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LETTER

Letter to the Editor

Electron temperature diagnostics for the quiet Sun using Si IV lines

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Abstract. We compare SUMER observations of six Si IV emission lines detected at the quiet Sun disk centre with recent theoretical line ratio calculations. Good agreement is found between theory and observation for ratios involving the 1394, 1403 and 818 Å line intensities. This agreement supports the theoretical prediction that the temperature where Si IV has its maximum ionisation fraction in ionisation equilibrium is $T_{\rm max} \simeq 10^{4.8}$ K, as well as showing that Lyman continuum absorption does not significantly effect line intensities for transitions with wavelengths below 912 Å. We find that the 815, 1122 and 1128 Å lines are blended by approximately 30, 55 and 45%, respectively, in the SUMER transitions.

Key words: atomic data – line: identification – Sun: transition region – Sun: UV radiation

1. Introduction

Emission line ratios of ions in the sodium isoelectronic sequence have been recognised as powerful electron temperature ($T_{\rm e}$) diagnostics for the solar atmosphere since the work of Flower & Nussbaumer (1975). This is because the difference in excitation energies of the lines needs to be large compared to the thermal energy of the exciting electrons. Unfortunately, this condition often means that the wavelength separation of two such diagnostic lines is large, which can lead to problems with instrumental calibration. Some ions however, produce these $T_{\rm e}$-sensitive emission lines relatively close together in wavelength. Si IV is one such species, and has ultraviolet emission lines grouped around ∼800, 1100 and 1400 Å. These emission lines, as well as being $T_{\rm e}$-sensitive, are insensitive to the electron density ($N_{\rm e}$), since the upper levels of the line transitions are not metastable. The theoretical temperature of maximum ionization fraction ($T_{\rm max}$) for Si IV is close to $10^{4.8}$ K, with Arnaud & Rothenflug (1985) and Mazzotta et al. (1998) predictions of $T_{\rm max}$=$10^{4.8}$ and $10^{4.85}$ K respectively. An observational benefit for Si IV is that this predicted formation temperature is close to the temperature of minimum emission measure in the solar atmosphere (Doschek et al. 1997). These considerations make Si IV emission lines potentially very useful $T_{\rm e}$-diagnostics.

Until recently, studies of Si IV line pairs have been confined to lines at wavelengths greater than 912 Å. This has been largely due to difficulties with the aluminium-coated mirrors used in instruments such as those on *Skylab* and the OSO IV satellite. The reflectance of these mirrors decreased rapidly below 912 Å which resulted in poor instrumental calibration, precluding accurate intensity measurements. Keenan et al. (1986) reported a large discrepancy between theory and low resolution (∼ 2 Å) OSO IV observations of the I(1128 Å)/I(1394 Å) ratio, and suggested a blend in the 1128 Å line due to ions of low ionization potential. Keenan & Doyle (1988) however pointed out that it was more likely that there was an error in the 1394 Å line flux, as it was near the edge of the instrumental spectral coverage, and hence its intensity may not have been well determined. They examined spectra of slightly higher resolution (∼1.6 Å) obtained using the Harvard S055 EUV spectrometer on board *Skylab*, and concluded that the 1128 Å line was relatively unblended (at least at the solar limb), whereas the 1122 Å line was probably blended with a low ionization potential Fe III transition, as previously suggested by Feldman & Doschek (1977).

The situation changed with the launch of the Solar and Heliospheric Observatory (SOHO) on December 2, 1995. The Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer on board SOHO is designed to obtain observations of the solar chromosphere, transition region and corona, and is ideal for measuring detailed spectroscopic line ratios between ∼800 and 1600 Å in first order. SUMER has an angular resolution of ∼1.0 arcsecond and a resolving power of $\lambda/\Delta\lambda$ = 17700–38300 at 800–1610 Å in first order (see Wilhelm et al. 1995 for a detailed description). Doschek et al. (1997) recently examined SUMER spectra containing some Si IV emission lines. They compared the I(1128 Å)/I(1403 Å) line ratio with the theoretical results of Keenan, Dufton & Kingston (1986) for the quiet Sun cell centre and network. They considered the Si IV 1394 Å line too strong to be placed on the most sensitive part of the detector, and ignored the Si IV 1122 Å line, since it had previously been identified as badly blended by other instruments. The Si IV lines around 800 Å were not considered.

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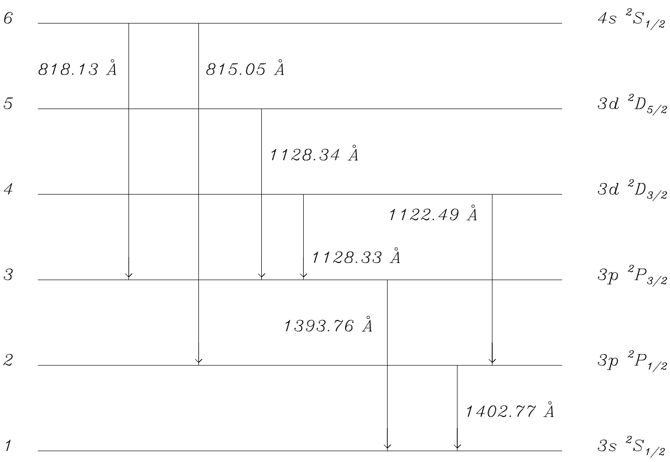

Fig. 1. Term diagram for Si IV showing the six energy levels and transitions considered in this paper. Each level is labelled with its electron configuration, and a reference number from 1 to 6.

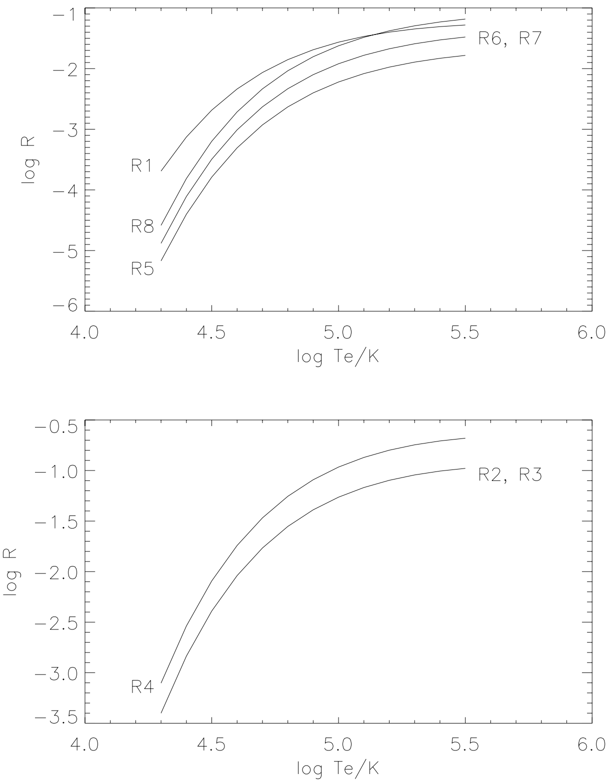

Fig. 2. Theoretical Si IV line intensity ratios R_1 to R_8, plotted as a function of electron temperature. We note that R_2 and R_6 are indistinguishable from R_3 and R_7 respectively, so only one ratio is plotted in each of these instances.

In this paper, we present SUMER observations of a quiet solar region covering six Si IV emission lines around ∼800, 1100 and 1400 Å, and compare eight T_e-sensitive diagnostic line ratios and three line ratios insensitive to changes in T_e and N_e with more recent level population calculations, and discuss line blending. We also investigate the hypothesis of Schmahl & Orral (1979), who suggest that Lyman continuum absorption may significantly decrease the intensities of solar emission lines at wavelengths below 912 Å.

2. Theoretical line ratios

The Si IV model ion used in this work consists of the four energetically lowest LS terms ($3s^2S$, $3p^2P$, $3d^2D$ and $4s^2S$), giving a total of six fine-structure levels. Energy levels were taken from Martin & Zalubas (1983), electron impact excitation rates from Dufton & Kingston (1994) and Einstein *A*–coefficients from Maniak et al. (1993). Level populations were calculated using the equilibrium code of Dufton (1977). Relative emission line strengths and resulting line ratios were calculated for electron temperatures ranging from $4.3 \leq \log T_e/K \leq 5.5$, in steps of 0.1 dex.

The Si IV transitions considered in this paper are illustrated in Fig. 1, and the emission line ratios we consider are as follows (using the reference numbers in Fig. 1): $R_1 = 4 \rightarrow 2/3 \rightarrow 1$, $R_2 = 4 \rightarrow 2/2 \rightarrow 1$, $R_3 = (4 \rightarrow 3, 5 \rightarrow 3)/3 \rightarrow 1$, $R_4 = (4 \rightarrow 3, 5 \rightarrow 3)/2 \rightarrow 1$, $R_5 = 6 \rightarrow 2/3 \rightarrow 1$, $R_6 = 6 \rightarrow 2/2 \rightarrow 1$, $R_7 = 6 \rightarrow 3/3 \rightarrow 1$, $R_8 = 6 \rightarrow 3/2 \rightarrow 1$, $R_9 = 2 \rightarrow 1/3 \rightarrow 1$, $R_{10} = 4 \rightarrow 2/(4 \rightarrow 3, 5 \rightarrow 3)$ and $R_{11} = 6 \rightarrow 2/6 \rightarrow 3$. R_1 to R_8 are T_e-sensitive, whereas R_9, R_{10} and R_{11} are independent of both T_e and N_e, and are all $\simeq 0.5$ under conditions applicable to the solar transition region. They are therefore very useful for identifying line blends. Fig. 2 contains two plots showing the T_e-sensitive line ratios R_1 to R_8. The large temperature sensitivity of the ratios is clear from the figures, with R_1 to R_4 increasing by a factor of ≈ 250 over the T_e range shown, and R_5 to R_8 changing by a factor of ≈ 2000 over the same T_e interval.

3. Observations

The Si IV observations were performed on April 22, 1996 on a quiet solar region. The 0.3 × 120 arcsecond slit (oriented North-South) was positioned at disk centre, and a raster of 39 by 120 arcseconds was performed, comprising 102 separate, 60-second exposures with a raster increment of 0.38 arcseconds East. Six spectral regions were obtained (each 2 Å wide), centred on the theoretical wavelengths of the Si IV emission lines; 815.05, 818.13, 1122.49, 1128.33, 1393.76 and 1402.77 Å. Standard SUMER software was used to correct for non–uniform detector sensitivity as well as wavelength and spatial distortions on the detector. Finally, the individual exposures for each spectral region were averaged to maximize the signal-to-noise ratios.

4. Results and discussion

Fig. 3 shows the averaged spectra for each wavelength region. We identified the Si IV lines using the SUMER line lists given in Curdt et al. (1997) and Feldman et al. (1997), and fitted the data using Gaussian profiles, and obtained the central wavelengths of the lines and the fluxes (with 1σ uncertainties) using the STARLINK DIPSO routine. Table 1 gives these observed values for

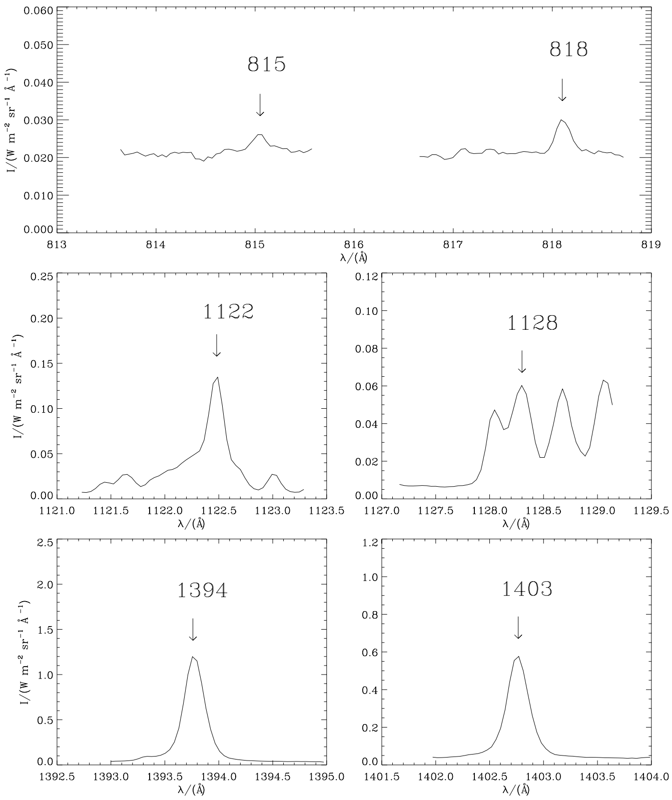

Fig. 3. Observed Si IV spectra, when intensities have been averaged over the full raster for each wavelength region. Arrows indicate the Si IV lines at 815.05, 818.13, 1122.49, 1128.33, 1393.76 and 1402.77 Å.

Table 1. Results of the Gaussian fits to the observed Si IV lines. The observed central wavelengths of the lines are given in the first column, each of which has an observed uncertainty of 0.01 Å by correlation with well-calibrated secondary standard reference spectra (Curdt 1999, in preparation). The line fluxes are given in the second column, with 1σ error bars imposed by the Gaussian fits.

Observed wavelength $\pm$ 0.01 (Å)	Line flux (mW m^{-2} sr^{-1})
1402.76	135.4 $\pm$ 2.2
1393.78	234.8 $\pm$ 5.7
1128.30	12.83 $\pm$ 0.35
1122.48	14.2 $\pm$ 0.7
818.11	1.44 $\pm$ 0.12
815.04	1.27 $\pm$ 0.35

each of the Si IV lines, as well as the derived line fluxes. By correlation with well-calibrated secondary standard reference spectra (Curdt 1999, in preparation), an uncertainty of 0.01 Å is assumed for the observed wavelengths. The 1σ uncertainties given for the line fluxes are from the Gaussian fits. The radiometric calibration is estimated to introduce a further 22% uncertainty in the ratios R_1 to R_8 and a further 5% in R_9 to R_{11} (Wilhelm et al. 1997). This estimate assumes that part of the systematic error cancels out in the ratios, leaving a 10% uncertainty at 800 Å and 1100 Å, and a 20% uncertainty at 1400 Å.

Table 2. Observed logarithmic line ratios R_1 to R_8 (with associated 1σ error bars) and derived values of $\log T_e$. The upper limits to R_1 and R_2 are larger than the temperature range covered by our line ratio calculations, so only lower limits of $\log T_e$ are given for these ratios.

Ratio	$\log$ Ratio	$\log T_e/K$
R_1	-1.22 $\pm$ 0.06	≥ 5.45
R_2	-0.98 $\pm$ 0.05	≥ 5.30
R_3	-1.26 $\pm$ 0.04	5.01 $\pm$ 0.05
R_4	-1.02 $\pm$ 0.03	4.96 $\pm$ 0.03
R_5	-2.27 $\pm$ 0.27	5.01 $\pm$ 0.18
R_6	-2.03 $\pm$ 0.27	4.97 $\pm$ 0.15
R_7	-2.21 $\pm$ 0.09	4.85 $\pm$ 0.03
R_8	-1.97 $\pm$ 0.08	4.84 $\pm$ 0.04

Table 3. The T_e- and N_e-insensitive ratios. The theoretical predictions for these ratios ($R_{\rm theo}$) are given in the second column, where the errors represent the small changes in these ratios over the T_e and N_e range of the solar transition region. The observed ratio values ($R_{\rm obs}$) are given with 1σ error bars.

Ratio	$R_{\rm theo}$	$R_{\rm obs}$
R_9	0.505 (8)	0.58 $\pm$ 0.02
R_{10}	0.5036 (2)	1.11 $\pm$ 0.06
R_{11}	0.5057 (1)	0.88 $\pm$ 0.25

The observed wavelengths in Table 1 agree with the theoretical predictions to within ~0.1 Å. The 818 and 1403 Å lines were well-defined and well-represented by single Gaussian fits. A faint Ni II line present in the blue wing of the 1394 Å line was separated using multi-Gaussian fits. The 1128 Å Si IV line lies on the red wing of the Fe III $3d^6\ ^5D_3 - 3d^5(a^6S)4p\ ^5P_3$ transition at 1127.75 Å, and on the blue wing of the $3d^6\ ^5D_2 - 3d^5(a^6S)4p\ ^5P_2$ Fe III transition at 1128.39 Å. We were able to obtain reasonable fits to these three lines, and saw no obvious evidence for resolvable blending in the residuals.

The 1122Å line lies within a C I multiplet between ~1121.91 and 1123.09 Å (Curdt 1999). The Si IV line is blended with C I and Fe III transitions at ~1122.52 Å, which could not be resolved. Multi-Gaussian fits were used to fit the lines, and we saw no evidence of further resolvable blending. Finally, a reasonable Gaussian fit was obtained to the 815 Å line, despite its weakness in our spectra.

Using the line fluxes in Table 1, observed values of the T_e-sensitive ratios R_1 to R_8 were derived, which are summarised in Table 2, along with the electron temperatures derived from Fig. 2. In Table 3 we list the observed values of the line ratios R_9, R_{10} and R_{11}, which are insensitive to both T_e and N_e.

It can be seen from Table 3 that the observed value of R_9 is in good agreement with the theoretical prediction. The theoretical value falls within 3σ of the observed value, which corresponds to an error of only 8% in the ratio. One can also see that pairs of ratios with the same line as the numerator, and the 1394 and

1403 Å lines as the denominators, produce very similar values of T_e. It thus seems highly probable that the 1394 and 1403 Å lines are unblended, at least at the level of a few percent.

The observed R_{11} ratio is 70% greater than the theoretical value, implying that the 815 Å line is blended by approximately 40%, although this figure could be as low as 20% to within the uncertainty. The R_7 and R_8 ratios produce values of T_e in good agreement with the theoretical predictions for the temperature of maximum ionization fraction, $T_e \simeq 10^{4.8}$ K, and it therefore seems very likely that the 818 Å line is unblended to within its uncertainty (∼10% level).

The upper limits to the $\log T_e$ values given by R_5 and R_6 are higher than theory predicts. A blending of about 30% in the 815 Å line intensity (in agreement with that found from R_{11}) would decrease the derived value of $\log T_e$ by approximately 0.2 dex, bringing it into good agreement with the temperature found from R_7 and R_8.

The observed R_{10} ratio is too high, suggesting that the 1122 Å line is blended by approximately 55%. The values of R_1 and R_2 are also higher than theory suggests they should be. Correspondingly, the electron temperatures derived from R_1 and R_2 are much larger than expected, with a lower limit of $\log T_e \geq 5.3$ compared to $\log T_{\max} = 4.8$. This agrees with the observations of Keenan & Doyle (1988) and Feldman & Doschek (1977).

The R_3 and R_4 ratios give values of T_e that are somewhat high. Adopting $\log T_e = \log T_{\max} = 4.8$, this suggests that the 1128 Å line is blended by approximately 45%. This may be due to the presence of cold lines, which could not be ruled out as a source of blending by Doschek et al. (1997), who observed that their values of R_4 consistently gave slightly high values of $\log T_e$.

Schmahl & Orral (1979) have argued that there is significant absorption in the Lyman continuum for $\log T_e < 5.8$ and derive a minimum neutral hydrogen column density of 3×10^{17} atoms cm^{-2}. If such a column density was applicable to the quiet Sun, the ratios $R_5 - R_8$ corrected for the hydrogen absorption would indicate temperatures of $\log T_e$ = 5.1–5.2. The agreement between the R_7 and R_8 ratios (which involve the 818 Å line) and the theoretical predictions for the temperature of maximum ionization fraction seems to rule out their hypothesis that Lyman absorption has a significant effect on line intensities at wavelengths below 912 Å.

The above results provide observational support for the accuracy of the Si IV diagnostic calculations used in this work. We have included, for the first time, analysis of the Si IV emission lines around 800 Å. Ratios involving the 1394, 1403 and 818 Å Si IV lines are found to give good agreement with theoretical predictions for the temperature of the Si IV emitting region of the quiet solar plasma, and are recommended for use as T_e-diagnostics at instrumental wavelength resolutions of 0.04 Å or smaller. The 1122, 1128 and 815 Å lines are considered to be blended, and their use should be treated with caution.

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