics for several other ions in this sunspot, such as S IV and O V, lead to values of T_e significantly lower than T_{max}, which probably indicates a cooling flow (Raymond and Foukal, 1982). The similar effect found here for Si IV is, therefore, not surprising.

5. Conclusions

The three principal conclusions are:

(1) The electron temperature derived from the $R_4 = I(1128.3\ \text{Å})/I(818.1\ \text{Å})$ ratio observed for a solar active region at the limb is in good agreement with ionisation balance calculations, providing support for the atomic data adopted in the analysis and, furthermore, implying that, at least for limb observations, the 1128.3 Å line is not significantly blended with other species, as suggested by Keenan *et al.* (1986).

(2) A discrepancy exists between theory and observation for the ratio $R_6 = I(1122.5\ \text{Å})/I(818.1\ \text{Å})$ in the active region, which is probably due to blending of the 1122.5 Å line. The fact that the blending in the active region data appears to be more severe than in the solar flare observations indicates that ions with relatively low ionization potentials are probably responsible, as previously suggested by Flower and Nussbaumer (1975). Burton and Ridgeley (1970) and Feldman and Doschek (1977) both note that the blending species is probably Fe III.

(3) In the case of the sunspot, slightly better agreement is found between electron temperatures deduced from R_4 and R_6, which is probably a result of the lines formed near $\log T_e = 5.0$ being enhanced, thereby making the contribution of Fe III ($\log T_{\max} = 4.4$) to the 1122.5 Å blend less important. The estimated electron temperature is about a factor of two smaller than $T_{\max}$, similar to the results derived using diagnostics for several other species in this sunspot, and indicates that a cooling flow is probably present.

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