Non-Maxwellian Analysis of the Transition-region Line Profiles Observed by the Interface Region Imaging Spectrograph

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Abstract

We investigate the nature of the spectral line profiles for transition-region (TR) ions observed with the Interface Region Imaging Spectrograph (IRIS). In this context, we analyzed an active-region observation performed by IRIS in its 1400 Å spectral window. The TR lines are found to exhibit significant wings in their spectral profiles, which can be well fitted with a non-Maxwellian $\kappa$ distribution. The fit with a $\kappa$ distribution can perform better than a double-Gaussian fit, especially for the strongest line, SiIV 1402.8 Å. Typical values of $\kappa$ found are about 2, occurring in a majority of spatial pixels where the TR lines are symmetric, i.e., the fit can be performed. Furthermore, all five spectral lines studied (from SiIV, OIV, and SIV) appear to have the same full-width at half-maximum irrespective of whether the line is an allowed or an intercombination transition. A similar value of $\kappa$ is obtained for the electron distribution by the fitting of the line intensities relative to SiIV 1402.8 Å, if photospheric abundances are assumed. The $\kappa$ distributions, however, do not remove the presence of non-thermal broadening. Instead, they actually increase the non-thermal width. This is because, for $\kappa$ distributions, TR ions are formed at lower temperatures. The large observed non-thermal width lowers the opacity of the SiIV line sufficiently enough for this line to become optically thin.

Key words: line: profiles – methods: data analysis – radiation mechanisms: non-thermal – Sun: transition region – Sun: UV radiation

1. Introduction

The solar transition region (hereafter, TR) is an interface between the cool solar chromosphere and the overlying hot corona. Typical TR temperatures span a few times $10^4$ K to almost $10^6$ K, resulting in strong ultraviolet (UV) emission lines from heavy ions, such as CIV, SiIV, and OIV. The TR is highly inhomogeneous and also temporally variable. Recent advances in understanding of this enigmatic part of the solar atmosphere enabled by the Interface Region Imaging Spectrograph (IRIS, De Pontieu et al. 2014) include, among others, observational confirmation of the existence of short-lived TR loops (Hansteen et al. 2014) predicted by Feldman (1983, 1987) as well as observational signatures of accelerated electrons at footpoints of coronal loops (Testa et al. 2014).

Even in the absence of clearly transient phenomena and aside from the ubiquitous observed redshifts (e.g., Brekke et al. 1997; Polito et al. 2016a), spectroscopic observations in the UV contain a number of features that have not been fully understood. These include (i) the fact that some lines can be much stronger than predicted, assuming ionization equilibrium and Maxwellian plasma, (ii) the large non-thermal line widths, and (iii) peculiar line profiles exhibiting enhanced wings. An example of the first category are the intensities of the allowed SiIV lines at 1393.76 Å and 1402.77 Å, which are stronger by a factor of $\approx 5$ or higher compared to the neighboring intercombination lines of OIV (e.g., Doyle & Raymond 1984; Hayes & Shine 1987; Judge et al. 1995; Curdt et al. 2001; Doschek & Mariska 2001; Del Zanna et al. 2002; Peter et al. 2014; Doschek et al. 2016; Polito et al. 2016a). These lines are now observed by IRIS within its 1400 Å spectral channel at a spectral resolution of about 26 mÅ and a spatial resolution of about 0″/33. The SiIV and OIV lines are formed at similar temperatures, $\log(T(K)) = 4.9$ and 5.15, respectively, if collisional ionization equilibrium and a Maxwellian distribution (i.e., no accelerated particles) are assumed (Dudík et al. 2014a). Under such conditions, the OIV 1401.16 Å line is expected to be stronger than the SiIV 1402.77 Å one for typical TR differential emission measure distributions. There are only a few such observation known to us. One is a case of the RR Telescopii nebula (Harper et al. 1999; Del Zanna et al. 2002; Keenan et al. 2002), while other stars, such as α Centauri, show similar SiIV / OIV ratios to the Sun (e.g., Pagano et al. 2004; Ayres 2015). The other observation is an umbral footpoint of a coronal loop reported by Chitta et al. (2016). Transient ionization, i.e., departures from the equilibrium ionic composition, has been invoked as a possible explanation of the discrepant SiIV / OIV ratios (Doyle et al. 2013; Olluri et al. 2015) as well as their correlation with the SiIV intensities (e.g., Martínez-Sykora et al. 2016). There is an extended literature where transient ionization was shown to significantly affect line intensities in TR hydrodynamical modeling (see Raymond & Dupree 1978; Dupree et al. 1979; Noci et al. 1987; Raymond 1990; Hansteen 1993; Spadaro et al. 1994; Bradshaw & Mason 2003a, 2003b; Bradshaw et al. 2004). Most of the literature discussed CIV lines, which behave similarly to the SiIV ones. Departures from the Maxwellian distribution have also been invoked as another possible explanation. Enhanced high-energy tails in the electron distribution function, modeled by a $\kappa$ distribution, lead to orders-of-magnitude enhancements in the ionization rate, resulting in the TR ions being formed at much lower temperatures (Dzifčáková & Dudík 2013). This effect is stronger for SiIV than for OIV (Dudík et al. 2014a), leading to a strong increase of SiIV intensities.
The typical non-thermal widths observed in TR lines are around 20 km s\(^{-1}\) or larger (e.g., Doschek et al. 1977; Kjeldseth Moe & Nicolas 1977; Dere et al. 1987; Dere & Mason 1993; Chae et al. 1998; Peter 1999, 2000, 2001; Keenan et al. 2002; Akiyama et al. 2003, 2005; De Pontieu et al. 2015). We note that a non-thermal width of 20 km s\(^{-1}\) translates to about 0.1 Å for the SiIV 1402.77 Å line. The thermal width is a factor of \(\approx 3\) lower, being 6.86 km s\(^{-1}\) for the SiIV line at its Maxwellian peak formation temperature (e.g., De Pontieu et al. 2015). Thus, the line width is dominated by the non-thermal component. These non-thermal widths derived from observations remain unchanged despite the significant advancement in the spatial resolution achieved so far. De Pontieu et al. (2015) and Testa et al. (2016) both found peaks of non-thermal width distributions (for SiIV and FeXII TR emission, respectively) at about \(\approx 15\) km s\(^{-1}\). While the peaks of the distributions are mostly unchanged with the spatial resolution, the full distributions do change (see, e.g., the discussion in Testa et al. 2016). This invariance with respect to the spatial resolution could be due to sub-resolution structures smaller than 250 km (De Pontieu et al. 2015), possibly even 3–30 km in size (Dere et al. 1987). Furthermore, several studies found different widths of allowed and intercombination lines. The first such reports started with Skylab observations, followed by reports based on HRRTS and SOHO/SUMER observations (Doschek et al. 1977; Feldman et al. 1977; Kjeldseth Moe & Nicolas 1977; Doschek & Feldman 1978, 2004). Different widths suggest that the allowed and intercombination lines could be formed in different conditions, for example, at different electron densities (Doschek 1984) owing to the different dependence of intensity of allowed and intercombination lines on electron density. This issue has recently been discussed and put forward using IRIS observations by Doschek et al. (2016), although the same authors show an example of a quiescent spectrum where the profiles of the two main SiIV and OIV lines are similar. However, Dere & Mason (1993) pointed out that the intercombination lines can be weak, so it could be difficult to accurately measure their line profiles even with the excellent HRTS instrument. Recently, Polito et al. (2016a) reported that SiIV and OIV lines had similar profiles.

Apart from this, profiles of the TR lines also show departures from a simple Gaussian shape. In particular, strong wings are often observed, even at supersonic velocities (Kjeldseth Moe & Nicolas 1977; Doschek & Feldman 1978; Dere & Mason 1993; Chae et al. 1998; Peter 1999, 2000, 2001, 2006). This is also the case for \(\alpha\) Centauri (Paganò et al. 2004) and even both \(\alpha\) Cen A and B components separately (Ayres 2015). These non-Gaussian profiles are usually fitted with two Gaussian components, a narrow and a broader one. The contribution of the broader Gaussian to the total intensity is up to 30%, with the largest values found in the middle TR (Chae et al. 1998; Peter 2001), i.e., at formation temperatures of SiIV and OIV. These two Gaussian components have been interpreted as the line emission originating in two distinct magnetic structures: the narrow one in closed magnetic loops and the broader one in open coronal funnels (Peter 1999, 2000, 2001).

In this paper, we attempt to unify the solution of these three spectroscopic challenges by using the non-Maxwellian \(\kappa\) distributions to analyze a particular IRIS observation of a bright closed TR loop. The \(\kappa\) distributions exhibit significant power-law tails at high velocities or energies. They have been detected in the solar corona (Dudík et al. 2015) using line intensity ratios.

In solar flares, profiles of Fe XVI and FeXXIII lines observed by Hinode/EIS (Culhane et al. 2007) can be confidently fitted with \(\kappa\) distributions (Jeffrey et al. 2016, 2017). The power-law component of the bremsstrahlung emission during flares can also be approximated by \(\kappa\) distributions (Battaglia & Kontar 2013; Oka et al. 2013, 2015; Battaglia et al. 2015).

The \(\kappa\) distributions are expected in the presence of turbulence if the diffusion coefficient is inversely proportional to velocity (Hasegawa et al. 1985; Laming & Lepré 2007; Bian et al. 2014). A turbulence could occur if the plasma is moving or if it has redshifts (Jeffrey et al. 2017), which is an ubiquitous phenomenon in the TR. The presence of \(\kappa\) distributions in the TR would lead to enhancements of SiIV intensities with respect to the neighboring OIV ones (Dudík et al. 2014a). Power-law distributions or enhanced high-energy particles are also expected in a closed loop, if such a loop is heated by reconnecting current sheets along its length (Gontikakis et al. 2013; Gordovskyy et al. 2013, 2014). Wave–particle interaction involving whistler waves also lead to enhancement of high-energy particles in a closed loop geometry (Vocks et al. 2008, 2016). The fundamental reason for the existence of power-law tails is that the cross-section for Coulomb collisions and the collision frequency decreases with velocity as \(v^{-4}\) and \(v^{-3}\), respectively. Particles with progressively higher energies are thus progressively more collisionless. Furthermore, density and temperature gradients in plasma can lead to the appearance of high-energy tails of the distribution (Roussel-Dupré 1980; Shoub 1983; Ljepojevic & MacNee 1988). Non-Maxwellians are expected to occur if the electron mean-free path is larger than about \(10^{-5}\) of the local pressure scale length at any point along a given magnetic field line (Scudder & Karimabadi 2013). Such conditions should be common in stellar coronae; however, they could occur also in the TR.

Having been thus motivated, in this work we first investigate whether the \(\kappa\) distributions could fit the TR line profiles and how such a fit compares to the classical double-Gaussian case. The fit to the TR lines observed by IRIS should be feasible, since the \(\kappa\) distributions were recently used successfully by Jeffrey et al. (2016, 2017) to fit the coronal lines observed by the Hinode/EIS instrument (Culhane et al. 2007), even though EIS has fewer points per profile than IRIS, as well as a much larger instrumental width, limiting its use for such purposes. Instead, IRIS not only has a very small instrumental width, but also samples the line profiles very well.

This paper is organized as follows. The non-Maxwellian \(\kappa\) distributions are described in Section 2. There, we also derive the theoretical \(\kappa\) profile of a spectral line and we discuss the relation of individual fit parameters, such as the characteristic width and \(\kappa\) to the observed full-width at half-maximum (FWHM) of the line and the ion temperature. The IRIS observations analyzed are described in Section 3. Gaussian and \(\kappa\) fits are performed in Sections 4 and 5, while the fitting of the line intensities relative to SiIV is performed in Section 6. The results are discussed in Section 7 and a summary is given in Section 8.

### 2. The Non-Maxwellian \(\kappa\) Distributions and the Line Profiles

#### 2.1. The \(\kappa\) Distributions

The \(\kappa\) distribution is a distribution of particle velocities \(v\) or energies \(E = mv^2/2\). It is characterized by a power-law high-
energy tail (Olbert 1968; Vasyliunas 1968a, 1968b; Owocki & Scudder 1983; Livadiotis & McComas 2009, 2013). In its energy form, the isotropic κ distribution is given by

\[ f_\kappa(E)dE = A_\kappa \frac{2}{\sqrt{\pi}} \left( \frac{E^{1/2}}{k_B T} \right)^{\kappa/2} \left[ 1 + \frac{E}{(\kappa - 3/2)k_B T} \right]^{-\kappa+1}, \tag{1} \]

where \( A_\kappa = \Gamma(\kappa + 1) / [\Gamma(\kappa - 3/2)\Gamma(\kappa + 1/2)] \) is the normalization constant and \( k_B = 1.38 \times 10^{-16} \text{ erg K}^{-1} \) is the Boltzmann constant. This form of the κ distribution is assumed for the electrons when calculating the optically thin synthetic non-Maxwellian spectra (e.g., Dudík et al. 2014a; Dzifčáková et al. 2015) where the ionization, recombinations, and excitation transitions are dominated by electron–ion collisions.

In the energy form, the κ distribution has two independent parameters, κ and T. Maxwellian is recovered for κ → ∞, while the opposite situation of κ → 3/2 corresponds to strongest deviation from the Maxwellian distribution. T is the thermodynamic temperature related to the mean energy \( \langle E \rangle = 3k_B T/2 \), which is independent of κ. More detailed discussion on the representation of T as temperature in the framework of generalized Tsallis statistical mechanics (Tsalis 1988, 2009) can be found in Livadiotis & McComas (2009).

The corresponding κ distribution in the velocity form is given by (Livadiotis 2015)

\[ f_\kappa(v)dv = \frac{C_\kappa}{\pi v^3} \left[ 1 + \frac{v^2}{(\kappa - 3/2)\theta^2} \right]^{-\kappa+1}, \tag{2} \]

where \( v = |v| = |v_1 + v_2|, C_\kappa = \Gamma(\kappa + 1) / \Gamma(\kappa - 1/2) \) is the normalization constant, \( \theta = \sqrt{2k_B T/m} \) is the thermal velocity, and m is the particle mass. In this form, the quantity T is the thermodynamic temperature and is independent of κ (Livadiotis 2015).

We note that the κ distributions are sometimes written in the form (see also Olbert 1968; Jeffrey et al. 2016; Lazar et al. 2016)

\[ f_\kappa(v)dv = \frac{C_\kappa}{\pi \theta^2 \kappa^{3/2}} \left[ 1 + \frac{v^2}{\kappa \theta^2} \right]^{-\kappa+1}, \tag{3} \]

which is equivalent to Equation (2) if the quantity \( \kappa \theta_\kappa = (\kappa - 3/2)\theta \), or, equivalently, if \( \theta_\kappa \) is related to T by the expression (see Lazar et al. 2015)

\[ T = \frac{m}{k_B} \int v^2 f_\kappa(v)dv = \frac{m}{2k_B} \frac{2\kappa}{\kappa - 3} \theta_\kappa^2. \tag{4} \]

From a mathematical standpoint, either the T or \( \theta_\kappa \) can be chosen as independent variable; if \( \theta_\kappa \) is chosen as independent, then T depends on both κ and \( \theta_\kappa \), and vice versa. Examples of the κ distributions for different κ and a constant T or \( \theta_\kappa \) are shown in Figure 1 left and right, respectively.

The definition of the κ distributions in Equation (2) corresponds to the κ distributions of the second kind (Livadiotis & McComas 2009) rather than of the first kind, which has been used to fit the Hinode/EIS lines by Jeffrey et al. (2017). The κ distributions of the second kind differ from those of the first kind by having the factor \(-(\kappa + 1)\) in the exponent rather than \(\kappa + 1\). The two kinds of κ distributions are equivalent under the transformation \(\kappa^* = \kappa + 1\) if the velocity scales are related as \(\kappa^{*1/2} \theta_{\kappa^*} = \kappa^{1/2} \theta_\kappa\) (Livadiotis & McComas 2009). This means that the lower asymptotic limit of κ* for the κ distributions of the first kind is 5/2, not 3/2 as in our case.

Finally, we note that the relative number of particles in the high-energy tail and the energy carried by them have been calculated by Oka et al. (2013). For example, in a κ = 4 distribution, the high-energy tail contains ≈20% of the particles, and these carry ≈50% of the energy. For κ = 2, about 35% of the particles are in the high-energy tail, which contains more than 80% of the energy.

### 2.2. Non-Maxwellian Line Profiles

It is well known that the line profiles can reflect the ion velocity distribution because of the Doppler effect,

\[ \Delta \lambda/\lambda_0 = v_\parallel/c, \tag{5} \]

where \( \Delta \lambda = \lambda - \lambda_0 \) is the wavelength difference from the rest wavelength \( \lambda_0, v_\parallel \) is the velocity component parallel to the line of sight, and c is the speed of light. Combining Equations (2)–(5), assuming isotropy and integrating over \( dv_\parallel = 2\pi v_\parallel dv_\perp \) (Jeffrey et al. 2017) and normalizing, we obtain the line profile as (see Dzifčáková 1989)

\[ \frac{I_\kappa(\lambda)}{I(\lambda_0)} = \left( 1 + \frac{mc^2(\lambda - \lambda_0)^2}{2k_B T(\kappa - 3/2)\lambda_0^2} \right)^{-\kappa}, \tag{6} \]

where \( I_\kappa(\lambda) \) is the intensity at wavelength \( \lambda \). The FWHM of this profile is given by

\[ \text{FWHM}^2_\kappa = 8\lambda_0^2 k_B T(\kappa - 3/2)(2^\kappa - 1)/mc^2. \tag{7} \]

The corresponding Gaussian (\( \kappa \to +\infty \)) profile is

\[ \frac{I_\kappa(\lambda)}{I(\lambda_0)} = \exp \left( -\frac{mc^2(\lambda - \lambda_0)^2}{2k_B T \lambda_0^2} \right). \tag{8} \]

and its FWHM^2_\kappa = 8 ln(2)\lambda_0^2 k_B T/ mc^2.

Following the above, if a line with an observed FWHM is fitted with a κ distribution, the temperature \( T_\kappa \) derived using Equation (7) is related to the temperature \( T_{\text{Maxw}} \) obtained from a Gaussian fit of the same line as (see Dzifčáková 1989)

\[ T_{\text{Maxw}}/T_\kappa = (\kappa - 3/2)(2^\kappa - 1)/\ln(2). \tag{9} \]

That is, the \( T_{\text{Maxw}} \) derived from the same observed FWHM is a lower limit to the ion kinetic temperature \( T_\kappa \) if the line profile is given by a κ distribution.

The normalized line profile of an emission line arising from plasmas characterized by ion κ distribution is shown in Figure 1 right. In this image, the line profile is assumed to have the same FWHM, which we chose to be 0.2 Å independently of κ. It can readily be seen that the changes in the line profile with κ are modest, less than ≈9.8% I(\( \lambda_0 \)) for κ = 1.55 compared to the Gaussian (Maxwellian) profile. The largest changes occur in the line wings at Δ\( \lambda \approx \) FWHM. The changes of the profile within the line core are small, below 3% of I(\( \lambda_0 \)). Considering the uncertainties related to the observations and the presence of an instrumental profile, this behavior makes the ion κ distributions difficult to be detected except in strong lines with wings well above the continuum, located in an uncrowded region of the spectrum. The TR lines observed with the IRIS instrument (Dudík et al. 2014a) offer such an opportunity (Sections 4.2 and 5).
I is present in the denominator instead of just $k^2$ respectively. Right: normalized line profile where $\kappa$ is the peak intensity and $\kappa^2$ is the characteristic width. We note that the above formula is different from the one used by Jeffrey et al. (2016). A factor of $\kappa - 3/2$ is present in the denominator instead of just $\kappa$. This factor is kept for consistency with the theoretical line profile (Equation (6)) arising only from the distribution of ion velocities (Section 2.2). Finally, we keep the factor 2 in the denominator for consistency with the Gaussian profile as implemented in the SolarSoft routine \texttt{comp_gauss.pro}. This factor can be dropped by a unique transformation of $\kappa^2 \rightarrow \kappa$, so it essentially only modifies the resulting characteristic width.

We note that the total intensity $\kappa_{\text{tot}}$ of the Gaussian profile is

$$I_{\kappa} = \int_{-\infty}^{+\infty} I_{\kappa}(\chi) d\chi = \kappa_{\text{tot}} = \kappa_{\text{tot}} (2\pi)^{1/2},$$

while for the $\kappa$ profile we obtain

$$I_{\kappa} = \kappa_{\text{tot}} (2\pi)^{1/2} (\kappa - 3/2)^{1/2} \Gamma(\kappa + 1/2) / \Gamma(\kappa + 1).$$

If the line width is given only by the isotropic ion motion due to a $\kappa$ distribution of ion velocities, $\kappa_{\text{tot}}$ is given by (Equations (2)–(7))

$$\kappa_{\text{tot}}^2 = \frac{4}{\kappa + 3/2} \frac{\kappa_{\text{tot}}^2}{(\kappa - 3/2)^{1/2} (2m^2/c^2)}.$$

The last equation between $\kappa_{\text{tot}}$ and FWHM$_{\text{Gauss}}$ is also valid in a general case, i.e., also for the FWHM derived from observations. We further note that this equation means that the relation between characteristic width $\kappa_{\text{tot}}$ of the line profile and the corresponding ion temperature $T$ does not depend on $\kappa$.

In the fitting, however, $\kappa_{\text{tot}}$ is a free parameter alongside $\lambda_0$, and $\kappa$; i.e., in principle, it is possible to obtain a different value of $\kappa_{\text{tot}}$ depending on whether the line is fitted with a Gaussian or a $\kappa$-profile.

3. \textit{IRIS} Observations

Since its launch in 2013, the \textit{IRIS} instrument has provided high spatial (0′′33–0′′4) and temporal (≈2 s) resolution images and spectra of the Sun in the far ultraviolet (FUV) at 1332–1407 Å and near-UV 2783–2835 Å spectral ranges, allowing the investigation of the highly dynamical nature of the low solar atmosphere. In this work, we analyze the spectra of the strongest TR lines at around 1400 Å observed by \textit{IRIS} in the active region (AR) NOAA 12356 on 2015 June 1. The observed transitions include Si IV at 1402.77 Å (log(T$_{\text{max}}$(K)) ≈ 4.9), O IV at 1399.77 Å, 1401.16 Å, and 1404.82 Å (log(T$_{\text{max}}$(K)) ≈ 5.15), and S IV at 1404.85 Å and 1406.01 Å (log(T$_{\text{max}}$(K)) ≈ 5.0), where T$_{\text{max}}$ refers to the Maxwellian peak formation temperatures of a given ion. It should be noted that the O IV and S IV lines around 1404.8 Å are blended together. A review of the experimental data for these ions indicated that the rest wavelengths should be separated by about 0.04 Å (Polito et al. 2016a, Appendix A therein). The spectra of these lines for the same \textit{IRIS} observation was analyzed by Polito et al. (2016a), who investigated the use of O IV and S IV lines as density and temperature diagnostics of the plasma from which they are emitted. We also note that the O IV 1397.198 Å and S IV 1398.040 Å lines are not included within the spectral range of the present \textit{IRIS} observation.

The \textit{IRIS} study presented in this work consists of a dense, 96-step single raster that scanned the AR under study over a field of view of 33″ × 119″ and with an exposure time of ≈60 s. The present observation included binning by two pixels in both the Solar Y direction as well as in wavelength $\lambda$. The level 2 \textit{IRIS} data were downloaded from the \textit{IRIS} website\(^4\) and are obtained from level 0 data after flat-field correction, geometry calibration, and dark current subtraction.\(^5\) In addition,

\(^4\) http://iris.lmsal.com/search/

\(^5\) http://iris.lmsal.com/documents.html
we performed a cosmic ray removal and calibration of the wavelength array as described in Polito et al. (2015) and Polito et al. (2016b). The level 2 data are expressed in number (DN) and, in order to convert them to physical units, one can perform the radiometric calibration detailed in the IRIS software note 24. However, the IRIS spectrograph has flat response curves in the long-FUV (FUVL) window where the observed lines are located, and thus the calibration factors would not change the line profiles nor affect their relative intensities. Therefore, the spectra of the TR lines analyzed in this work are expressed in DN, as they are measured by the spectrograph. The error associated with the data counts in each detector pixel is obtained by summing in quadrature the photon counting error (which is given by the square root of the photon counts) and the readout noise. We assume a gain (photons DN$^{-1}$) of 4 for the FUV channel and a readout noise of $\approx 3.1$ DN (see De Pontieu et al. 2014).

Figure 2 shows the intensity images in solar coordinates $X = [-95.1, -70.1]$ and $Y = [-260, -215]$ for the two strongest lines, Si IV 1402.77 Å and O IV 1401.16 Å observed during the dense IRIS raster analyzed in this study. The intensity of the Si IV and O IV at each pixel is obtained by summing the total counts over the line profile and normalizing it with respect to the exposure time. Therefore, the units of the images are expressed in DN s$^{-1}$. The Si IV and O IV images show the presence of different features, including bundles of cool AR loops and compact brightenings, as described in detail in Polito et al. (2016a).

4. Line Profile Analysis in a Selected Pixel

Since non-Maxwellian analysis is quite involved, we first analyze the spectrum in a single selected pixel along one of the bundle of bright TR loops. This is instructive, as it enables us to show and discuss the differences among fitting all five lines with single and double Gaussians and a $\kappa$ distribution. The chosen example pixel is indicated by a cross symbol overlaid on the images in Figure 2 and its coordinates within the raster are [49, 101] in pixel units. The line fitting of the five TR lines observed by IRIS is presented here, while an analysis of line profiles elsewhere together with the spatial distribution of the derived $\kappa$ values is postponed to Section 5. We note that analysis of a single-pixel spectrum, as opposed to averaging over a spatial box, allows us to take advantage of the high-resolution of IRIS and thus avoid the contributions from different plasmas that could be present in a larger spatial region as much as possible.

4.1. Line Profiles: Symmetry and Tails

Following Jeffrey et al. (2016), we first performed the analysis of line profile symmetry and peakedness by calculating the first four moments of the line profile. Aside from the peak wavelength $\lambda_0$, the variance $w^2$, skewness $S$, and kurtosis $K$ are defined by (see Jeffrey et al. 2016)

$$w^2 = \frac{\int_A I(\lambda)(\lambda - \lambda_0)^2d\lambda}{\int_A I(\lambda)d\lambda},$$

$$S = \frac{1}{w^2} \frac{\int_A I(\lambda)(\lambda - \lambda_0)^3d\lambda}{\int_A I(\lambda)d\lambda},$$

$$K = \frac{1}{w^4} \frac{\int_A I(\lambda)(\lambda - \lambda_0)^4d\lambda}{\int_A I(\lambda)d\lambda},$$

where $S$ and $K$ are distribution normalized. Because of the factor $\lambda - \lambda_0$ raised to the 3rd or 4th power, the values of $S$ and $K$ are dominated by points located further away from $\lambda_0 \pm w$. Hence, $S$ and $K$ represent measures of the symmetry of the line profile and presence of strong tails, respectively. We note that a Gaussian distribution has $S = 0$ and $K = 3$.

To calculate these values, we subtracted the pseudo-continuum (15.3 DN; see Section 4.2) and used a wavelength range of $\lambda_0 \pm 0.4$ Å for O IV and S IV lines, while for Si IV, we used the wavelength range of $\lambda_0 \pm 0.6$ Å. These wavelength ranges are larger than those used by Jeffrey et al. (2016) for EIS lines ($\lambda_0 \pm 0.2$ Å). We require a larger interval because of the pronounced wings of the observed TR lines. The $\lambda_0 \pm 0.4$ (0.6) Å interval is wide enough to contain the line profile and several pseudo-continuum points at both extremities while avoiding the weak line-like features, such as Fe II, occasionally present above the pseudo-continuum.

The values of $w^2$, $S$, and $K$ together with the first moment $\lambda_0$ and their respective uncertainties for the five IRIS TR lines are given in Table 1. This Table indicates that all five lines are redshifted by a similar amount (43–55 mÅ) with respect to the rest wavelengths (see the discussion in Appendix A of Polito et al. 2016a). This small dispersion in the observed redshift is not surprising given that the IRIS pixel in the present observation is 25 mÅ. Table 1 also indicates that all five lines have nearly the same width; furthermore, they are all close to being symmetric and show the presence of strong tails.

The value of $|S|$ is below the value of 0.1 (within the uncertainties) for all lines, although the value may not be meaningful for the weaker lines (especially S IV) due to its uncertainty. We also note that the strongest O IV line at 1401 Å is blended in the far red wing with a weak but recognizable Si I 1401.5 Å transition (Figure 3, second row). However, in this case this Si I transition is too weak to affect the value of $|S|$ significantly. The S IV 1406 Å line does not have visible blends (see Polito et al. 2016a). The Fe II 1405.6 Å line is, however, distinguishable outside the S IV 1406.1 Å line.
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The Kurtosis $K$ is for all five TR lines higher than 3.5. This indicates presence of significant wings, in accordance with the visual inspection of the spectrum. For the strongest line in the spectrum, Si IV, $K$ is 5.8, which is even larger than the value of $K$ for the other lines. This indicates stronger wings of the Si IV line compared to the O IV and S IV ones. Restricting the wavelength range to $\lambda_0 \pm 0.4$ Å would decrease the value of $K$, this being due to the line still having significant wings (of the order of 50 DN, i.e., about 3 times the local pseudo-continuum) at the edges of this smaller interval. We note that the value of $w$ for the Si IV line is higher than for other lines; however, this is an effect of the larger wavelength range. Restricting it to $\pm 0.4$ Å would produce $w \approx 0.26$, in accordance with other lines.

4.2. Line Profile Fitting with Gaussian and $\kappa$ Profiles
The line profile fitting is performed for the full IRIS FUV window around 1400 Å and the selected single-pixel spectrum (Section 3 and Figure 2). The fitting assumes a constant “background” pseudo-continuum with intensity $I_{BG}$ and the presence of five strong TR spectral lines of Si IV, O IV, and S IV. These are fitted at the same time using the fitting formulae for the Gaussian and $\kappa$ line profiles for each line (Equations (8) and (6)). Values of the fitting parameters and their uncertainties are found using the Levenberg–Marquardt least-squares method (see, e.g., Press et al. 1992) as implemented in the mcuvesfit.pro IDL routine available under SolarSoft.

The goodness-of-fit is evaluated using the reduced $\chi^2_{\text{red}}$, given by

$$
\chi^2_{\text{red}} = \frac{1}{\nu} \sum_{i=0}^{N-1} \frac{(I_{\text{obs}}(\lambda_i) - I_{\text{fit}}(\lambda_i))^2}{\sigma^2(I_{\text{obs}}(\lambda_i))},
$$

where $N = 326$ is the total number of spectral bins in the present IRIS raster, $\nu = N - N_{\text{fit}} - 1$ is the number of degrees of freedom in the fit, $N_{\text{fit}}$ is the number of free parameters in the fit, and $I_{\text{obs}}(\lambda_i) \pm \sigma(I_{\text{obs}}(\lambda_i))$ are the observed intensities in the spectral bin $i$ and their respective uncertainties (see Section 3). The Levenberg–Marquardt fitting procedure minimizes the $\chi^2_{\text{red}}$. Since the fitting is performed at the same time for the pseudo-continuum and all lines, there is only a single value of $\chi^2_{\text{red}}$ for the entire IRIS FUV window around 1400 Å. This value is listed for each type of line profile fit in the top panels of Figure 3.

We note that the blended O IV line around 1404.82 Å is also fitted at the same time and in the same manner as other unblended lines. This is done since the blending O IV and S IV transitions are located close in wavelength (see Appendix A of Polito et al. 2016a) as well as for completeness. Not including this strong line could lead to difficulties with the determination of $I_{BG}$ and in turn affect the fit parameters for other lines.

In addition, we included the weak Si I 1401.5 Å line in the far red wing of the O IV 1401.2 Å line, as well as the Fe II 1405.6 Å line that can be recognized above the pseudo-continuum. In practice, we find that the inclusion of these two lines only has a small impact on the $\chi^2_{\text{red}}$ value. Similarly, adding other weak lines (some of unknown origin) does not improve the $\chi^2_{\text{red}}$, and we decided not to include these weak line-like components to fit the small “lumps and bumps” above the pseudo-continuum. The influence of these line-like components on the overall $\chi^2_{\text{red}}$ is further discussed in Appendix B.

We note that the $\chi^2_{\text{red}}$ has been criticized as a goodness-of-fit measure for nonlinear functions (Andrae et al. 2010), since the degrees of freedom may not be properly defined using the formula mentioned above. However, we found that the lower the $\chi^2_{\text{red}}$ obtained, the better the overall fit to the IRIS FUV spectrum. This is confirmed by the behavior of the residuals $I_{\text{obs}}(\lambda_i) - I_{\text{fit}}(\lambda_i)$, which are supplied for each fit in this section.

4.2.1. Single- and Double-Gaussian Fits
We first tried to fit the observed line profiles using single- and double-Gaussian components. We note that this is a standard fitting procedure for spectral lines. The results of the fitting are shown in Figure 3, which is organized as follows. Each of the five individual observed lines is shown in a given row in black color, with the corresponding error bars in each spectral bin. Colors denote individual fitting components, with the single and double-Gaussian fits being shown in the first two columns, while the fitting with a $\kappa$ distribution is shown in the third and fourth columns. Individual parameters obtained from the fitting are listed in each panel, with errors given by the fit shown in parentheses. Residuals $I_{\text{obs}} - I_{\text{fit}}$ are also shown at the bottom of each panel.

We see that the single-Gaussian fitting does a poor job of approximating the peaks of all lines and also the far wings. The situation is worst for the strongest line, i.e., Si IV, where the peak is underestimated by 200–400 DN. The far wings are also underestimated. The overall $\chi^2_{\text{red}}$ is 21, indicating a poor fit. However, we note that single-Gaussian fitting for these non-Gaussian profiles does not show large uncertainties in the width as reported by Akiyama et al. (2005, Section 2.3.4 therein). We also note that the $w_G$ obtained from the fitting is nearly the same for all five TR lines, including the allowed Si IV line. This is contrary to most results reported in literature (but see Polito et al. 2016a and Figure 8 of Doschek et al. 2016).
Figure 3. IRIS TR line fitting for the spectrum of the selected pixel marked in Figure 2. Each of the five rows represent one of the five observed TR lines, while each columns represent a particular type of fit. Fit parameters are listed in each panel, with uncertainties in parentheses. Residuals \( I_{\text{obs}} - I_{\text{fit}} \) are also shown. See the text for details.
Double-Gaussian fits do a much better job at approximating the observed line profiles. Peaks and far wings of all lines are approximated well, except for the peak of Si IV, where the largest residual still reaches about 200 DN. The overall \( \chi^2 \) has decreased to 4.1. Adding a third Gaussian component into the Si IV line would remove this discrepancy and lower the \( \chi^2 \). However, this would also mean that we require nine free parameters to fit a single unblended line profile.

We note that in this fitting we did not assume the same value of \( \lambda_0 \) for both Gaussian components. Tying the \( \lambda_0 \) of both Gaussian components to a single value does not improve the goodness-of-fit in terms of the \( \chi^2 \) for the double-Gaussian fitting. Furthermore, the \( \lambda_0 \) obtained for the narrow and broader Gaussian do not differ by more than about a half of the \( \text{IRIS} \) wavelength bin, i.e., \( \approx 15 \text{ mA} \). This is not surprising, since the five TR lines are all symmetric (Section 4.1).

Finally, in calculating the intensities of each Gaussian component (Equation (12)), we found that the relative contribution of the broader second Gaussian to the total line intensity is about 30% for Si IV, in agreement with the highest values reported by Peter (2001), occurring in the middle TR. However, for O IV, we find higher contributions of the second Gaussian, 39%, 50%, and 48% for O IV 1399.78 Å, 1401.16 Å, and 1404.82 Å (b), respectively. For the Si IV line at 1406.06 Å, the second Gaussian contributes 58% of its intensity. Such high values have not previously been reported in literature. Although the significance of these numbers is questionable for the weaker O IV and Si IV lines because of the larger relative uncertainties in both the \( I_{G2}(\lambda_0) \) and \( w_{G2} \) compared to the narrow Gaussian, we find that this is not the case for the strongest O IV line at 1401.2 Å. Such a large contribution of the broad Gaussian to the total intensity, together with the intensity originating in closed TR loop (Figure 2), casts doubt on the interpretation that this broader component originates in a coronal funnel (Peter 1999, 2000, 2001). Alternative interpretations for the two Gaussian components could, however, still be possible, but we do not engage in such speculations further.

### 4.2.2. Fits with a \( \kappa \) distribution

We next fitted the lines with a \( \kappa \) distribution (Equation (11)). The results are shown in red color in the third column of Figure 3. We see that the \( \kappa \) distribution fits most of the profiles well, including the peaks and far wings. The total \( \chi^2_{\text{red}} = 3.1 \) is lower than for the double-Gaussian fit. This is in spite of the fact that a \( \kappa \) distribution requires fewer free parameters than a double-Gaussian fit. It is, however, not surprising given that the \( \kappa \) distributions, or indeed any distributions broader than a Maxwellian, can be approximated by a sum of several Maxвелlians (Hahn & Savin 2015). The lower \( \chi^2_{\text{red}} \) value comes in particular from a better match to the Si IV line center produced by the \( \kappa \) fit. There, the highest residuals are about 150 DN and occur in fewer pixels than in the double-Gaussian case. The \( \chi^2_{\text{red}} \), however, is still larger than unity. In Appendix A, we show that this is not due to optical thickness effects within the Si IV line, while in Appendix B it is shown that the residuals in the Si IV line contribute only about 0.31 to the total \( \chi^2_{\text{red}} \) and that it is the pseudo-continuum that dominates the \( \chi^2_{\text{red}} \) value.

The values of \( \kappa \) obtained from the line fitting are low, of about 1.9–2.1, see Table 2. For the O IV 1401.2 Å line, we obtain \( \kappa = 2.35 \pm 0.08 \), higher than for other lines. The cause of this is uncertain. It is possible that the \( \kappa \) and \( w_k \) are coupled, and we found that the \( w_k \) for this line is lower compared to other lines. To test this, we tried to arbitrarily restrict \( w_k \) to \( w_k \geq 0.14 \), i.e., to be larger than the lowest value found for other lines (Table 2). By doing so, we found \( \kappa = 2.09 \pm 0.07 \) for this O IV 1401.2 Å line, and a slightly worse \( \chi^2_{\text{red}} = 3.2 \). Such a value of \( \kappa \) is in good agreement with the values obtained from other four TR lines. This exercise indicates that a restricted value of one of the \( \kappa \) and \( w_k \) parameters could be mitigated by changes in the other one; however, at the expense of \( \chi^2_{\text{red}} \). We note that \( \chi^2_{\text{red}} \) is the quantity is minimized by the fitting procedure and we did not a priori enforce the same value of \( \kappa \) for all five TR lines.

The values of \( \kappa \) obtained here are low, located in the far-equilibrium thermodynamic region (see Livadiotis & McComas 2010, 2013), i.e., near the extreme lower limit of \( \kappa \approx 3/2 \) for physically realizable \( \kappa \) distributions. A similar value was found for a transient coronal loop by Dudik et al. (2015). Jeffery et al. (2017) obtained similarly low \( \kappa \) values in flare loops, albeit they used the \( \kappa \) distribution of the first kind, meaning that their \( \kappa^* \) values correspond to our \( \kappa = 1 \) (see Section 2.1). Such low \( \kappa \approx 2 \) values are interesting, since if the line profile is given by the ion motions, then the energetic particles manifested in line wings would carry \( \approx 80\% \) of total energy contained in the \( \kappa \) distribution (Oka et al. 2013, Figure 1(b) therein). Finally, we note that the discussion on the characteristic widths \( w_k \) obtained from the fitting, the contribution of non-thermal broadening, as well as the quantities derived from \( w_k \) are presented in Section 7.3.

| Line  | \( \lambda_0 \) (Å) | \( I_0 \) (DN) | \( w_k \) (Å) | \( \kappa \) | FWHM (Å) | \( T_e \) (MK) |
|-------|-------------------|----------------|-------------|--------------|-----------|------------|
| O IV 1399.78 Å | 1399.831 ± 0.001 | 385 ± 6 | 0.143 ± 0.010 | 2.16 ± 0.17 | 0.20 ± 0.08 | 1.81 ± 0.26 |
| O IV 1401.16 Å | 1401.218 ± 0.000 | 1399 ± 10 | 0.127 ± 0.003 | 2.35 ± 0.08 | 0.20 ± 0.05 | 1.43 ± 0.06 |
| Si IV 1402.77 Å | 1402.820 ± 0.000 | 4598 ± 18 | 0.136 ± 0.001 | 2.16 ± 0.03 | 0.19 ± 0.02 | 2.26 ± 0.06 |
| O IV 1404.82 Å (b SI IV) | 1404.855 ± 0.001 | 383 ± 6 | 0.163 ± 0.018 | 1.91 ± 0.13 | 0.19 ± 0.13 | 2.35 ± 0.52 |
| Si IV 1406.06 Å | 1406.103 ± 0.001 | 282 ± 5 | 0.144 ± 0.021 | 1.91 ± 0.18 | 0.17 ± 0.17 | 3.64 ± 1.08 |

Note. Derived FWHM and \( T_e \) quantities are listed as well.
Lorentzian (formally corresponding to $\kappa = -1$). We note, however, that the FWHM$_{\text{instr}}$ is nearly the same as the size of a single wavelength pixel (with binning) in the present study; therefore, the influence of the instrumental profile is expected to be small.

This is indeed what we found. However, assuming either Gaussian or Lorentzian shapes of the instrumental profile does not improve upon the $\kappa$ fit. The Lorentzian leads to increased spread of $\kappa$ varying between 1.7 and 2.5 depending on the line, with overall $\chi^2_{\text{red}} = 3.2$. For the Gaussian instrumental profile, both the the $\chi^2_{\text{red}}$ and the resulting values of $\kappa$ do not change appreciably compared to the purely $\kappa$ fit (Figure 3, right column). The only changes are the decreased characteristic widths $\nu_{\kappa}$. However, since the true IRIS instrumental profile is not known at present, we use the purely $\kappa$ fit (Section 5) and the parameters derived from it (Section 7 and Appendix A) in the remainder of this work. In Section 5.2, we further investigate the effects of the instrumental profile providing additional evidence that it is unlikely to explain the observed non-Gaussian profiles.

5. Spatial Distribution of $\kappa$ Profiles

We next performed the fitting in each suitable pixel within the field of view of Figure 2. A pixel is defined as suitable if the Si IV 1402.8 Å line satisfies $[S] < 0.1$ and $I(\lambda_0) > 10^3$ DN. There are 291 pixels satisfying these criteria. We do not invoke such constraints on other O IV or Si IV lines, since their intensities vary relatively to the Si IV 1402.8 Å one. Furthermore, these lines can be blended, such as O IV 1401.2 Å with Si 1 1401.5 Å in the far wing, which can distort the value of $|S|$ if the blend is relatively strong.

The 291 pixels, however, still contain spectra where the Si IV is strong but obviously asymmetric, such as saturated, extremely wide lines, or lines with closely spaced double peaks, for which $|S| < 0.1$ is still satisfied. Such lines obviously cannot be fitted well with a $\kappa$ distribution. Therefore, we present the results of the $\kappa$ fits only in pixels where an additional constraint of $\chi^2_{\text{red}} \leq 7$ is met. This value was found empirically upon reviewing the 291 fit results. This third constraint removes badly fitted spectra and results in 120 pixels where a satisfactory fit is performed. We note that the three constraints do not introduce a preference toward spectra with a $\kappa$ distribution as opposed to a more Gaussian ones.

The 120 suitable pixels are located in the TR loops, as well as in the plage region located at about Solar $Y = -227^\circ$ (Figure 4; see Polito et al. 2016a, Figure 4 therein). A single suitable pixel is located further north, in a point-like bright dot (triangle in Figure 4). An inventory of the $\kappa$ values obtained by fitting the Si IV 1402.8 Å and O IV 1401.2 Å lines is presented in Figure 4. There, the suitable pixels are shown as plus symbols, whose color depends on the $\kappa$ value in the given line. Four pixels including the bright dot are denoted by different symbols. The spectra observed in these pixels are shown in Figure 5 and discussed in Sections 5.1 and 5.2.

Overall, we see that a vast majority of the suitable Si IV profiles have $\kappa \leq 2.5$. Values as low as $\kappa \approx 1.7$ are the most common, being present in 21 pixels. An example of such a spectrum is discussed in Section 5.1.2. Contrary to that, the $\kappa$ values found from the O IV 1401.2 Å profiles are typically higher, $\kappa = 2.0$–2.5, with a peak at 2.3 (17 pixels). This is probably at least in part due to the lower intensities of the O IV lines, and thus lower S/N ratio. We did not, however, find a correlation ($r < 0.4$) between $\kappa$ and $I_0$. Furthermore, there are several pixels where the $\kappa$ derived from O IV 1401.2 Å line is significantly higher than those from Si IV 1402.8 Å, up to a factor of several. This suggests that in some pixels, the $\kappa$ values could indeed differ among the two lines in some cases. One such case is discussed in Section 5.1.3.

5.1. Example Spectra with Strong $\kappa$ Profiles

We now present the spectra and their fitting in three additional pixels, corresponding to the first three columns of Figure 5. The first one (denoted by a diamond) is located along the same loop bundle as the spectrum analyzed in Section 4. The second one (asterisk) is a spectrum from a neighboring loop bundle, and the third one (× symbol) is an example of a spectrum with different shapes of the Si IV and O IV profiles.

5.1.1. Loop Bundle

Figure 4 shows that the example spectrum analyzed in Section 4 occurs in a cluster of suitable pixels located along the same loop bundle. Here, we discuss a spectrum located in the center of the cluster, $1^{\circ}33$ (two spatial pixels) northward of the one analyzed in Section 4. The five TR line profiles are shown in the first column Figure 5. There, the values of $\kappa$ are nearly the same as those obtained in Section 4.2.2. In particular, $\kappa_{\text{Si IV}} = 2.11 \pm 0.03$ and $\kappa_{\text{O IV}} = 2.37 \pm 0.09$. These two strong lines are very well approximated with the $\kappa$ fits and we obtain $\chi^2_{\text{red}} = 3.0$, lower than in Section 4.2.2.

The other lines have similar $\kappa$ values, except the O IV 1399.8 Å one, whose $\kappa = 3.5 \pm 0.5$ is higher, and only consistent with the other ones within three times its uncertainty. A possible contributor is a single spurious higher intensity (by about 40 DN) wavelength bin in its red wing, which could correspond to a known Fe II 1399.97 Å blend. Since the chromospheric lines are typically very narrow, with widths of only a few wavelength bins, we cannot reliably verify the
Figure 5. Example spectra in four pixels spatial pixels discussed in Sections 5.1 and 5.2. The pixels are denoted by the diamond, square, cross, and triangle symbols. The location of these pixels is shown in Figure 4.
presence of such a blend from a single spurious wavelength bin. Adding a narrow Gaussian at this wavelength to the fitting procedure would lower the $\kappa = 3.1 \pm 0.4$ and produce a better fit of the O IV 1399.8 Å line, as well as an overall $\chi^2_{\text{red}} = 2.8$. We note that the value of $\kappa$ can be further lowered to values consistent with the Si IV line by restricting the width $w_{\kappa}$ similarly as in the exercise mentioned in Section 4.2.2, again, however, at the expense of a somewhat higher $\chi^2_{\text{red}}$.

5.1.2. Neighboring Loop

Intense TR lines with $\kappa$ line profiles can also be found in a neighboring bright TR loop, located further $\approx 1''$ westward. The spectra of this loop are suitable for fitting in many neighboring pixels located along the north–south direction of the loop. We present an example spectrum in second column of Figure 5. The values of $\kappa$ obtained there are among the lowest in the 120 pixels where fitting was performed, with $\kappa = 1.65 \pm 0.02$ for Si IV and $\kappa = 1.86 \pm 0.06$ for the strongest O IV line. The weaker O IV lines have higher $\kappa \approx 2.3$, but again lower $w_{\kappa}$ (see discussion in Section 4.2.2). The overall $\chi^2_{\text{red}} = 2.9$ is among the lowest found for the 120 suitable pixels.

5.1.3. Example Spectrum with Different Si IV and O IV Profiles

As an example of a spectrum with different types of profiles obtained from fitting of Si IV and O IV lines, we discuss the spectrum obtained in the pixel denoted by the symbol $\times$, i.e., pixel [41, 128] of the raster. The profiles of the five TR lines are shown in the third column of Figure 5. The Si IV line has about 1950 DN in its peak; i.e., it is more than a factor of two weaker than the examples studied in Sections 4 and 5.1.1–5.1.2. Its profile is somewhat asymmetric in the peak, but still having $|S| = 0.05$. The line nevertheless can be fitted with $\kappa = 2.90 \pm 0.11$, with a maximum residual of about 200 DN.

Contrary to that, for the O IV 1401.2 Å and 1404.8 Å blend we obtain $\kappa = 9.8 \pm 4.0$ and $7.2 \pm 5.6$, respectively, which are much higher than for the Si IV line. We again tried restricting the $w_{\kappa}$ to that of the Si IV line, but this does not lower $\kappa$ to a value consistent with the Si IV profile, indicating that in this case, the $\kappa$ value can indeed differ for O IV and Si IV. Finally, the two weak O IV and S IV lines appear asymmetric and have indeterminable $\kappa$, with uncertainties of more than $\pm 130$.

5.2. Are the $\kappa$ Profiles an Instrumental Effect?

Since we found the prevalence of small $\kappa$, especially derived from the Si IV line, is it possible that such profiles are an instrumental effect? Although the influence of the instrumental profile is small (as discussed in Section 4.2.3), it could still be conceivable that the wings are created somehow by the instrumental profile itself, e.g., if it has very large wings. Alternatively, the observed line wings could be due to stray light (i.e., the point-spread function) within the IRIS instrument. We therefore searched for the presence of a strong line with a Gaussian line profile, since the presence of such an observed line profile would rule out the instrumental effects.

We indeed found one single pixel among the 120 suitable ones, denoted by a triangle in Figure 4. This pixel is located in a bright dot-like feature. There, the Si IV line is both nearly Gaussian, as well as very strong. With $I_0 = 5715 \pm 19$ DN, it is among the third strongest Si IV line within the 120 suitable spectra. The corresponding spectrum of the five TR lines is shown in the fourth column of Figure 5. The Si IV 1402.8 Å line does not show the presence of large wings. We obtain $\kappa = 25.1 \pm 3.6$, which indicates that the shape is almost indistinguishable from a Gaussian (compare Figure 1, right; see also Jeffrey et al. 2016). We have verified this by fitting the line with a single Gaussian (Figure 6) and found that the single-Gaussian fit is indeed similar, but slightly better than a fit with $\kappa \approx 25$. The detection of a Gaussian Si IV profile, moreover in the direct neighborhood of an even brighter pixel (with $I_0 \approx 7000$ DN), means that the strong wings in the line profiles, approximated by a $\kappa$ distribution, and not present in this spectrum, do not arise as a result of an instrumental effect.

We note that although the Si IV line can be fitted with a single Gaussian, the corresponding residuals are asymmetric, which can indicate either a double-component line or presence of optical thickness effects. The line could indeed be fitted well with two Gaussian components (overall $\chi^2_{\text{red}} = 3.7$ instead of 6.3, Figure 6), with the stronger Gaussian being more redshifted. However, the likely presence of large electron densities, on the order of $10^{11}$ cm$^{-3}$ or higher indicated by the weak O IV lines and the Si IV 1406 Å being stronger than the O IV 1404.8 Å blend (see Polito et al. 2016a, Figures 9, 11, B.1, and B.4 therein) means that optically thick effects cannot be dismissed for this Si IV line. For further discussion of optically thick effects, see Appendix A.
The other O\textsc{iv} and S\textsc{iv} lines are very weak, with peaks less than 150 DN, and have a correspondingly indeterminable shape with large uncertainties in $\kappa$ (last column of Figure 5).

6. Line Intensities

The $\kappa$ distributions also influence the intensities of the emission lines studied (e.g., Dudík et al. 2014a, 2015; Dzifčáková et al. 2015). Unlike the line profiles, the line intensities are influenced by distribution of electron energies, since the ionization, recombination, and excitation processes all occur dominantly via electron–ion collisions (e.g., Phillips et al. 2008). Although the line intensities of IRIS TR lines depend on $\kappa$ (Dudík et al. 2014a), the lines are too close in wavelength (excitation energy) to offer unique diagnostics of $\kappa$ from observations using the line ratio–ratio method (Dudík et al. 2014b, 2015).

Nevertheless, the fact that the $\kappa$ distributions influence the Si\textsc{iv}/O\textsc{iv} ratios can be used to constrain the value of $\kappa$, if additional assumptions on the nature of the emitting region are made. Only five TR lines are observed, which provides four intensity ratios. Therefore, these additional assumptions are indispensable to restrict the number of free parameters in the calculations of synthetic intensities. Since Si is an element with low ionization potential, unlike oxygen, these assumptions necessarily involve elemental abundances. Further assumptions on the thermal structure of the emitting region are also required, such as on the differential emission measure. Since we observe a bright TR loop, we invoke an isothermal and iso-density assumption. This assumption is coupled with the assumption of the collisional ionization equilibrium common in calculation of synthetic spectra for $\kappa$ distributions (Dzifčáková & Dudík 2013; Dudík et al. 2014a; Dzifčáková et al. 2015). We note that possible transient ionization effects are discussed in Section 7.2.

Under these assumptions, we compare a grid of synthetic intensities with the observed ones in all 120 pixels analyzed in Section 5. We use the intensities relative to the Si\textsc{iv} 1402.8 Å, calculated for $\log(T_e)(\text{K}) = 4.0–6.0$ with a step of 0.05, $\log(N_e(\text{cm}^{-3})) = 9–12$ with a step of 0.1, and $\kappa = 1.6, 1.7, 1.8, 1.9, 2, 3, 4, 5, 7, 10, 15, 25, 33, 50$, and Maxwellian, for which the corresponding ionization equilibrium files are available in the KAPPA database (Dzifčáková et al. 2015). The line intensities are calculated using the method of Dudík et al. (2014a). In doing so, we use the atomic data of Liang et al. (2009, 2012) and Del Zanna & Badnell (2016) for Si\textsc{iv}, O\textsc{iv}, and S\textsc{iv}, respectively. We note that for the transitions from levels 3–20 in O\textsc{iv}, we use the $A_{ij}$ values from Corrégé & Hibbert (2004) instead of Liang et al. (2012). This is for consistency with the CHIANTI database, version 8 (Del Zanna et al. 2015). Details on the O\textsc{iv} and S\textsc{iv} atomic data used can be found in Appendix A of Polito et al. (2016a).

In summary, we invoke three free parameters, $T_e$, $N_e$, and $\kappa$, to approximate four observed line intensity ratios. This is done for each of the 120 suitable pixels. The best approximation is found by minimizing the quantity $\chi^2 = \sum_i (O_i - C_i)^2/C_i$, where $O_i$ and $C_i$ are four observed and calculated line intensity ratios, respectively.

We found that the observed intensity ratios are typically best approximated with $\kappa = 1.9–2$ (12.5% and 78.3% of the suitable pixels, respectively) if photospheric abundances of Asplund et al. (2009) are assumed. In Figure 7 top, we plot in black an example of the spectrum from a single pixel analyzed in Section 4. The synthetic spectrum calculated for $\kappa = 2$, $\log(T_e)(\text{K}) = 4.15$, and $\log(N_e(\text{cm}^{-3})) = 10.1$ is shown in red. The synthetic spectrum has been shifted by 0.05 Å to compensate for the ubiquitous redshift of TR lines, and we assumed the widths derived from line fitting (Section 4.2). The synthetic spectrum is a good match to the observed one, despite the rather simplifying assumptions. The $\chi^2$ obtained for this approximation is about 2 times lower than the minimum $\chi^2$ if $\kappa = 3$, and about 14.8 times lower than for a Maxwellian. Discrepancies, however, still occur in the O\textsc{iv} 1401.2 Å and S\textsc{iv} 1406.1 Å lines, which are overestimated and underestimated by about 100 DN, respectively. The reason for this discrepancy is not clear; we suspect it may be related to the discrete $\kappa$ values used, which, e.g., do not contain a value of $\kappa = 2.1$ (Section 4.2.2). We tried using a different set of photospheric abundances of Caffau et al. (2011), but this resulted in a worse match.

If the abundances are assumed to be coronal, the best approximation is obtained for $\kappa = 3–4$ (78.3% and 15.8% of the suitable pixels, respectively). In the case of the single pixel analyzed in Section 4, the best match obtained is a synthetic spectrum with $\kappa = 4$, $\log(T_e)(\text{K}) = 4.55$, and $\log(N_e(\text{cm}^{-3})) = 10.6$, shown in green color in the bottom panel of Figure 7. This synthetic spectrum fits the S\textsc{iv} line better; however, the O\textsc{iv} 1401.2 Å remains overestimated similarly as in the case of photospheric abundances.

Finally, if the synthetic line intensity calculations are restricted by a further assumption of only a Maxwellian distribution, the closest match to the observations is found for coronal abundances, $\log(T_e)(\text{K}) = 5.2$ and $\log(N_e(\text{cm}^{-3})) = 12.9$. Even so, the O\textsc{iv} lines at 1399.8 Å and 1401.2 Å are over and underestimated by about 150 and 170 DN, respectively. This agreement is significantly worse than for the $\kappa$ distributions. Furthermore, such extremely high densities are not realistic (see Polito et al. 2016a and Judge 2015). Under the assumption of photospheric abundances, no good approximation to the observed line intensity ratios can be found.

7. Discussion

7.1. On the Consistency of Electron and Ion Distributions

It is not obvious that the electron and ion velocity distributions should be the same. The classical relaxation time theory predicts that both electrons and ions should thermalize quickly at the high densities typical of the TR (see, e.g., Chapter 5 of Spitzer 1962, or Chapter 3.2.4 of Goedbloed & Poedts 2004). For example, using the values of $T_e$ and $N_e$ obtained in Section 6 together with Equation (3.50) of Goedbloed & Poedts (2004), the estimated relaxation timescale to an electron fluid is about $4 \times 10^{-6}$ s. The corresponding electron–ion equipartition time, i.e., the timescale for both ions and electrons to reach Maxweilians at the same $T$, is longer by a factor of $m_i/m_e$. For oxygen, it is 0.1 s.

These classical relaxation timescales, however, are applicable only for particles with $v < \theta$. That means that they are not valid for the case of $\kappa \approx 2$, where approximately 35% of particles have $v > \theta$ (Oka et al. 2013). Furthermore, since the collision frequency of the high-energy particles scales as $v^{-3}$, such particles become increasingly collisionless. Derivation of the corresponding equilibration timescales for $\kappa$ distributions, however, is out of the scope of this work.
7.2. Notes on Transient Ionization Effects

The relative line intensities, especially the ratios of \( \text{Si IV} / \text{O IV} \), can exhibit departures from equilibrium values due to transient ionization effects, i.e., in situations where the plasma is ionizing or recombining (e.g., Judge et al. 2012; Doyle et al. 2013; Olluri et al. 2013, 2015; De Pontieu et al. 2015; Martínez-Sykora et al. 2016). Smith & Hughes (2010) calculated the ionization equilibration timescales for astrophysically important elements as a function of temperature. Using their Figure 1, which assumes a Maxwellian distribution, known \( T \), and no flows, we find that the typical ionization equilibration timescales for Si and O can be on the order of 10 s or higher at electron densities on the order of \( 10^{10} \text{ cm}^{-3} \), which we obtained in Section 6. For the \( \kappa \) distributions, such ionization timescales will be shorter, since the total ionization rate is enhanced by orders of magnitude, while the total recombination rate is enhanced by a factor of about two for low \( \kappa \) values compared to the Maxwellian (Dziřičáková & Dudík 2013). However, detailed hydrodynamic or magnetohydrodynamic modeling of TR loops, which is beyond the scope of this work, would be required to study the presence of non-equilibrium ionization. Without it, we cannot exclude the presence of transient ionization effects. We note, however, that the non-equilibrium ionization effects would primarily impact the line intensity ratios. Their influence on the line profiles occurs only through the distribution of temperatures over which the individual ions exist when out of ionization equilibrium. In this regard, the observed shape of the line profiles in a chosen single pixel could serve as a strong constraint on the transient ionization simulations.

7.3. Line Widths and Temperatures for the \( \kappa \)-fit

Having obtained the fit parameters (Figure 3 and Table 2), we calculated the FWHM, and the corresponding ion temperatures \( T_i \) for the example spectrum studied in Section 4. To do this, we used Equation (14). In doing so, the uncertainties of the fit parameters are propagated to obtain the uncertainties of the resulting FWHM, and \( T_i \). The derived values are also listed in Table 2. The large uncertainties for the O IV 1404.8 Å and S IV 1406.0 Å lines come from the corresponding uncertainties in both \( \kappa \) and \( w_\kappa \); however, visual inspection of the observed line profiles (Figure 3) show that the derived value of FWHM \( \approx 0.2 \) is in accordance with the observations, despite its large calculated uncertainty.

We note that the FWHM \( \approx 0.2 \) is the same for all five lines, including Si IV. We note that the allowed Si IV line is often reported to have different width compared to the intercombination O IV lines (e.g., Doschek et al. 1977; Feldman et al. 1977; Kjeldseth Moe & Nicolas 1977; Doschek & Feldman 1978, 2004; Akiyama et al. 2005; Doschek et al. 2016). Our result indicates that the observed spectrum is unlikely to contain structures with wildly different electron densities.
Table 3  
Thermal and Non-thermal Widths, $w^{(th)}$ and $w^{(nth)}$, Derived for the Maxwellian and $\kappa = 2$ Distributions, Respectively

| Line | $w_c$ (Å) | $\log(T_{\text{max,Maxwell}})$ (K) | $w^{(th)}_{\text{Maxwell}}$ | $w^{(nth)}_{\text{Maxwell}}$ | $\log(T_{\text{max,κ=2}})$ (K) | $w^{(th)}_{\kappa=2}$ | $w^{(nth)}_{\kappa=2}$ |
|------|-----------|----------------------------------|-----------------|----------------|------------------|----------------|----------------|
| O IV 1399.78 Å | 0.143 ± 0.010 | 5.15 | 0.040 | 0.137 | 4.45 | 0.018 | 0.141 |
| O IV 1401.16 Å | 0.127 ± 0.003 | 5.15 | 0.040 | 0.121 | 4.45 | 0.018 | 0.126 |
| Si IV 1402.77 Å | 0.136 ± 0.001 | 4.90 | 0.023 | 0.134 | 4.10 | 0.009 | 0.136 |
| O IV 1404.82 Å (bl S IV) | 0.163 ± 0.018 | 5.15 | 0.040 | 0.158 | 4.45 | 0.018 | 0.162 |
| S IV 1406.06 Å | 0.144 ± 0.021 | 5.05 | 0.025 | 0.141 | 4.20 | 0.009 | 0.143 |

Note. The $T_{\text{max}}$ represent electron temperatures corresponding to the peak of the relative ion abundance in ionization equilibrium. The corresponding $w^{(th)}$ are derived using Equation (14) with $T = T_{\text{max}}$. The non-thermal widths are derived using Equation (19) from the observed $w_c$ and $w^{(th)}$.

The interpretation of the line profile as being given by the ion $\kappa$ distribution does not remove the need for non-thermal broadening. This is obvious from the ion temperatures $T_i$ derived from the line widths (Table 2), which are all above 1.4 MK and varying among the lines. This variation is likely being caused by the factor $(\kappa - 3/2)w^2_c$ being present in the denominator of Equation (6), which makes the $w_c$ not completely independent from $\kappa$ (see the discussion in Section 4.2.2) even if FWHM$_c$ of the line is a well-defined quantity. Low uncertainties on both $\kappa$ and $w_c$ are found only for the strongest lines; the lower the $I_0$, the larger the corresponding uncertainty on these fit parameters (see Table 2).

The non-thermal broadening can be for the case of $\kappa$ distributions derived analogously as for the Maxwellian. Recalling Equation (14) and assuming that the thermal and non-thermal broadening have the same $\kappa$, we can write

$$w^2_c = \frac{1}{2} \frac{\lambda_0}{c^2} \left[ \theta^2 + (\theta^{(nth)})^2 \right] = (w^{(th)}_c)^2 + (w^{(nth)}_c)^2,$$

where $w_c$ is now the observed width and $w^{(th)}_c$ and $w^{(nth)}_c$ are the thermal and non-thermal contributions. We note that these numbers differ for each $\kappa$ due to the shift of the electron temperature $T_{\text{max}}$ at which the relative ion abundance has its peak. For $\kappa$ distributions and TR ions, the shift is toward lower $\log(T_{\text{max}})$ (K) for smaller $\kappa$ (Dzičáková & Dudík 2013; Dudík et al. 2014a), with the corresponding decrease of $w^{(th)}$ if the ions are assumed to have the same temperature as electrons. These numbers are shown in Table 3 for the Maxwellian and $\kappa = 2$ distributions, respectively, together with the resulting $w^{(nth)}$. It is obvious that the $\kappa$ distributions with low $\kappa$, detected by fitting the line profiles in this work, lead to a small increase of the non-thermal characteristic widths.

However, there is no reason to assume that the thermal and non-thermal broadening components have the same $\kappa$, as we have done in Equation (19). For example, the ion distribution could be a Maxwellian at temperatures close to $T_{\text{max}}$, while it could be only the broadening component (e.g., due to turbulence) that has a $\kappa$ distribution. The resulting line profile would then be a convolution of a Gaussian and a $\kappa$ profile (see 4.2.3). We have attempted to fit such convolved profiles to the observed TR lines, assuming a Gaussian FWHM$_C$ corresponding to $w^{(th)}_{\text{Maxwell}}$ (Table 3) and a $\kappa$ component. The resulting fits have somewhat lower $\kappa$ values than a purely $\kappa$ fit. For the example spectrum studied in Section 4.2.2, we obtained $\kappa = 2.00 \pm 0.08$ for O IV 1401.2 Å, while for Si IV 1402.8 Å, we got $\kappa = 2.06 \pm 0.03$. These lower $\kappa$ values are not surprising. If the Gaussian component of the convolution has non-negligible width, the convolved $\kappa$-Gaussian profile has lower wings than a purely $\kappa$ one. Therefore, the fit has to decrease the fitted $\kappa$ in the convolved profile in order to match the observed line profiles.

8. Summary

We analyzed the IRIS FUV observations of an AR containing closed, bright TR loops and a plage. Spectra containing strong and symmetric spectral lines, belonging to O IV, Si IV, and S IV, were fitted using $\kappa$ distributions. An example spectrum of a closed TR loop was also fitted using single- and double-Gaussian fits. The single-Gaussian fits failed to properly account for the line profiles, which showed both pronounced peaks and wings. Two Gaussians fitted the profiles much better, but the fit required the relative intensities of the two Gaussians to be nearly the same, especially for weaker lines of O IV and S IV.

All five TR lines can be fitted with a $\kappa$ distribution of ion velocities equally well, or in the case of Si IV better than the double-Gaussian fits. The $\kappa$ fit, however, contains fewer free parameters. The values of $\kappa$ obtained from the line profile fitting are low, about two, and are typical especially for the strongest 1402.8 Å line of Si IV. Similar values of $\kappa$ were found for all five lines in the majority of pixels, but there were some pixels where the O IV lines can have higher values of $\kappa$. However, a single spectrum from a dot-like bright point exhibited a nearly Gaussian Si IV profile, which allowed us to rule out the instrumental profile or the point-spread function as a cause of the large line wings. In addition to the line profile analysis, the line intensities relative to the Si IV one can also be well fitted with an electron $\kappa$ distribution with a similar value of $\kappa = 2$, if photospheric abundances are assumed.

We found, however, that the $\kappa$ distributions do not remove the non-thermal broadening component. If anything, they increase the non-thermal width, since for $\kappa$ distributions the TR ions are expected to exist at lower $T_e$ than for the Maxwellian case. We also found that all five TR lines can have the same FWHM, of about 0.2 Å, irrespective of whether the line is an allowed or an intercombination one. This is contrary to most reports within the literature (although see Polito et al. 2016a as well as Figure 8 of Doschek et al. 2016) and suggests that the allowed and intercombination lines in our case do not form in regions with highly different densities (see Doschek 1984; Doschek et al. 2016). Furthermore, since the optical thickness of a line depends inversely on its width, we found that the observed non-thermal width, which is about an order of magnitude larger than the thermal one, is sufficient to make the Si IV 1402.8 Å line optically thin. This is because for the large
non-thermal width, the potential absorbers are spread throughout the wavelength range of the line, decreasing the number of absorbers at any given $\lambda$.

These results mean that, at least in the cases where the FWHM and $\kappa$ are the same for all five lines, the mechanism creating the line profile has to act in the same way on all TR ions observed, Si IV, O IV, and S IV, i.e., through at least the range of temperatures where these ions are formed. However, similar values of $\kappa$ have been obtained for a transient coronal loop observed by Hinode/EIS in Fe XI–Fe XII emission (Dudik et al. 2015) and for flare loops emitting in Fe XVI and Fe XXIII by Jeffrey et al. (2016, 2017). This could mean that the range of temperatures is not limited to the TR investigated here, but could be present throughout the outer solar atmosphere.

Although the values of $\kappa$ obtained here from the line profile fitting and the line intensity ratios are consistent, we finally note that the present data do not provide unambiguous evidence for the presence of $\kappa$ distributions of ion and electron velocities in the solar TR. A unique diagnostic can only be obtained from ratios of lines originating from levels with widely different excitation energies within the same ion (Dudik et al. 2014b, 2015), but such lines cannot be observed by IRIS due to its limited wavelength range. In this regard, a coordinated IRIS observations together with the future SPICE instrument on board the Solar Orbiter could be helpful, since both instruments are designed to observe O IV lines, but at wavelength ranges different by a factor of two.

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Facility: IRIS.

Appendix A

Is the Si IV 1402.8 A Line Optically Thick?

In Sections 4.2 and 5 we found that the $\chi^2_{\text{red}}$ is always higher than 1, with the lowest values found being of about 3 despite the $\kappa$ distribution providing a good approximation of all five TR line profiles. We also reported that the largest residuals occur within the Si IV profile and that the $\chi^2_{\text{red}}$ does not depend on the small “lumps and bumps” above the pseudo-continuum, such as the Si I or Fe II lines.

A possible explanation of these high residuals is that the Si IV 1402.8 A line is not entirely optically thin. Although we do not observe any self-absorption features (Yan et al. 2015), weak optically thick effects could still lead to the flattening of the peak of the line. Since the IRIS observation analyzed here does not contain the other Si doublet line at 1393.8 A (see, e.g., Section 5.1 in Del Zanna et al. 2002), we resort to an estimate of the optical depth $\tau$ in the Si IV 1402.8 A line. To do that, we use the classical formula (e.g., Buchlin & Vial 2009, Equation (15) therein)

\[
\tau(\lambda) = \tau_0(\lambda_0) \Phi(\lambda) = \frac{\lambda^2_0 A_I \Phi(\lambda) N(Si^{+3})}{4\pi^3/2 N(\text{Si}) A(Si) N_H} \langle N_e \rangle \Delta s, \tag{20}
\]

where $\Delta s$ is the (Doppler) width of the absorption profile $\Phi(\lambda)$, which is normalized to $\Phi(\lambda_0) = 1$, $N(Si^{+3})/N(\text{Si})$ is the relative ion abundance of Si IV, $A(\text{Si})$ is the abundance of Si, which we take to be photospheric (see Section 6), $\langle N_e \rangle$ is the average electron density in the emitting source, and $\Delta s$ is the path length along the line of sight through the source.

Taking for simplicity $\Delta s = w_{\text{Max}}^0$ corresponding to the Maxwellian distribution (Table 3), $N(N(Si^{+3})/N(Si)) \approx 0.19$ according to CHIANTI 8 (Del Zanna et al. 2015) for the Maxwellian distribution at log ($T_{\text{max}}$ (K)) = 4.9, and $\Delta s = 0^\circ 33 f$, where $f$ is the path length filling factor in an IRIS pixel, we obtain

\[
\tau_0 \approx 0.26 f \frac{\langle N_e \rangle}{10^{10} \text{ cm}^{-3}} \tag{21}
\]

at the line center of Si IV. The corresponding numerical factor for the O IV and S IV lines is negligible (see also Doschek & Feldman 1978), on the order of $10^{-6}$, because of the correspondingly lower $A_{ij}$ values for these intercombination lines.

Interestingly, for $\kappa = 2$, the numerical factor changes to $\approx 1.5$, mostly due to (i) the decrease of $\Delta \lambda_D = w_{\text{Max}}^0$ with respect to the Maxwellian (Table 3), and (ii) the increase in $N(Si^{+3})/N(\text{Si})$ to about $0.39$ for such $\kappa$ at log ($T_{\text{max}}$ (K)) = 4.10 (see Figure 1 in Dudik et al. 2014a).

We note, however, that the value of $\tau_0$ depends inversely on the choice of $\Delta \lambda_D$. Taking the observed $\Delta \lambda_D = w_{\text{Max}}^0$ instead of $w_{\text{Max}}^0$ would lead to a substantial decrease,

\[
\tau_0 \approx 0.02 f \frac{\langle N_e \rangle}{10^{10} \text{ cm}^{-3}}, \tag{22}
\]

for a Maxwellian distribution. The corresponding numerical factor for $\kappa = 2$ is about 0.06.

If $\tau_0 > 0$, optical thickness effects should change the shape, and thus the width, of the line profile. Assuming that the source function $S_\lambda$ is constant, the emergent intensity $I$ is given by (e.g., Doschek & Feldman 2004; Hubeny & Mihalas 2014)

\[
I(\lambda) = \int_0^{\tau(\lambda)} S_\lambda \exp(-t_\lambda) dt_\lambda = S_\lambda[1 - \exp(-\tau(\lambda))], \tag{23}
\]

where $\tau(\lambda)$ is given by Equation (20). If we now assume that $\Phi(\lambda) = I_0(\lambda)/I_0$, i.e., a line profile given by a $\kappa$ distribution (Equation (11)), the FWHM$_{\kappa}$ of such an optically thick profile is given by

\[
\text{FWHM}_{\kappa}(\tau_0)^2 = 8(\kappa - 3/2) w_{\kappa}^2 \times \left[ \left( \ln(2) - \ln(\exp(-\tau_0) + 1) \right)^2 - 1 \right], \tag{24}
\]
which reverts to the expression for $\text{FWHM}^2_0$ (Equation (14)) for $\tau_0 \to 0$. For a Gaussian profile $\Phi(\lambda) = I_0(\lambda)/I_0$ (Equation (8)), we obtain

$$\text{FWHM}^2_0(\tau_0) = 8w_0^2[\ln(\tau_0) - \ln(2) - \ln(1 + e^{-\tau_0})].$$

(25)

The $\text{FWHM}^2_0(\tau_0)/\text{FWHM}_0$ ratios are shown in the left panel of Figure 8. The corresponding profiles given by Equation (23) are shown for the Gaussian and $\kappa = 2$ cases in the middle and right panels, respectively. The profiles for $\tau_0 = 0$ have progressively increased widths, which occurs dominantly in the peak of the line. We note that such profiles could still be fitted with a $\kappa$ distribution, but the goodness-of-fit decreases with increasing $\tau_0$, since a significant mis-match in the peak occurs if $\tau > 1$. The resulting $\kappa$ obtained from the fit also increases with $\tau_0$. For example, a profile with $I_0 = 10^3$ DN, $\kappa = 2$, and $\tau_0 = 1$ could be fitted with $\kappa_{\text{fit}} = 2.36 \pm 0.06$, while a $\kappa = 5$ profile with the same optical thickness would yield $\kappa_{\text{fit}} = 11.1 \pm 1.3$. These resulting $\kappa_{\text{fit}}$ are only weakly dependent on the $I_0$.

So is the line optically thick? To hint at the answer, we make use of the formulae derived above. Taking $\tau_0 = 1.5$ (see the discussion following Equation (21)), for $\kappa = 2$ we find that the observed FWHM of the line should be a factor of $\approx 1.34$ higher than if the line is optically thin. Considering now the example spectrum investigated in Section 4, which has nearly the same FWHM, for all five TR lines (Table 2 and Figure 3), and taking into account that the intercombination lines are optically thin, we are forced to conclude that the Si IV line is also optically thin, as suggested by Equation (22). It is the large non-thermal width of these TR lines that leads to suppression of $\tau_0$: essentially, a line with a large non-thermal width means that the potential absorbers are spread throughout the wavelength range of its profile, leaving correspondingly fewer absorbers at any given wavelength $\lambda$.

This result also means that the large residuals for the $\kappa$ fit of the Si IV line in the example spectrum studied in Section 4.2.2 cannot be explained by optically thick effects. The relative symmetry of the $\kappa$-fit residuals around 1402.8 Å (Figure 3) could then suggest the presence of a weak additional component, with a peak intensity of at most $\approx 4\%$ of the dominant $\kappa$ component.

**Appendix B**

**What Dominates the $\chi^2_{\text{red}} \approx 3$?**

In Appendix A, we found that the optical thickness effects in the Si IV 1402.8 Å line were not a likely source that increases the $\chi^2_{\text{red}}$. Why, then, is the $\chi^2_{\text{red}}$ almost never lower than 3?

To answer this question, in Figure 9 we plot the contribution of individual spectral bins $\lambda_i$ to the total $\chi^2_{\text{red}}$. This is done for the $\kappa$ fit of the example spectrum reported in Section 4.2.2. The S/N ratio, equal to $I_{\text{obs}}(\lambda_i)/\sigma(I_{\text{obs}}(\lambda_i))$, is overplotted in dark red color. The values of S/N follow approximately $I_{\text{obs}}^{1/2}$. This is because the noise for the for strong lines is dominated by the photon noise, while in the pseudo-continuum, the readout noise of 3.1 DN can be an important contribution.

The top panel of Figure 9 shows that there are numerous spectral bins that contribute more than 0.02, some up to 0.08–0.11 to the total $\chi^2_{\text{red}}$. Here, the value of 0.02 was chosen as an indicative one, since larger values produce a net contribution of about $\approx 2$ to the overall $\chi^2_{\text{red}}$. Within the Si IV 1402.8 Å line, there are six such spectral bins, contributing a net $\approx 0.31$ to the overall $\chi^2_{\text{red}}$. Very few such bins are located in other TR lines. Therefore, the majority of dominant contributors to $\chi^2_{\text{red}}$ come from the pseudo-continuum.

Could these contributions from the pseudo-continuum arise from weak, barely resolvable spectral lines that were not fitted? In Section 4.2.2, we reported that fitting small “lumps and bumps” above the pseudo-continuum does not help decrease the $\chi^2_{\text{red}}$. To find out which pseudo-continuum pixels dominate the $\chi^2_{\text{red}}$, in Figure 9, we plot the dependence of the contribution to $\chi^2_{\text{red}}$ on the S/N, as well as $I_{\text{obs}}$ and $\sigma(I_{\text{obs}})$. The results indicate that there are two dominant branches: one having a very low $S/N \approx 1$, and the other having $S/N \approx 7–10$. Some contribution comes also from the high residuals in the Si IV line; these can be identified easily since their S/N is among the highest present, above 100.

The first branch originates in pixels where both the signal and noise is dominated by the readout noise. These pixels are
close to the 3.1 DN readout noise limit, shown by the vertical azure line in the bottom panels of Figure 9. The other branch, with S/N ≈ 7–10, arise from pseudo-continuum pixels having intensities several times larger than \( I_{BG} \), which is shown by the vertical blue line. At least some of these could be due to weak lines from low ionization stages, such as Fe II 1399.97 Å (already mentioned in Section 5.1.1), 1401.7 Å, 1404.12 Å, etc., as well as HeII 1399.89 Å, 1403.98 Å, and a few unidentified lines at 1400.31 Å, 1401.96 Å, and so on. More details on these weak lines can be found in Sandlin et al. (1986), Keenan et al. (2002), Young (2015), Tian et al. (2015, Figure 2 therein), and Polito et al. (2016b, Figure 14 therein). However, since the width of such lines is small, about two wavelength bins in the present spectrum, these lines cannot be clearly recognized in the spectrum if they are weak, much less reliably fitted with a single Gaussian having three free parameters. Although including badly constrained fits to “lumps and bumps” would remove some of the contributions to the overall \( \chi^2_{\text{red}} \) as shown in Figure 9, doing so would also increase the number of fit parameters \( N_{\text{fit}} \) and thus reduce the \( \nu \) factor (see Equation (18)), which in turn increases the \( \chi^2_{\text{red}} \) if too many pseudo-features are forced to be fitted.

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