SOLAR TRANSITION REGION LINES OBSERVED BY THE INTERFACE REGION IMAGING SPECTROGRAPH: DIAGNOSTICS FOR THE O IV AND SI IV LINES

J. Dudík1,4,5, G. Del Zanna1, E. Dzifčáková2, H. E. Mason1, and L. Golub3

1 DAMTP, CMS, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK; J.Dudik@damtp.cam.ac.uk
2 Astronomical Institute of the Academy of Sciences of the Czech Republic, Fricova 298, 251 65 Ondrejev, Czech Republic
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

The formation of the transition region O IV and Si IV lines observable by the Interface Region Imaging Spectrograph (IRIS) is investigated for both Maxwellian and non-Maxwellian conditions characterized by a $\kappa$-distribution exhibiting a high-energy tail. The Si IV lines are formed at lower temperatures than the O IV lines for all $\kappa$. In non-Maxwellian situations with lower $\kappa$, the contribution functions are shifted to lower temperatures. Combined with the slope of the differential emission measure, it is possible for the Si IV lines to be formed at very different regions of the solar transition region than the O IV lines; possibly close to the solar chromosphere. Such situations might be discernible by IRIS. It is found that photoexcitation can be important for the Si IV lines, but is negligible for the O IV lines. The usefulness of the O IV ratios for density diagnostics independently of $\kappa$ is investigated and it is found that the O IV 1404.78 Å/1399.77 Å ratio provides a good density diagnostics except for very low $T$ combined with extreme non-Maxwellian situations.

Key words: atomic data – atomic processes – radiation mechanisms: non-thermal – Sun: transition region – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

The solar transition region (TR), is the plasma region with temperatures between chromospheric and coronal temperatures. While the TR emission can originate in closed magnetic loops that do not reach the corona, there are large regions of the strong magnetic field, such as plages, where the field lines can be “open” and reach into the corona. Such regions will be characterized by strong gradients of temperature and density. Under these conditions, the distribution of electron energies can depart from the Maxwellian distribution and become non-Maxwellian (e.g., Roussel-Dupre 1980; Shoub 1983; Ljepojevic & MacNiece 1988). Some indication of the presence of non-Maxwellian distributions was found from Si III TR spectra (Dufton et al. 1984; Keenan et al. 1989; Pinfield et al. 1999), while other authors (e.g., Doschek 1997) did not find any evidence.

Dzifčáková & Kulinová (2011) used the Solar and Heliospheric Observatory Solar Ultraviolet Measurement of Emitted Radiation (SOHO/SUMER) Si III line intensities reported by Pinfield et al. (1999) and performed diagnostics of temperature and density. It was found that different ratios do not yield consistent results if a Maxwellian distribution is assumed. Large discrepancies between theory and observations were found for active region (AR) spectra. The authors also performed diagnostics under the assumption of $\kappa$-distributions (e.g., Vasylunas 1968; Owocki & Scudder 1983; Livadiotis & McComas 2009). Consistency in terms of temperature and density was found only if the additional effect of photoexcitation by photospheric radiation was included. The authors diagnosed $\kappa = 7$ for the AR spectra and $\kappa = 10–11$ for the quiet-Sun (QS), meaning that the AR TR is more non-Maxwellian than the QS. Furthermore, these diagnostics were also shown to be valid for multithermal plasma characterized by a differential emission measure (DEM).

The Interface Region Imaging Spectrograph (IRIS) is a new, powerful instrument dedicated to observations of the solar chromosphere and TR. Its second far-ultraviolet (FUV) channel (1390–1406 Å) contains several lines belonging to Si IV, O IV, and S IV (Table 1). We note that while direct diagnostics of the electron distribution function are not expected because of the similarity of the transitions observed and wavelength constraints of the instrument, the non-Maxwellian distributions can still have large effects on the formation of these lines. In this Letter, we investigate the formation of the TR lines under non-Maxwellian conditions characterized by $\kappa$-distributions. We also investigate the effects of photoexcitation on line formation and the possible influence of non-Maxwellian effects on the density diagnostics known for the Maxwellian distribution (e.g., Doschek 1984). Finally, we are not concerned in this Letter with the formation of lines belonging to low ionization stages, such as O II, C I, or others, since these may be heavily influenced by opacity effects in dense plasmas. We also note that the response of the IRIS TR lines to non-equilibrium ionization already has been investigated by Doyle et al. (2013) and Olluri et al. (2013).

2. METHODS

The $\kappa$-distributions are defined as a two-parametric distribution with parameters $T$ and $\kappa$ (e.g., Owocki & Scudder 1983; Livadiotis & McComas 2009)

$$f_\kappa(E)dE = A_\kappa \frac{2}{\pi^{1/2}(k_B T)^{3/2}} \frac{E^{1/2}dE}{(1 + \frac{E}{\kappa - 1.5k_B T})^{\kappa + 1}},$$  \hspace{1cm} (1)
and exhibits a high-energy power law tail and a near-Maxwellian distribution has an increased number of both low-energy and high-energy electrons compared to the Maxwellian distribution.

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Table 1

| Ion   | Transition | Levels |
|-------|------------|--------|
| Si IV | 1393.76    | 3s^2S_{1/2} - 3p^2P_{3/2} | 1-3 |
| Si IV | 1402.77    | 3s^2S_{1/2} - 3p^2P_{3/2} | 1-2 |
| O IV  | 1397.20    | 2s^2p^2P_{1/2} - 2s2p^2P_{3/2} | 1-4 |
| O IV  | 1399.77    | 2s^2p^2P_{1/2} - 2s2p^2P_{3/2} | 1-3 |
| O IV  | 1401.16    | 2s^2p^2P_{1/2} - 2s2p^2P_{3/2} | 2-5 |
| O IV  | 1404.78    | 2s2p^2P_{1/2} - 3s3p^2P_{3/2} | 2-4 |
| S IV  | 1398.04    | 3s^2p^2P_{1/2} - 3s3p^2P_{3/2} | 1-4 |
| S IV  | 1404.81    | 3s^2p^2P_{1/2} - 3s3p^2P_{3/2} | 1-3 |
| S IV  | 1406.02    | 3s^2p^2P_{1/2} - 3s3p^2P_{3/2} | 2-5 |

where $k_B = 1.38 \times 10^{-16}$ erg cm$^{-1}$ is the Boltzmann constant and $A_\kappa = \Gamma(\kappa + 1)/[\Gamma(\kappa - 0.5)(\kappa - 1.5)\Gamma(3/2)]$ is the normalization constant. We note that $\kappa \in (3/2, +\infty)$ and $T$ is defined in terms of mean energy $\langle \hat{E} \rangle$ as $T = 2\langle \hat{E} \rangle / 3k_B$. The Maxwellian distribution is recovered for $\kappa \rightarrow +\infty$. For finite $\kappa$, the distribution has an increased number of both low-energy and high-energy electrons compared to the Maxwellian distribution and exhibits a high-energy power law tail and a near-Maxwellian core with temperature $T_{\text{core}} = T(\kappa - 3/2)/\kappa$ (Oka et al. 2013). The differences with respect to the Maxwellian distribution increase with decreasing $\kappa$ (see, e.g., Figure 1 in Dzifčáková & Dudík 2013).

The intensity $I_{ji}$ of an optically thin emission line with a wavelength $\lambda_{ji}$ can be written as (see, Phillips et al. 2008)

$$I_{ji} = \int G_{ji}(T, n_e, \kappa) A_\lambda n_e^2 \psi dl$$

$$= \int G_{ji}(T, n_e, \kappa) A_\lambda \text{DEM}(T) dT,$$

where $n_e$ is the electron density, $A_\lambda$ is the relative abundance, and DEM$(T)$ is the differential emission measure along the line of sight $l$, defined as DEM$(T) = n_e^2 \psi dl / dT$. $G_{ji}(T, n_e, \kappa)$ is the line contribution function, which can be expressed as

$$G_{ji}(T, n_e, \kappa) = \frac{hc}{\lambda_{ji}} A_{ji} \frac{N_{X,i}^k n_{X,i}^k}{N_{X,i}^k n_{X,i}^k n_H},$$

where $hc / \lambda_{ji}$ is the photon energy, $A_{ji}$ is the Einstein coefficient for spontaneous emission, $n_H$ is the hydrogen density, $n_{X,i}^k / n_X$ is the relative abundance of the ion $k$, and $N_{X,i}^k / N_X^k$ is the fraction of the ion $k$ with the electron in the excited upper level $i$. $G_{ji}(T, n_e, \kappa)$ is a function of $\kappa$ because of the changes in both ionization equilibrium with $\kappa$ (Dzifčáková & Dudík 2013) and excitation rates (e.g., Dzifčáková 2006; Dzifčáková & Dudík 2008). The relative ion abundances, obtained from Dzifčáková & Dudík (2013), are shown in Figure 1, top.

We calculated the distribution-averaged collision strengths $\gamma_{ji}(T, \kappa)$ by integration of the collision strengths $\Omega_{ji}$ (non-dimensionalized excitation/de-excitation cross-sections) over the distribution function (Seaton 1953)

$$\gamma_{ji}(T, \kappa) = \frac{\sqrt{\pi}}{2} \exp \left( \frac{hc}{\lambda_{ji} k_B T} \right) \times \int_0^\infty \Omega_{ji}(E) \left( \frac{E}{k_B T} \right)^{-1/2} f_{\kappa}(E) dE.$$

The $\Omega_{ji}$ used here were calculated within the APAP network by Liang et al. (2009) and Liang et al. (2012) for Si IV and O IV, respectively. These represent state-of-art atomic data and will be implemented in the upcoming CHIANTI version 8. The numerical integration of the collision strengths for these ions was performed using a method similar to Bryans (2006). We compared the $\gamma_{ji}(T, \kappa)$ obtained, shown in Figure 1 (bottom), with the ones calculated by the approximative method of Dzifčáková & Mason (2008). Excellent agreement within a few per cent was found. For comparison, previous atomic data calculations of Sampson et al. (1990), Martin et al. (1995), and Aggarwal & Keenan (2008), available within CHIANTI version 7.1 (Dere et al. 1997; Landi et al. 2013), are also plotted in Figure 1, bottom. The differences for the O IV 1401.16 Å line are up to 12% and for the Si IV 1402.77 Å line up to 26%.

Our $G_{ji}(T, n_e, \kappa)$ for O IV and Si IV using $\gamma_{ji}(T, \kappa)$ from the original collision strengths are subsequently calculated using our own modification of the CHIANTI version 7.1 software. For Si IV, we utilize the atomic data of Kelleher et al. (1999), Tayal (2000), and Hibbert et al. (2002) available within CHIANTI version 7.1 and the method of Dzifčáková & Mason (2008), since no collision strength data are available. The abundances are taken from Asplund et al. (2009), i.e., are assumed to be photospheric. We also assume a contribution from photoexcitation by a Sun-like black-body, characterized by $T_{\text{eff}} = 6000$ K and $R / R_{\odot} = 1$.

3. RESULTS

3.1. Contribution Functions for $\kappa$-distributions

The $G_{ji}(T, n_e, \kappa)$ of O IV 1401.16 Å and Si IV 1402.77 Å are shown in Figure 2, top. We chose these two lines since they are close in wavelength and belong to the strongest TR lines observed by IRIS. The contribution functions are calculated either under the assumption of constant pressure $P_c = 3 \times 10^{15}$ K cm$^{-3}$, or constant density of log$(n_e/cm^{-3}) = 10$. The first assumption is appropriate for a locally “open” magnetic structure, such as a TR portion of a coronal loop footpoint, while the second one is necessary for investigating the density sensitivity (Section 3.3). Note that the same value of $P_c$ was used to derive the DEM files within CHIANTI (Dere et al. 1997).

With decreasing $\kappa$, i.e., increasing departure from the Maxwellian distribution, the contribution functions for both lines become broader in temperature and their maxima move toward lower $T$. This is caused chiefly by the changes in the relative ion abundances (Figure 1, top). However, temperatures corresponding to the $G(T, n_e, \kappa)$ peak are not as low as the temperatures at which the O IV and Si IV ions have maximum abundance. This is caused by the level population, which increases with $T$ in the temperature interval where the ion is formed. For log$(n_e/cm^{-3}) = 10$, the O IV 1401.16 Å line has peak formation temperature at log($T/K$) $\approx 5.15$ for the Maxwellian distribution and at $\approx 4.8$ for $k = 2$. For Si IV, these values are $\approx 4.9$ and $4.3$, respectively. We note that the peak formation temperature for the Maxwellian distribution is significantly higher than the one given by Doyle et al. (2013, Figure 1 therein). The peak temperatures obtained here for both the Si IV and O IV are largely independent of $n_e$. However, the contribution function does change with $n_e$ (Section 3.3). For this reason, the peak temperatures are located at slightly higher $T$ if constant pressure is assumed (Figure 2, top).

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We investigated the O\textsc{iv} line ratios for possible diagnostics of $\kappa$. Since the lines are formed from similar energy levels (Table 1), ratios of these lines do not allow for simultaneous diagnostics of $T$ and $\kappa$. Lines with wavelengths shorter or longer by several tens or hundreds of Å would be required for direct diagnostics of $\kappa$ (see Dzičáková & Kulinová 2011; Mackovjak et al. 2013). In particular, combination of the IRIS O\textsc{iv} lines with those observed by SOHO/SUMER can lead to diagnostics of $\kappa$. We recommend using, e.g., the 554.51 Å, 787.71 Å, and 790.20 Å lines. As an example, the 1401.16 Å/787.71 Å ratio in combination with the 790.20 Å/1399.77 Å ratio could lead to diagnostics of $T$ and $\kappa$, if $n_e$ is known. Note that combinations with the Hinode/EIS O\textsc{iv} lines (e.g., 279.93 Å) could lead to very sensitive diagnostics, but these lines are weak even in long exposures (Brown et al. 2008). However, calibration and cross-calibration uncertainties limit the usefulness of the line ratio method, leaving modeling the entire observed O\textsc{iv} spectrum (as done for Si\textsc{iii} in Dzičáková & Kulinová 2011) as the most viable option for determining $\kappa$.

3.2. Effect of DEM on Line Formation

The shifts of the peak temperatures of the contribution function with $\kappa$ is potentially important, given the slope of the DEM at TR temperatures. To illustrate the effect of the DEM on the contribution function, we chose the AR and QS DEMs available within CHIANTI version 7.1, based on the data of Vernazza & Reeves (1978). The AR DEM has a much steeper TR than the QS DEM. We note that the spectra used to produce these DEMs are averages over many exposures and thus represent average physical conditions in the solar atmosphere over a selected type of structure on the solar surface; e.g., a QS or an AR. This means that such DEMs may not be representative of any particular, sub-arcsecond feature observed by IRIS. Moreover, the DEMs were derived under the assumption of a Maxwellian distribution, so that using them in conjunction with finite $\kappa$ is not self-consistent. Nevertheless, we use these DEMs to illustrate the general effect of the DEM slope on the formation of the IRIS TR lines. We note that the true DEMs for $\kappa$-distributions may differ mainly for very low temperatures due to the behavior of $G(T, n_e, \kappa)$ with $\kappa$ described in Section 3.1. However, evaluating the DEMs for $\kappa$-distributions is beyond the scope of this Letter.

The results are shown in Figure 2, middle and bottom. In this figure, the contribution functions are also multiplied by the $dT = T d(\log T)/\log(e)$ factor, so that the intervals of $\log(T/K)$ which contribute most to the total intensity can be immediately discerned. It is seen that for $\kappa = 2–7$ and the QS DEM, the Si\textsc{iv} 1402.77 Å line is dominantly formed in regions with very low temperature: $\log(T/K) \rightarrow 4$. The situation is even more pronounced for the AR DEM, where the line is formed at such a low temperature even for $\kappa = 10$. The situation is different for the O\textsc{iv} 1401.16 Å line, which is formed at very low $T$ only for
Figure 2. Contribution functions $G(T, n_e, \kappa)$ for the Si IV 1402.77 Å (Left) and O IV 1401.16 Å transitions (right). The middle and bottom rows depict the contribution functions multiplied by the $dT$ factors and the QS and AR DEMs, respectively. (A color version of this figure is available in the online journal.)

Figure 3 shows the synthetic spectra arising in regions characterized by such DEMs. For higher $\kappa$, the contribution function is slightly shifted to lower $T$ and has a pronounced low-temperature wing. The synthetic spectra arising in regions characterized by such DEMs are shown in Figure 3. These spectra have been scaled by the $IRIS$ effective area and the FWHMs of $IRIS$ lines have been artificially increased so that the line intensities for different $\kappa$ are better visible. We note here that the Si IV 1393.76 Å/1402.77 Å ratio is approximately constant and equal to 2 independently of $\kappa$ or any other assumptions. This is in agreement with the SUMER results presented by Doschek & Mariska (2001). As shown in Figure 3, the O IV lines are strongly sensitive to $\kappa$. For the AR DEM, they are very weak except for $\kappa = 10$. For the QS DEM, they are weaker compared to the Maxwellian distribution, but still observable even for $\kappa = 5$.

We note that given the possible values of $\kappa$, which are $\approx 7$ for the AR and $\approx 9$–12 for QS (Dzifčáková & Kulinová 2011), the Si IV and O IV lines may be formed under very different conditions, i.e., in different structures. These differences might be resolvable by $IRIS$. The effect of finite $\kappa$ would be to move the Si IV emission into the low $T$ closer to the chromosphere, i.e., into lower-lying, more dense structures that are possibly more narrow due to constriction by the expanding magnetic flux tubes. In this scenario, the O IV emission would lie higher up, in
the region where \( \log(T/K) \approx 5 \). We finally note that the relative intensities might be modified by abundance effects, especially for Si \( \text{iv} \), which is an element with a low first ionization potential.

### 3.3. Electron Density Diagnostics

It is known that the intercombination multiplet of O\( \text{iv} \) can be used for diagnostics of \( n_e \) (e.g., Vernazza & Mason 1978; Feldman 1981; Nussbaumer & Storey 1982; Doschek 1984; Hayes & Shine 1987; Dwivedi & Gupta 1992; Keenan et al. 2009). Here, we investigate the effect of \( \kappa \) on the density diagnostics. To do that, we plot the \( n_e \)-dependence of a chosen ratio of O\( \text{iv} \) lines observable by IRIS (Table 1) for the peak formation temperature and temperatures corresponding to the 1% of the contribution function peak. This gives the indication of the sensitivity of the given ratio to \( T \) (Figure 4, top).

If the Maxwellian distribution is assumed, the O\( \text{iv} \) line ratios yield a good density diagnostics in the \( \log(n_e/\text{cm}^{-3}) = 9–11 \) range (black lines in Figure 4, top), with lines at different \( T \) producing variations of about \( \pm 0.2 \) in \( \log(n_e/\text{cm}^{-3}) \). At even higher densities, the ratios reach a plateau and are unusable for \( \log(n_e/\text{cm}^{-3}) > 11.5 \).

In principle, the density diagnostics can depend on \( \kappa \), but the exact manner can be different for each ratio. The 1401.16 \( \AA \)/1404.78 \( \AA \) ratio is not recommended for density diagnostics, since it changes with \( \kappa \) (Figure 4, top left). On the other hand, the 1404.78 \( \AA \)/1399.77 \( \AA \) ratio is only weakly dependent on \( \kappa \) for \( \kappa \geq 5 \), yielding slightly lower \( n_e \). For the extreme non-Maxwellian situation, i.e., \( \kappa = 2 \), the ratio is useful only for temperatures close to or higher than the peak formation temperature. For very low \( \log(T/K) \to 4 \), the density dependence is lost (Figure 4, top right).

We note that the O\( \text{iv} \) 1404.78 \( \AA \) line is blended with the S\( \text{iv} \) 1404.81 \( \AA \) transition. This blend can become important at higher densities, since the intensity of the O\( \text{iv} \) 1404.78 \( \AA \) line decreases with \( n_e \). The contribution of this blend can in principle be estimated using the neighboring S\( \text{iv} \) 1406.02 \( \AA \) line, since the ratio of these two S\( \text{iv} \) lines is insensitive to \( n_e \) except for very high densities of \( \log(n_e/\text{cm}^{-3}) \geq 12 \) (Doschek 1984, Figure 1 therein). We note that the peak formation temperature of these S\( \text{iv} \) is \( \log(T/K) = 5.0 \) for the Maxwellian distribution and 4.6 for \( \kappa = 2 \).

#### 3.4. Photoexcitation

To quantify the effect of photoexcitation, we recalculated the contribution functions without it. It is found that the O\( \text{iv} \) lines are unaffected by photoexcitation, which contributes less than 0.1% to the O\( \text{iv} \) 1401.16 \( \AA \) line (Figure 4, bottom).

The situation is different for the S\( \text{iv} \) 1402.77 \( \AA \) line. Here, the effect of photoexcitation is dependent on the conditions under which the line is formed. For constant 3, photoexcitation contributes 2%–7%. For constant density, the relative contribution depends on \( T_e \), \( n_e \), and \( \kappa \). In general, the relative contribution increases with decreasing \( T_e \), \( n_e \), or \( \kappa \) (Figure 4). It can be larger than 10% for \( \log(n_e/\text{cm}^{-3}) = 10 \), and much larger still for even lower \( n_e \). We conclude that the effect of photoexcitation cannot be neglected for the S\( \text{iv} \) lines, and suggest that a real radiation field should be used instead of a black-body spectrum as done here.

### 4. SUMMARY

We have investigated the formation of the O\( \text{iv} \), S\( \text{iv} \), and S\( \text{iv} \) lines observable in the second FUV channel of IRIS. To achieve this, we utilized the state-of-art atomic data that will be part of the upcoming CHIANTI version 8. The O\( \text{iv} \) 1401.16 \( \AA \) line is formed at higher temperatures than the neighboring S\( \text{iv} \) 1402.77 \( \AA \) line. This is true for all values of \( \kappa \) considered. Taking into account the slope of the DEM in the TR, the S\( \text{iv} \) line can predominantly be formed at very low temperatures of \( T_e \approx 5 \). In general, the relative contribution increases with decreasing \( T_e \), \( n_e \), or \( \kappa \) (Figure 3).}

![Figure 3. Synthetic TR line spectra of O\( \text{iv} \), S\( \text{iv} \), and S\( \text{iv} \) in the second FUV channel of IRIS, calculated for the AR or QS DEMs. (A color version of this figure is available in the online journal.)](image-url)
Figure 4. Top: density diagnostics using O iv line ratios. Individual line styles correspond to different log(T/K). Colors correspond to different $\kappa$. Bottom: relative contribution (in %) from photoexcitation to the total $G(T, n_e, \kappa)$ for the Si iv 1402.77 Å (bottom left) and O iv 1401.16 Å lines (bottom right).

(A color version of this figure is available in the online journal.)

We recommend using realistic spectra to calculate the photoexcitation contribution to these lines. The O iv lines are not found to be sensitive to photoexcitation.

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