Analysis of optically thin lines observed by IRIS

Release 1.0

Vanessa Polito and Paola Testa

Oct 28, 2019
# CONTENTS

1 Introduction .......................... 1

2 Formation of optically thin lines 3
   2.1 Excitation and de-excitation of atomic levels .......................... 3
   2.2 Ionization/Recombination ................................................. 4
   2.3 Line intensity and contribution function ............................... 6
   2.4 Non-equilibrium effects ................................................. 7

3 Optically-thin lines observed by IRIS 11
   3.1 O I .................................................. 11
   3.2 Cl I .................................................. 12
   3.3 Si IV ............................................... 12
   3.4 O IV, S IV .......................................... 12
   3.5 Fe XII ............................................ 14
   3.6 Fe XXI ........................................... 14

4 Analysis of IRIS line profiles 17
   4.1 Line fitting .............................................. 17
   4.2 Wavelength calibration .............................................. 21
   4.3 Radiometric calibration ........................................... 23

5 Plasma diagnostics using IRIS lines 25
   5.1 Density diagnostics ....................................... 25
   5.2 Plasma motions: Doppler shifts and non-thermal line widths ........... 27
   5.3 Opacity using ratio of Si IV lines ................................ 32
The very high temperatures (millions of Kelvin (K)) reached in the solar atmosphere mean that the chromosphere, transition region (TR) and corona strongly emit at UV and X-ray wavelengths. In particular, the contribution to the UV spectrum from different layers of the solar atmosphere can be summarized as follows:

- **EUV (~100-1200 Å):** mainly from the hot corona and TR
- **FUV (~1200-2000 Å):** mainly from TR & chromosphere
- **NUV (~2000-3900 Å):** mainly from chromosphere & photosphere

In contrast to the dense chromosphere (with electron number densities $N_e$ of about $10^{10.5} - 10^{14} cm^{-3}$, e.g. Avert & Loser 2008, ApJS, 175, 229), the tenuous corona (with $N_e \sim 10^8 cm^{-3}$, e.g. Warren & Brooks, 2009, ApJ, 700, 1) is mostly optically-thin to visible, UV and X-ray radiation, which means that photons at these wavelengths will not be absorbed while passing through the coronal plasma and will eventually reach the observer. The focus of this tutorial is on lines formed under these optically-thin conditions, whereas the analysis of optically thick lines observed by IRIS is discussed in detail in ITN 39.
At UV and X-ray wavelengths below 1600 Å, the solar spectrum is dominated by emission lines and continuum background emission (see Fig. 1.1). This latter is mainly due to:

- **Free-free, or Bremsstrahlung emission**: produced by the deceleration of a free electron in the Coulomb field of an ion.
- **Free-bound emission**: a free electron is captured by an ion into a bound state.

Emission lines result from the spontaneous decay of an excited electron from one energy level to a lower energy level within an atom or an ion, the excess energy being carried on by a photon. The details of line formation will be discussed in Section 2. An introduction to the most important IRIS lines which can be formed under optically thin conditions is presented in Section 3. Section 4 will introduce some of the tools to analyze the spectra of these lines whereas in Section 5 we will describe in details some of the diagnostics that can be obtained from them.
CHAPTER TWO

FORMATION OF OPTICALLY THIN LINES

This section aims to provide a basic overview of the atomic processes which give rise to the UV optically-thin line spectra observed by IRIS and some of the tools to derive important atomic physics parameters for the IRIS lines. For a more complete review on solar UV spectroscopy, the reader is referred to e.g. the book by Phillips et al. 2009 or the recent review by Del Zanna & Mason 2018, LRSP, 15, 5.

The intensity of an emission line strongly depends on:

• the number of emitting ions in the $z$-th ionization state of the element: $X^{+z}$
• the fraction of the ions $X^{+z}$ which are in an energy level $j$ giving rise to a particular spectral line: $X_j^{+z}$

For each ion in the solar plasma, there is a continuous interplay between the processes that change its ionization state (ionization/recombination, see Sect.2.1) and processes that populate/depopulate its excited levels (excitation/de-excitation, see Sect.2.2). In the low density plasma in the upper solar atmosphere, the timescales for ionization and recombination are usually much longer than those for excitation and de-excitation, so that the two sets of processes can often be de-coupled (e.g. Mariska 1992, Del Zanna & Mason 2018, LRSP, 15, 5). The intensity of an optically-thin line is proportional to the product of the contribution function, which contains the information on the relevant atomic processes, and the emission measure, which is determined by the physical conditions of the local plasma (see Sect.2.3). The freely available CHIANTI atomic database (Dere et al. 1997, A&AS, 125, 149, Del Zanna et al. 2015, A&A, 582, 56, see also the CHIANTI user guide ) provides a comprehensive set of atomic data covering the UV and X-ray wavelength ranges along with IDL routines to calculate the emission of optically thin, collisionally-dominated plasma for equilibrium conditions. A Phython version of CHIANTI is also available here.

It should be noted that the atomic processes are often evaluated assuming that the emitting plasma is in equilibrium conditions. However, during transient heating phenomena or in inhomogeneous plasma conditions, this assumption might not be longer valid. The most important non-equilibrium conditions which can be found in the solar atmosphere (i.e. non-equilibrium ionization and non-thermal equilibrium) will be briefly discussed in Sect. 2.4.

2.1 Excitation and de-excitation of atomic levels

In the upper solar atmosphere, the most important contributors to the level excitation are collisions between ions and free electrons (e.g. Phillips et al. 2009). By colliding with an electron, an ion can be excited from a lower energy state $i$ to a higher one $j$:

$$X_i^{+z} + e^- \rightarrow X_j^{+z} + e'$$

Other processes, such as proton-ion collisions and photo-excitation, can also contribute to change the ion energy state but are usually less important (however, see e.g. Seaton 1964, MNRAS, 127, 191, Doschek 1971, ApJ, 170, 573).

Spontaneous radiative decay and collisional de-excitations are the main de-excitation mechanisms:

$$X_j^{+z} \rightarrow X_i^{+z} + \frac{hc}{\lambda}$$
where \( \frac{hc}{\lambda} \) is the energy of the emitted photon. For \textit{allowed transitions}, the excitation is usually followed by de-excitation through spontaneous decay. The collisional de-excitation becomes important at sufficiently high density for \textit{forbidden lines}, where the probability of spontaneous radiative decay is very small.

In the \textit{coronal model approximation} (i.e. in the low-density limit when all the population of an ion is assumed to be in the ground state), spontaneous radiative decay and electron collision excitation are mainly competing to change the ion energy state.

### 2.2 Ionization/Recombination

An ion undergoes an ionization process when it is subject to a perturbation resulting in one of its bound electrons becoming free and leaving the ion. Correspondingly, if an electron is captured by an ion, the latter undergoes a recombination process. The balance between the ionization and recombination processes in a plasma determines the fractional abundances of all the ionization stages of each element in the plasma. In the solar atmosphere, there are three main \textit{ionization–recombination pair of processes}:

- Photoionization \( <-> \) Radiative recombination
- Collisonal ionization \( <-> \) Three-body recombination
- Excitation-autoionization \( <-> \) Dielectric recombination

The \textit{abundance} \( N(X^{+z})/N(X) \) of each ion at the \( z \)-th ionization stage of an element \( X \) can be obtained by solving the equations which describe the interplay between the ionization and recombination processes. The time required to reach equilibrium in a coronal plasma of density \( 10^9 \text{ cm}^{-3} \) may be of the order of 100 s or more depending on the element (e.g. Smith et al., 2010, ApJ, 718, 583). Plasma regions which remain stable on longer timescales than the typical ion equilibration times are considered to be in a so-called \textit{ionization equilibrium}. \textit{Figure 2.1} shows the ion fractional abundances for most of the strongest optically-thin lines observed by IRIS, obtained using the IDL routine \texttt{read_ioneq.pro}.

#### \texttt{pro read_ioneq}

**Purpose:** reads files containing the ionization equilibrium values

**Usage:**

\[
\text{read_ioneq, ioneq_file, logt_ioneq, ioneq, ioneq_ref}
\]

**Parameters**

- \texttt{ioneq_file}: input ionization file, e.g. \( !xuvtop+/ioneq/chianti.ioneq' \)
- \texttt{logt_ioneq}: output array of temperatures in a logarithmic scale
- \texttt{Ioneq}: output 3D array (T,element,ion) of the fractional abundance of the ion in ionization equilibrium. For example, the ionization balance of Si IV will be: \texttt{ioneq_si4=ioneq[*,13,3]}
- \texttt{ioneq_ref}: reference in the scientific literature

**Note:** Note that the ionization balances in CHIANTI version 8 and earlier are calculated in low-density (coronal model) approximation. Taking into account the effects of high densities on the ionization equilibrium (in particular the suppression of dielectric recombination) may affect the ionization balances significantly. See an example of the high-density effects on the formation of the IRIS TR lines in \textit{Figure 2.2}, as studied by Polito et al. 2016, ApJ, 594, 64. See also Nikolic et al, ApJ, 768, 1 ; Young et al. 2018, ApJ, 857, 5 and chapter 3.5.6 of Del Zanna & Mason 2018, LRSP, 15, 5 for more on this topic. See also Sect. 5.1. \textbf{NB:} CHIANTI version 9.0 allows for the exploration of the density sensitivity of some of the satellite lines in a limited wavelength range. Young et al. 2019.
Fig. 1: Figure 2.1. Ionization equilibrium balances for some of the optically-thin lines observed by IRIS, obtained using the CHIANTI routine read_ioneq.pro and atomic data included in CHIANTI v.8.

Fig. 2: Figure 2.2. Ionization equilibrium balances for the TR lines observed by IRIS calculated taking into account the effect of high densities on the line formation using atomic data from the OPEN-ADAS database. From Polito et al. 2016, ApJ, 594, 64.
2.3 Line intensity and contribution function

In optically-thin conditions, the number of photons in a spectral line observed at a distance $d$ is given by the sum of all the photons emitted by each plasma volume $dV$ along the line-of-sight. Considering a photon of energy $\hbar \nu$ emitted by spontaneous radiative decay from the energy level $j$ to $i$, the total emissivity $\epsilon_{ji}$ of the $j \rightarrow i$ transition will be given by:

$$\epsilon_{ji} = \frac{\hbar \nu}{\lambda} A_{ji} N(X_j^{\text{zz}})$$

where $A_{ji}$ is the Einstein coefficient of spontaneous emission of the transition $j \rightarrow i$ and $N(X_j^{\text{zz}})$ is the number density of the the $X^{\text{zz}}$ ion in the excited level $j$. The $A_{ji}$ value depends on the atomic number of the ion and is usually much larger for allowed transitions, smaller for intercombination transitions and very small for forbidden transitions.

The intensity of an optically thin spectral line at wavelength $\lambda$ is thus given by:

$$I(\lambda) = \frac{1}{4\pi d^2} \int_A \frac{\hbar \nu}{\lambda} A_{ji} N(X_j^{\text{zz}}) dV \ [\text{erg cm}^{-2}\text{s}^{-1}]$$

$N(X_j^{\text{zz}})$ can be expressed as:

$$N(X_j^{\text{zz}}) = \frac{N(X_j^{\text{zz}})}{N(X)} \frac{N(X)}{N(H)} A_b(X) \frac{N(H)}{N_e} N_e$$

where $\frac{N(X_j^{\text{zz}})}{N(X)}$ and $\frac{N(X)}{N(H)}$ represent the relative level and ion populations respectively and $N_e$ is the plasma number electron density. $A_b(X) = N(X)/N(H)$ is the abundance of the element $X$ relative to hydrogen and $N(H)/N_e$ is the hydrogen abundance relative to the free electron density, which in the solar atmosphere is usually taken as ~0.83.

Using the equations above, we can define the contribution function $G(T, N_e, \lambda)$ as:

$$G(T, N_e, \lambda) = \frac{N(X_j^{\text{zz}})}{N(X)} \frac{N(X)}{N(H)} A_b(X) \frac{N(H)}{N_e} \frac{\hbar \nu}{\lambda} \ [\text{erg cm}^3\text{s}^{-1}]$$

The contribution function contains all the information on the atomic processes which contribute to give rise to the emission line. Figure 2.3 shows the contribution functions for a set of spectral lines observed by IRIS, which have been calculated using the IDL routine `gofnt.pro` (see below) and atomic data available in CHIANTI v.8.

**pro gofnt**

**Purpose:** calculates contribution functions (line intensity per unit emission measure)

**Usage:**

```
gofnt, Ion, Wmin, Wmax, Temperature, G, Desc, density=density, lower_levels=lower_levels, upper_levels=upper_levels [+keywords]
```

**Parameters**

- **Ion**: the CHIANTI style name of the ion, i.e., `si_4` for Si IV
- **Wmin**: minimum wavelength (Å) in the wavelength range of interest
- **Wmax**: maximum wavelength (Å) in the wavelength range of interest

The lower/upper level of the transition can be also specified, in addition with the abundance and ionization equilibrium files. For example, the calling sequence for calculating the contribution function for the Si IV 1402.77Å will be:

```
gofnt, 'si_4', 1402., 1404., t_si_4_1403, gof_si_4_1403, desc_si_4_1403, dens=dens, lower_levels=1, upper_levels=2, abund_name=abund_name, ioneq_name=ioneq_name
```
Analysis of optically thin lines observed by IRIS, Release 1.0

where one can choose e.g. abund_name=!xuvtop+’/abundance/sun_photospheric_2009_asplund.abund for photospheric abundances from Asplund et al. 2009. The idl routine which_line.pro can be used to find the lower/upper levels of a specific atomic transition given the input wavelength in Angstrom.

pro which_line

Usage:

which_line, ionname, wvl, [+keywords]

Fig. 3: Figure 2.3 Contribution functions (in a log scale) for a set of spectral lines observed by IRIS. Calculated using the CHIANTI routine gofnt.pro, assuming photospheric element abundances from Asplund et al. 2009, ARA&A, 47, 481 and an electron number density $N_e$ of $10^{11}$ cm$^{-3}$.

The intensity of an emission line can thus be re-written as:

$$I(\lambda) = \frac{1}{4\pi d^2} \int \Delta V G_m(T, N_e)N_eN_H dV \ [\text{erg cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$$

The quantity $N_eN_H dV = d(EM)$ defines the differential emission measure (DEM) of the plasma in the volume $dV$. The total EM of the plasma is given by integrating over the total emitting volume $V$:

$$EM = \int_V N_eN_H dV \ [\text{cm}^{-3}]$$

2.4 Non-equilibrium effects

The spectra of optically-thin lines are often interpreted assuming equilibrium conditions, i.e. the physical conditions of the plasma are time-independent and are described assuming that the particles possess an isotropic, Maxwellian distribution of velocity. Departures from these conditions can occur during highly dynamic phenomena and can lead to non-equilibrium ionization and non-thermal particle distributions. Both effects can be important for plasma diagnostics, as mentioned in Sect. 5.

Non-equilibrium ionization: If the temperature of the plasma changes on a very short timescale, an ion population may be present at much different temperatures than those at which it would normally form in equilibrium. Under non-equilibrium ionization conditions, one needs to solve the set of all time-dependent ionization balance equations to determine the ion populations over time. The intensity of a spectral line can be significantly different in non-equilibrium conditions.

**Fig. 4:** Figure 2.4: Contribution functions for Si IV (top) and OIV (bottom) in ionization equilibrium (violet curve) and time-dependent ionization at different times, as marked. From Doyle et al. 2013, A&A, 557, 9.

**Non-thermal particle distributions:** The assumption of Maxwellian distribution for the electron and ion velocities in a plasma is valid if the energy redistribution through particle collisions takes place on a sufficiently short time scale. In low density and inhomogeneous hot plasma, such as in the outer solar atmosphere, or in the presence of dynamic phenomena such as flares, the timescales for equilibration may be longer. The presence of non-Maxwellian distributions can significantly alter the properties and ionization balance of the plasma (see e.g. Figure 2.5). $\kappa$ (or generalized Lorentzian) distributions provide a very convenient tool to describe the non-thermal behavior of the particles, as they are characterized by only three independent parameters ($n, T,$ and $\kappa$). The KAPPA-package (Dzifčáková et al. 2015, ApJS, 217, 14) provides a collection of atomic data based on the CHIANTI database for non-Maxwellian $\kappa$-distributions.
Fig. 5: Figure 2.5: Contribution functions for the Si IV 1402.77 Å (left) and O IV 1401.16 Å (right) lines for Maxwellian as non-Maxwellian distributions with different values of $\kappa$, as indicated by the legend. From Dudík, et al. 2014, ApJ, 780, 12.
CHAPTER
THREE

OPTICALLY-THIN LINES OBSERVED BY IRIS

The IRIS spectra contain several lines which can be formed under optically thin conditions (e.g., ITN 26 http://iris.lmsal.com/itn26). In Figure 3.1 we show a reference spectrum on which we highlight (blue boxes) the position of some of the strongest and most interesting optically thin lines observable with IRIS.

Fig. 1: Figure 3.1: IRIS reference spectra in the FUV bands, in which position of the most prominent optically thin lines are highlighted in blue.

In the following sections, we provide an overview of the strongest optically-thin lines observed by IRIS, and their diagnostic potential. We note that some of these lines (e.g. Si IV) can also be formed under optically thick conditions.

3.1 O I

Recent studies of the mechanism of formation of the IRIS OI 1355.598Å emission line (from Lin & Carlsson 2015, ApJ, 813, 34) have shown that this line is mostly formed under optically thin conditions formed throughout the whole chromosphere. Lin & Carlsson (2015) also show that its Doppler shift is a good diagnostic of the velocity averaged over its formation region (see Figure 3.2).

Being optically thin, the line width of the IRIS OI 1355Å line provides a good diagnostic of non-thermal motions in the chromosphere (e.g., Chae et al. 1998, ApJ, 505, 957).
Fig. 2: Figure 3.2. Correlation between O I 1355 Doppler shifts and velocity of plasma emitting this line, from Bifrost simulations (Lin & Carlsson 2015, ApJ, 813, 34).

3.2 Cl I

The formation of the IRIS Cl I 1351.657Å line is affected by a fluorescence effect driven by the C II 1335.7Å line (Shine 1983, ApJ, 266, 882). The IRIS Cl I 1351.657Å line is very prominent in on-disk observations, and also in the so-called IRIS bombs (e.g., Peter et al. 2014, Science, 346, 315). (See also, e.g., Ayres et al. 2003, ApJ, 583, 963, for stellar observations of this Cl I 1351 line.)

3.3 Si IV

The Si IV lines at 1393.755Å and 1402.770Å are, for many targets, some of the strongest lines in the IRIS FUV spectra.

They are often optically thin, and provide very good diagnostics of transition region structuring and dynamics. However, in some cases, a departure from optically thin regime can be observed for these Si IV lines. The 1393.755Å/1402.770Å intensity ratio is a diagnostic for opacity effects (e.g., Peter et al. 2014, Science, 346, 315, see also Sect. 5.3): a ratio ~2 can indicate that the lines are optically thin, while values different than 2 may indicate some degree of optical thickness.

The Si IV 1402.770Å line is typically unblended. The Ni II (1393.330Å, at ~90 km/s from the Si IV 1393Å line core), and CO (1393.51Å) are possible blends for the Si IV 1393.755Å line.

The ratio of Si IV to O IV has sometimes been used as density diagnostic (e.g. Young et al. 2018). See Sect. 5.2 for further discussion.

3.4 O IV, S IV

Three O IV emission lines (1399.780Å, 1401.157Å, 1404.806Å) can be observed with IRIS, and provide useful diagnostics of e.g., plasma densities (see e.g., Dudik et al. 2014, ApJL, 780, 12). The O IV 1404.806Å line is however blended with a S IV line (at 1404.808Å) formed at a similar temperature. The intensity of the S IV 1404.808Å line can be estimated by measuring another S IV unblended line at 1406.016Å (see also Sect. 5.1).

The IRIS O IV lines, when compared with the nearby Si IV 1402.77Å line, are weaker than predicted by equilibrium models. The discrepancy is due to several possible effects:

Fig. 3: Figure 3.3. Si IV 1402.77Å peak line intensity map for an active region (from single Gaussian fits to the observed line profiles — see sec. 4.1; De Pontieu et al., 2015, 799, 12).
Fig. 4: Figure 3.4. Intensity map for an active region for 4 different optically thin transition region lines observed with IRIS: Si IV 1402Å, O IV 1399Å, O IV 1401Å, S IV 1406Å (Polito et al., 2016, A&A, 594, 64).

3.5 Fe XII

The IRIS 1349.400Å line is a weak forbidden line with a peak formation temperature of ~1.5MK. These line is generally too weak to be routinely observed with IRIS. However, using appropriate observation strategies (e.g., longer exposures, lossless compression) it can be observed, at least for dense plasmas. This is the case for instance of the dense upper transition region of hot coronal loops (moss), as shown by Testa et al., 2016, ApJ, 827, 99.

3.6 Fe XXI

The IRIS FeXXI 1354.067Å line is a hot (peak formation temperature of ~11MK) coronal line that can be observed during flares:

- above loop top (reconnection region): ~200 km/s red shift (Tian et al. 2014)
- in post-flare loops: emission often strong, zero or small Doppler shift; oscillations detected (Tian et al. 2016)
Fig. 5: Figure 3.5. Fe XII 1349.4Å line intensity map for an active region (from Testa et al., 2016, ApJ, 827, 99).

Fig. 6: Figure 3.6: Example of Fe XII 1349.4Å emission line (in the blue box) in an IRIS FUV spectrum of an active region above the limb (red line).

3.6. Fe XXI
Fig. 7: Figure 3.7. Fe XXI 1354.07Å line intensity map for a flare (right panel), compared with emission observed by SDO/AIA in the 131Å passband which is also sensitive to FeXXI emission (from Young et al., 2015, ApJ, 799, 218).

Fig. 8: Figure 3.8: Example of Fe XXI 1354.07Å emission line (in the blue box) in IRIS FUV spectra of a flare: the broad Fe XXI line is visible both in the flare ribbons (black line), and in the flare loop (red line).
The analysis of line profiles provides crucial information on the physical conditions of the emitting source. In the solar atmosphere, the optically thin lines are mostly observed to have a Gaussian shape caused by the thermal broadening due to the motion of the atoms in the plasma. A set of routines which can be used to perform Gaussian (single or multi-component) fits are described in Sect. 4.1.

The parameters that can be derived through a Gaussian fit are:

- **Doppler shift**: due to motions along the line-of-sight. It requires an accurate wavelength calibration (see Sect. 4.2)
- **Line width**: includes instrumental broadening, thermal and non-thermal motions (see also Sect. 5.2)
- **Intensity**: is a measure of the amount of emitting plasma. To express the intensity into physical units, a radiometric calibration needs to be performed (see Sect. 4.3).

**Note**: If the ions have a non-Maxwellian distribution of velocities, the line profile may not be Gaussian but rather a generalized Lorentzian (see e.g. Dudík et al. 2017, ApJ, 842, 19). However, in the rest of this tutorial we will focus on Gaussian line profiles, which represent the simplest and the most commonly observed case. Note that this does not mean that the optically thin lines are always observed to have a symmetric Gaussian profile: if flows are present in the atmosphere, the line profile might be asymmetric (see Sect. 5.2). Nevertheless, in the following we will assume that such asymmetric line profiles can be fitted as a superposition of different Gaussian components.

### 4.1 Line fitting

*Figure 4.1* shows an example of the single Gaussian fit (light blue) of the observed IRIS Fe XXI line profile (black). The Gaussian function \( f(\lambda) \) is given by the following formula:

\[
f(\lambda) = I_p e^{-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}}
\]

where \( I_p \) is the peak of the line, \( \lambda_0 \) is the expected at-rest centroid wavelength of the line and \( \lambda \) its observed centroid. \( \sigma \) is the standard deviation, which is related to the **Full Width Half Maximum (FWHM)** of the line by:

\[
w_{FWHM} = 2\sqrt{2\ln2}\sigma
\]

Using the FWHM of the fitted Gaussian function, it is possible to derive the **non-thermal line width** \( w_{nth} \):

\[
w_{nth} = \sqrt{w_{FWHM}^2 - w_{th}^2 - w_I^2}
\]
where \( w_{\text{th}} \) is the \textbf{thermal width} and \( w_I \) is the \textbf{instrumental width} expressed in FWHM. The thermal width depends on the temperature \( T \) and mass \( m_{\text{ion}} \) of the emission ion and is given by:

\[
w_{\text{th}} = \frac{\lambda}{c} \sqrt{\frac{8\ln(2)k_BT}{m_{\text{ion}}}}
\]

where \( k_B \) is the Boltzmann constant.

\textbf{Note:} The IRIS instrumental width (FWHM) is about 26 mÅ for the FUV channel (De Pontieu et al. 2014, SoPh, 289, 2733).

The routine \texttt{iris_nonthermalwidth.pro} can be used to estimate the non-thermal width given the parameters of the line fit. See ITN 26, \texttt{useful code} for an explanation of this routine and Sect. 5.2 for more details on the possible physical interpretations of the non-thermal broadening in spectral lines.

The \textbf{total intensity} of a line can be obtained by integrating the area underneath the Gaussian function:

\[
I_{\text{TOT}} = \sqrt{2\pi \sigma}
\]

Further, measuring the line centroid provides information about the velocity of the emitting source. If the emission source is moving towards the observer, the center of the line profile will be shifted towards shorter wavelength, i.e. it will be \textbf{blue-shifted}. If the source is moving away from the observer, the line will be \textbf{red-shifted}. The Doppler shift velocity of the moving source can be calculated the following formula:

\[
v = \frac{\lambda - \lambda_0}{\lambda_0} \cdot c \quad [\text{km} \cdot \text{s}^{-1}]
\]

where \( c \) is the speed of light \( \sim 3 \times 10^5 \) km s\(^{-1}\)

Finally, the goodness of the fit can be expressed by the \( \chi^2 \) parameter:

\[
\chi^2 = \frac{1}{N} \sum_{i=0}^{N-1} \frac{I_{\text{obs}}(\lambda_i) - I_{\text{fit}}(\lambda_i)}{\text{err}^2}
\]

where \( I_{\text{obs}} \) and \( \text{err} \) represent the observed spectrum and relative uncertainties and \( I_{\text{fit}} \) is the Gaussian fit. \( N \) is the total number of spectral bins in the IRIS raster, \( n = N - N_{\text{fit}} - 1 \) the number of degrees of freedom in the fit and \( N_{\text{fit}} \) the number of free parameters in the fit (i.e. NTERMS in the \texttt{gaussfit.pro} routine described below in Sect. 4.1).

---

Fig. 1: \textit{Figure 4.1: Example of Gaussian fit of the Fe XXI 1354.08 Å line observed by IRIS using the routine gaussfit.pro.}
4.1.1 Single-Gaussian fitting

There are several IDL routines which can perform a single Gaussian fit of a line, some of them are listed below. In the following, \( wvl \) and \( sp \) indicate the wavelength array and spectrum of the IRIS line respectively.

**function gaussfit**

**Purpose:** Computes a non-linear least-squares fit to a function \( f(x) \) with from three to six unknown parameters.

**Usage:**

\[
yfit = \text{gaussfit}(wvl, sp, A, \text{NTERMS}=\text{nterms} \ [+\text{keywords}])
\]

**Parameters**

- \( A \): is the variable that contains the coefficients of the fit
- \( \text{NTERMS} \) is an integer value between 3 and 6 used to specify the function for the fit.

For example, if \( \text{NTERMS}=5 \),

\[
\]

where \( A[0] \) is the peak value, \( z = \frac{x - A[1]}{A[2]} \) with \( A[1] \) being the peak centroid and \( A[2] \) the gaussian \( \sigma \). Using the results of the fit, the FWHM and totally intensity of the line can be calculated as follows:

\[
\text{FWHM} = 2 \sqrt{2 \ln 2} \cdot A[2]
\]

\[
I_{\text{TOT}} = \sqrt{2\pi} \cdot A[0] \cdot A[2]
\]

See the IDL documentation [http://www.harrisgeospatial.com/docs/GAUSSFIT.html](http://www.harrisgeospatial.com/docs/GAUSSFIT.html) for a list of all the keywords and more details on this routine.

**function mpfitpeak**

Similar to `gaussfit.pro` but can be used also to fit a Lorentzian or Moffet function.

**Usage:**

\[
yfit = \text{mpfitpeak}(wvl, sp, A, \text{NTERMS}=\text{nterms} \ [+\text{keywords}])
\]

See the IDL documentation [http://www.harrisgeospatial.com/docs/mpfitpeak.html](http://www.harrisgeospatial.com/docs/mpfitpeak.html) for more details on the `mpfitpeak.pro` routine.

4.1.2 Multi-gaussian fitting

For a double-(or multi-) Gaussian fit (see Figure 4.2), the following routines may be used:

**function cfit and xcfit**

**Purpose:** Given a structure describing the set of components to be fitted, finds the best fit of the sum of components to the supplied data

**Usage:**

\[
yfit = \text{cfi}(wvl, sp, A, \text{fit} [,\text{SIGMAA} \ [+\text{keywords}])}
\]

**Parameters:**

- \( A \): Array of parameter values before/after fit. If defined on entry, then these values are used as initial values for the fit, unless the reset keyword is set.
Fig. 2: Example of a multi-Gaussian fit for the IRIS OI 1355.6 spectral window. The Fe XXI 1354.08 Å, C I 1354.30 Å and O I 1355.60 Å lines are indicated by the respective labels. The Fe XXI line has been fitted with two Gaussian components (indicated by the dotted blue lines): one at-rest dominant component and one fainter component on the blue wing of the line. In addition, the C I line is partially blended on the red wing of the Fe XXI line. Adapted from: Polito et al. 2015, ApJ, 803, 84.
4.1.3 2D automatic fitting

To perform an automatic fit over the 2D X- and Y- spatial arrays in a IRIS raster for a particular spectral line, one can either use the routines described above and repeat the fit for each of the pixels or use some dedicated routines to handle 2D data arrays, as described below.

**pro iris_auto_fit**

**Purpose:** automatically fits single or multiple Gaussians to two-dimensional spatial arrays.

**Usage:**

```
iris_auto_fit, windata, fitdata, /perpixel [+keyword]
```

**Parameters:**

- **windata:** the window data cube
- **fitdata:** a structure containing the fit (see below)

To extract information from the FITDATA structure, one can use:

```
IDL> intensity = eis_get_fitdata(fitdata, /int)
IDL> velocity = eis_get_fitdata(fitdata, /vel)
IDL> width = eis_get_fitdata(fitdata, /wid).
```

`iris_auto_fit` is adapted from `eis_auto_fit`, which was originally written by Dr Peter Young for the analysis of Hinode/EIS data. More information can be found at: [http://www.pyoung.org/quick_guides/iris_auto_fit.html](http://www.pyoung.org/quick_guides/iris_auto_fit.html). An example of automatic fit of the IRIS Fe XXI line profile is shown in Figure 4.3.

4.2 Wavelength calibration

When measuring Doppler shifts in spectral lines, it is important to perform an accurate absolute calibration of the wavelength array.

**Note:** The wavelength calibration is automatically performed in IRIS level 2 data. However, this should be always checked manually using the centroid positions of strong neutral lines, which are not supposed to vary significantly over time (within an uncertainty of 5–10 km s\(^{-1}\)). Suitable lines for performing the wavelength calibration are the O I 1335.60 Å line for the FUVS detector, the S I 1401.515 Å line (when strong enough) for the FUVL detector and the Ni I 2799.474 Å line in the NUV.

See also Sect. 6.1 of ITN 26, Calibration of IRIS observation.
Fig. 3: Figure 4.3 Intensity (left panel, in logarithmic scale), Doppler shift (middle panel) and width (right panel) of the IRIS Fe XXI line obtained by using the automatic fitting routine iris_win_fit.pro applied to IRIS data. Adapted from Figure 12 of ‘Young et al 2015, ApJ, 799, 218.
4.3 Radiometric calibration

The intensities of IRIS spectral lines should always be converted in physical units (e.g. from DN to \( \text{erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) or \( \text{phot cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-1} \)) before comparing the intensities of different lines and/or using them as plasma diagnostics tools (see Sect. 5).

The calibration data is included in the IRIS solarsoft branch, and Sect. 6.2 of ITN 26, Calibration of IRIS observation shows in details how to perform the radiometric calibration of IRIS lines. In addition, one might use the IDL routine `iris_calib.pro` written by Dr. Peter Young.

```
pro iris_calib
    Purpose: converts an IRIS DN value to \( \text{erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \)
    Usage:
    iris_calib, int, wavelength, date, texp=texp, [+keywords]

Parameters
• int: the total intensity of the line in DN
• wavelength : the wavelength of the line in Angstrom
• date: the date of the observation in a standard SSW format.
• texp: the exposure time in seconds. If not specified, then 1 second is assumed.
```

Note: The exposure time `texp` can be different for each exposure in the same sequence, when the Automatic Exposure Control (AEC) is switched on. See the note in Sect. 6.2 of ITN 26, Calibration of IRIS observation for more information.
Spectral lines represent the richest source of information on the physical properties of the observed plasma, which can be evaluated using plasma diagnostic tools. The most relevant diagnostics provided by the IRIS optically-thin lines are described in the following sections.

### 5.1 Density diagnostics

The intensity ratio of spectral lines with a different dependence on the electron number density represents a reliable density diagnostic. Ideally, lines from the same ion should be used, in order to remove the uncertainties associated with the ion fractional abundance and chemical abundance. In addition, the lines should have a similar temperature dependence, so that their ratio will be mostly independent on the plasma temperature.

The density sensitivity of line ratios from a single ion requires the existence of *metastable* levels (which can decay radiatively only via forbidden transitions with small $A$-values, see Sect. 2.3) within the ion. For an allowed line excited from the ground state, the intensity is proportional to $N_e^2$, whereas for forbidden transitions, the radiative decay rate is so small that collisional de-excitation can become an important de-populating mechanism and in that case the intensity will be proportional to $N_e$. Density diagnostics based on either the ratio of two forbidden transitions, two allowed transitions or an allowed and a forbidden transition can be found. The density sensitivity of two forbidden lines arises from the relative importance of collisional and radiative de-excitation. The ratio of two allowed lines could also be density sensitive if one of the lines is excited from a metastable state. For more details on density sensitive line ratios see e.g. Gabriel & Mason, 1982 and Phillips et al. 2009.

The best density-sensitive line ratios observed by IRIS is given by the intersystem (spin-forbidden) O IV transitions at 1399.77 Å and 1401.16 Å included in the Si IV 1403 Å spectral window. These lines are particularly suitable for density measurements as their ratio is largely independent of the electron temperature, and only weakly dependent on the electron distribution Dudík et al. 2014, ApJ, 780,12. The other advantage is that the lines are close in wavelength, minimizing any calibration effects.

Some useful routines for estimating the density are described below.

**pro dens_plotter**

**Purpose:** A widget-based routine to allow the analysis of density sensitive ratios.

**Usage:**

```plaintext
dens_plotter, 'o_4'
```

Electron density diagnostics can be obtained by comparing the observed and theoretical O IV λ 1399.77/1401.16 ratio as a function of density, as shown in *Figure 5.1.*

(see also the CHIANTI user guide).

**pro iris_ne_oiv**
Fig. 1: Figure 5.1. Left panel: density sensitive line ratio involving two IRIS O IV lines, calculated using theoretical emissivities from CHIANTI v.8. Right Panel: level diagrams of the O IV multiplets around 1400 Å observed by IRIS. The grey arrows indicate each forbidden transition and the wavelengths are expressed in Å.

**Purpose:** derives the electron density from the O IV 1401.16 Å and 1399.77 Å line pairs.

See ITN 26, useful codes for a description of this routine.

**Note:** Note that the line intensities should be converted from DN to physical units before calculating the ratios (see Sect.4.3 and ITN 26, Calibration of IRIS observation).

**Note:** Most of the density diagnostic techniques assume that the emitting plasma is thermal and in ionization equilibrium, which might not always be the case in the solar atmosphere. In particular, if the plasma is outside ionization equilibrium, the estimated density may vary significantly (see e.g. Olluri et al. 2013, ApJ, 767, 43; Martínez-Sykora, Juan et al. 2016, ApJ, 871, 46; Dzifčáková & Dudík 2018, A&A, 610, 67).

The IRIS Si IV 1403 Å spectral window also includes the O IV line at 1404.81 Å, which is blended with the S IV transition at 1404.85 Å, and the S IV line at 1406.06 Å (Figure 5.2), which is included in selected linelists (large linelists since October 2013, flare linelists since May 2015). The S IV line ratio is sensitive to higher electron densities (up to \(10^{13}\) cm\(^{-3}\)) compared to the O IV line ratios (up to \(10^{12}\) cm\(^{-3}\)) and therefore is particularly useful to diagnose very high densities, which might occur during flares and energetic events. The O IV + S IV line around 1404 Å can be de-blended using the other O IV lines observed by IRIS, taking into account that the importance of the S IV to the O IV line in the blend varies with the plasma density and temperature. For instance, Polito et al. 2016, ApJ, 871, 46 used the observed λ 1399.77/1401.16 ratio to de-blend the O IV + S IV lines and obtain density estimates using the S IV λ 1404.85/1406.06 ratio for different solar features.

Line ratios involving an O IV forbidden transition and a Si IV allowed transition have been sometimes used to provide electron densities during solar flares and transient brightenings (e.g. Cheng at al., 1981, ApJ, 248, 39; Peter et al. 2014, Sci, 346, 315; Doschek et al. 2016, ApJ, 832, 77). The validity of using the O IV to Si IV ratios has been debated because these ratios tend to give very high densities compared to the more reliable ones obtained from the O IV ratios alone (see Hayes & Shine, 1987, ApJ, 312, 943). In particular, Judge, 2015, ApJ, 808, 11 recalled several issues related to the use of this ratio, including the fact that O IV and Si IV are formed at quite different temperatures in equilibrium and thus a change in their ratio could also imply a change in the temperature rather than in the plasma density. In addition, the chemical abundances of O and Si are not known with accuracy and could be varying during the observed events. Further, these ions show a very different response to transient ionization because of their different formation processes. Finally, as mentioned in Section 2.2, it should be noted that taking into account the effect of high-densities on the ionization balance will cause the fractional ion abundances of O IV and Si IV to depart significantly

Nevertheless, as pointed out by e.g. Doschek et al. 2016, ApJ, 832, 77 and Young et al. 2018, ApJ, 857, 5, one limitation in the use of the O IV lines is that they are normally observed to be extremely weak (the O IV 1399.7 line in particular). In that case, the Si IV to O IV ratio might still be used to provide some estimate for the electron density, keeping in mind the issues described above.

Note: The O IV lines are partially blended with some photospheric lines, especially during the impulsive phase of flares (e.g. Polito et al. 2016, ApJ, 816, 89). The strongest of those lines is the S I neutral line at 1401.51 Å on the red wing of the O IV 1401.16 Å line. Most of the times, the S I narrow line can be separated from the broad neighbor O IV line and used to perform wavelength calibration (see Sect. 4.2). Further, the photospheric Fe II lines at 1405.61 Å and 1405.80 Å are blended with the S IV 1406.06 Å line. It is important to remove these blends before measuring the line intensities and use their ratios to estimate the density.

5.2 Plasma motions: Doppler shifts and non-thermal line widths

IRIS spectral lines provide useful diagnostics of plasma motions. In sec. 4.1 we briefly discuss the line fitting of IRIS spectral lines, when they can be approximated with Gaussian profiles. The Gaussian fit provides the line center (i.e., the line Doppler shift, when compared with the line rest wavelength), and line width.

Doppler shift of a spectral line indicates that the emitting plasma has a velocity \( v \) along the line-of-sight either toward/away from the observer, causing a blueshift/redshift (\( \Delta \lambda / \lambda_0 = v/c \)). Fig. 5.3, 5.4, 5.5, show some examples of velocity maps obtained from IRIS observations of a variety of targets (coronal jets, post flare loops, flare loops).

The spectral line width provides additional diagnostics of plasma motions. As discussed in sec. 4.1, intrinsic thermal broadening (\( w_{th}^2 = 8ln(2) \lambda k_B T/m_{ion} c \) if expressed as FWHM, where \( k_B \) is the Boltzmann constant, \( T \) is the temperature of the emitting plasma, and \( m_{ion} \) is the mass of the ion emitting the line), instrumental broadening...
Fig. 3: Figure 5.3. Total intensity (left panel) and Doppler velocity (right panel) in the Si IV 1394Å line for a coronal jet observed by IRIS. The velocity map suggests helical motions of the jet plasma (from Cheung et al., 2015, ApJ, 801, 83).
Fig. 4: Figure 5.4. Fe XII 1349.4 Å line intensity (top) and Doppler shift (bottom) map for post flare loops (from Testa et al., 2016, ApJ, 827, 99).

\[ w = \sqrt{w_{th}^2 + w_{instr}^2 + w_{nth}^2} \]

The non-thermal line width \( w_{nth} \) (i.e., broadening in excess of the thermal and instrumental broadening) can be caused by several different processes, including for example fine scale unresolved flows, waves, turbulence (see e.g., Chae et al., 1998, 505, 957 and De Pontieu et al., 2015, 799, 12, Testa et al., 2016, ApJ, 827, 99 for a discussion). Some examples of thermal FWHM (calculated at the peak formation temperature of the ions \( T_p \), without taking into account the instrumental width) for some of the IRIS lines discussed in this tutorial are reported in the following table:

<table>
<thead>
<tr>
<th>Line</th>
<th>Wavelength (Å)</th>
<th>log ( T_p ) [K]</th>
<th>FWHM (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IV</td>
<td>1402.77</td>
<td>4.9</td>
<td>0.05</td>
</tr>
<tr>
<td>O IV</td>
<td>1401.16</td>
<td>5.15</td>
<td>0.09</td>
</tr>
<tr>
<td>Fe XII</td>
<td>1349.40</td>
<td>6.2</td>
<td>0.16</td>
</tr>
<tr>
<td>Fe XXI</td>
<td>1354.08</td>
<td>7.05</td>
<td>0.43</td>
</tr>
</tbody>
</table>

**Note:** A large number of papers in the literature analyze and discuss the “non-thermal line width” properties of solar emission lines. However we note several different definitions are used by different authors. In particular, some authors define \( w_{nth} \) as the FWHM of the line \( (FWHM = 2\sqrt{2\ln2}\sigma) \), where \( \sigma \) is the Gaussian \( \sigma \), others refer to the \( w_{1/e} \) \((w_{1/e} = \sqrt{2}\sigma)\), while others might use the Gaussian \( \sigma \).

Another useful spectroscopic diagnostics is provided by possible line asymmetries. Several approaches can be used to quantify the degree of asymmetry in line profiles, such as, for instance, determining the “red-blue asymmetry” of the line \( (FWHM = 2\sqrt{2\ln2}\sigma) \), where \( \sigma \) is the Gaussian \( \sigma \), others refer to the \( w_{1/e} \) \((w_{1/e} = \sqrt{2}\sigma)\), while others might use the Gaussian \( \sigma \).

5.2. Plasma motions: Doppler shifts and non-thermal line widths
Fig. 5: Figure 5.5. Si IV 1402.77Å peak line intensity (left panel) and non-thermal line width (right panel) map for an active region (from single Gaussian fits to the observed line profiles — see sec. 4.1; in De Pontieu et al., 2015, 799, 12).

Fig. 6: Figure 5.6. Fe XXI 1354.07Å line intensity map for a flare (second panel), compared with emission observed by SDO/AIA in the 131Å passband which is also sensitive to FeXXI emission. Maps of Doppler shifts (third panel) and line width (fourth panel) of the IRIS FeXXI 1354.07Å line are also shown (from Young et al., 2015, ApJ, 799, 218).
Fig. 7: Figure 5.7. Examples of Si IV 1394Å and C II 1336Å line profiles showing asymmetries, produced by type II spicules (from Rouppe van der Voort et al., 2015, ApJL, 799, 3).
5.3 Opacity using ratio of Si IV lines

IRIS observes two Si IV lines at 1393.75 Å and 1402.77 Å whose ratio can be used to test whether the ion is formed under optically thin or thick conditions. In particular, a ratio close to 2 is compatible with the lines being optically thin (see e.g., Peter et al. 2014, Science, 346, 315 and Yan et al. 2015, ApJ, 811, 48). However, it is possible that the lines are optically thick and still have a ratio of about 2, so one cannot use the line ratio to conclusively state that the lines are optically thin.

While the 1402.77 Å line is largely free of blends, the 1393.75 Å line is blended with a Ni II 1393.33 Å line at around ∼90 km/s from at the Si IV core and with an unidentified transition, which is only visible during flares. These blends should be removed from the line intensity before calculating the $\lambda$ 1393.755/1402.770 ratio.