SF2A 2019
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MEASURING RELATIVE ABUNDANCES IN THE SOLAR CORONA WITH OPTIMIZED LINEAR COMBINATIONS OF SPECTRAL LINES

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Abstract. Elemental abundances in some coronal structures differ significantly from photospheric abundances, with a dependence on the First Ionization Potential (FIP) of the element. Measuring these FIP-dependent abundance biases is important for coronal and heliospheric physics. We aim at building a method for optimal determination of FIP biases in the corona from spectroscopic observations, in a way that is in practice independent from Differential Emission Measure (DEM) inversions. We optimize linear combinations of spectroscopic lines of low-FIP and high-FIP elements so that the ratio of the corresponding radiances yields the relative FIP bias with a good accuracy, for any DEM in a small set of typical DEMs. These optimized linear combinations of lines allow to retrieve a test FIP bias map with a good accuracy, for all DEMs in the map. The method provides a convenient, fast, and accurate way of computing relative FIP bias maps. It could be used to optimize the use of existing observations and the design of new observations and instruments.

Keywords: techniques: spectroscopic – Sun: abundances – Sun: corona – Sun: UV radiation

1 Introduction

Accurate plasma diagnostics of the Solar Wind (SW) and corona as well as precise modeling of the solar magnetic field and plasma flows in the interplanetary medium are crucial when trying to determine the source regions of the SW (Peleikis et al. 2017). Indeed, the chemical composition of coronal plasma (the abundances of the different elements) may vary from structure to structure (Baker et al. 2013; Guennou et al. 2015; Saba 1995) and in time (Feldman & Widing 2003), but it becomes fixed at low heights in the corona. Determining the composition of the different structures would then allow us to pinpoint the source of the SW by comparing and linking remote sensing abundance measurements to in situ analysis. These variations are linked to the FIP or First Ionization Potential (Saba 1995) of the different elements. Coronal abundances, which are derived from UV spectroscopy, are difficult to measure accurately (Schmelz et al. 2012). FIP biases (the ratio of the coronal vs the photospheric abundance of a given element) are usually calculated either from the line ratio of two spectral lines (hereafter 2LR method) or following Differential Emission Measure (DEM) analysis; both these methods can yield different results when used on the same data. Using DEM inversions yields the most accurate results, but DEMs are difficult to estimate accurately (Craig & Brown 1976; Judge et al. 1997; Landi et al. 2012; Testa et al. 2012; Guennou et al. 2012), especially when trying to design an automated method.

We present a method that aims at providing an optimal determination of the abundance biases in the corona from a spectroscopic observation, even when the DEM cannot be precisely determined.

2 The Linear Combination Ratio (LCR) method for FIP bias determination

To determine the FIP bias, let us consider two spectroscopic lines, emitted by ions of two different elements, X_{LF} that has a low FIP ($< 10\,\mathrm{eV}$) and X_{HF} that has a high FIP. We will denote the radiance of the low FIP element's considered spectral line I_{LF} and I_{HF} that of the high FIP element line. Assuming that abundances

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are uniform along the relevant part of the line-of-sight, in the corona, we can write the radiances for both lines as

$$I_{\rm LF} = A^{\rm P}_{X_{\rm LF}} f_{X_{\rm LF}} \langle C_{\rm LF}, {\rm DEM}\rangle \quad \& \quad I_{\rm HF} = A^{\rm P}_{X_{\rm HF}} f_{X_{\rm HF}} \langle C_{\rm HF}, {\rm DEM}\rangle \tag{2.1}$$

where we define the FIP bias $f_X \equiv A^{\rm C}_X / A^{\rm P}_X$ for element X in which $A^{\rm C}_X$ and $A^{\rm P}_X$ are the coronal and photospheric abundances for that element, $C_{\rm LF}$ and $C_{\rm HF}$ are the contribution functions for the lines of the low-FIP and high-FIP elements, and $\langle a, b\rangle \equiv \int a(T)\, b(T)\, dT$ is a scalar product. The contribution functions contain all the atomic physics necessary for line formation, while the DEM reflects the plasma conditions along the line-of-sight. The ratio of the FIP biases (the relative abundance between element $X_{\rm LF}$ and $X_{\rm HF}$) is

$$\frac{f_{X_{\rm LF}}}{f_{X_{\rm HF}}} = \frac{I_{\rm LF}}{I_{\rm HF}} \left(\frac{A^{\rm P}_{X_{\rm LF}}}{A^{\rm P}_{X_{\rm HF}}} \frac{\langle C_{\rm LF}, {\rm DEM}\rangle}{\langle C_{\rm HF}, {\rm DEM}\rangle} \right)^{-1} \tag{2.2}$$

One then needs to either determine the DEM in order to compute this ratio or use the 2LR method which requires finding two lines with contribution functions similar enough that the ratio $\langle C_{\rm LF}, {\rm DEM}\rangle / \langle C_{\rm HF}, {\rm DEM}\rangle$ is constant for any DEM.

The idea of the LCR method is to use two sets of lines instead of only two lines. We ought to use linear combinations of lines, so that the corresponding contribution functions for low FIP (LF) and high FIP (HF) elements match better. We start by defining two radiance-like quantities, that would be the analogs of the radiances of Eqs. 2.1, as linear combinations of radiances from individual lines of low-FIP and high-FIP elements:

$$I_{\rm LF} \equiv \sum_{i \in ({\rm LF})} \alpha_i \, \frac{I_i}{A^{\rm P}_i} \quad \& \quad I_{\rm HF} \equiv \sum_{i \in ({\rm HF})} \beta_i \, \frac{I_i}{A^{\rm P}_i} \tag{2.3}$$

If the FIP biases of all used low-FIP elements are the same (and equal to $f_{\rm LF}$), and the FIP biases of all used high-FIP elements are the same (and equal to $f_{\rm HF}$), the ratio of the FIP biases is

$$\frac{f_{\rm LF}}{f_{\rm HF}} = \frac{I_{\rm LF}}{I_{\rm HF}} \left(\frac{\langle C_{\rm LF}, {\rm DEM}\rangle}{\langle C_{\rm HF}, \ {\rm DEM}\rangle} \right)^{-1}, \tag{2.4}$$

where the low FIP and high FIP contribution functions have been defined by

$$C_{\rm LF}(T) \equiv \sum_{i \in ({\rm LF})} \alpha_i \, C_i(T) \quad \& \quad C_{\rm HF}(T) \equiv \sum_{i \in ({\rm HF})} \beta_i \, C_i(T) \tag{2.5}$$

We have developed a Python module (`https://git.ias.u-psud.fr/nzambran/fiplcr`) to compute the optimal coefficients α_i and β_i so that the linear combinations of spectral lines can be used to obtain accurate relative FIP bias maps from observations.

3 Testing the LCR method with synthetic radiances

We test the LCR method by applying it to maps of synthetic radiances. We also test the 2LR method with the same criteria for comparison. The test case consists in a uniform abundance map for any given element, combined with a data cube of DEMs, as detailed below. Using both these inputs and atomic physics, we can build "synthetic" radiances, from which we compute FIP biases with both methods. The test is considered successful for a given FIP bias determination method if the output relative FIP bias map is consistent with the input elemental abundance maps, both in uniformity and in value.

The test has four main steps, detailed below:

1. We derive a DEM cube from an observation (active region shown in the left hand side of Fig. 1) obtained with the AIA (AIA; Lemen et al. 2012) instrument aboard the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) using the Cheung et al. (2015) code.

2. We choose the sets of lines to use for the test (listed in Table 1). Then, using the CHIANTI atomic database (Dere et al. 1997, Del Zanna et al. 2015) for the contribution functions, and the DEMs derived just earlier, we calculate the synthetic radiances. We assume different uniform abundances for different elements.

Ion	Wavelength (Å)	$\log T_{\max}$ (K)	LCR coeff	2LR coeff (10^{20})	FIP (eV)	f_X/f_S
Fe XII	195.119	6.2	0.0845		7.90	2.05
Fe XIII	201.126	6.2	-0.0738		7.90	2.05
Fe XIII	202.044	6.2	0.0294		7.90	2.05
Si X	**258.374**	6.1	1.36	4.26	8.15	1.82
Si X	261.056	6.1	1.46		8.15	1.82
S X	**264.231**	6.2	2.16	3.34	10.36	1.00
Fe XIV	264.789	6.3	0.503		7.90	2.05
Fe XIV	274.204	6.3	0.0404		7.90	2.05

Table 1. Spectral lines used to perform the calculations for both methods (coefficients computed for a density of $\log n = 8.3$). The lines in bold correspond to those used for the 2LR method. We also include the FIP of the elements used for the tests, and their abundance bias relative to sulfur (Schmelz et al. 2012; Grevesse et al. 2007).

3. We determine the optimal linear combination coefficents for the LCR method, and the coefficients for the 2LR method.

4. We use these coefficients to retrieve the FIP bias (see right panel of Fig. 1) in each pixel assuming $\langle C_{\mathrm{LF}}, \mathrm{DEM}\rangle / \langle C_{\mathrm{HF}}, \mathrm{DEM}\rangle \approx 1$ is verified for any DEM. If this is the case, the retrieved FIP bias map should be uniform.

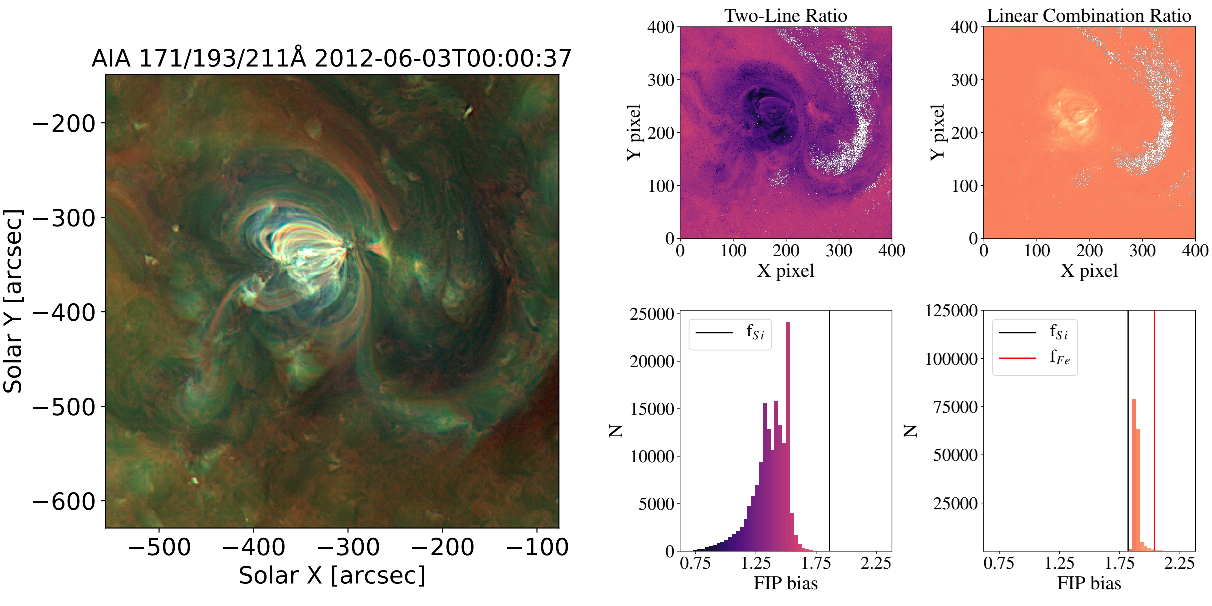

Fig. 1. Left: Composite map of an AR observed on June 3rd 2012, in the 171 Å (red), 193 Å (green), and 211 Å (blue) channels of the AIA instrument aboard SDO. **Right:** Results of FIP bias determination using the 2LR (left) and LCR (right) methods on the synthetic radiances in the AR: relative FIP map (top) and its corresponding histogram (bottom), with matching color scales. The vertical lines in the histograms correspond to the imposed uniform values of the relative FIP bias (for each of the low-FIP elements, see Table 1), that should ideally be retrieved.

We obtain relative FIP bias maps for both methods. We present the results in the right hand side of Fig. 1. The top left panel clearly shows that we do not retrieve a uniform relative FIP bias using the 2LR method, as confirmed by the width of the corresponding histogram (bottom left). Its standard deviation is of 0.15. Furthermore, the histogram peak at about 1.51 is far from the imposed value for the relative FIP bias between the two elements used, silicon and sulfur (1.82). The LCR method gives a much more uniform map (top right panel), as confirmed by the corresponding histogram (bottom right) that has a standard deviation of 0.03. This histogram peaks at 1.87, and almost all obtained values are between the relative FIP biases for Fe and Si. These results show the accuracy of the linear combination ratio method.

4 Conclusions

We have presented the Linear Combination Ratio (LCR) method, which aims at providing an optimal determination of the relative FIP biases in the corona from spectroscopic observations without the need to previously determine the DEM. This technique relies on linear combinations of spectral lines, optimized for FIP bias determination. We have developed a Python module implementing the method and that can be found at `https://git.ias.u-psud.fr/nzambran/fiplcr`.

Using two linear combinations of spectral lines, one with low FIP elements and one with high FIP elements, we tested the accuracy of the method performed on synthetic observations: these tests show that the method does indeed perform well, without prior DEM inversions.

Once the optimized linear combination coefficients have been determined for a given set of lines, the LCR method directly gives the corresponding FIP bias maps. This makes the method simple to apply on observations containing a pre-defined set of lines, with a potential for automation.

Hopefully, producing such FIP bias maps semi-automatically would allow for direct comparison with in-situ data of the Solar Wind. This method could also allow better exploitation of observations not specifically designed for composition studies, and an optimal design of future observations. We plan to apply the method to the future Solar Orbiter/SPICE spectra, to prepare the observations and analysis of the SPICE data.

NZP is grateful for the opportunity of giving a talk about this work at the 2019 SF2A meeting. The authors thank Mark Cheung for the SDO/AIA DEM inversion code, and Giulio Del Zanna, Susanna Parenti, and Karine Bocchialini for their comments. The idea for this work came following a presentation by Hardi Peter at the Solar Orbiter joint SPICE-EPD-SWA meeting in Orsay in November 2015. AIA is an instrument on board SDO, a mission for NASA's Living With a Star program. NZP thanks ISSI for support and participants to the ISSI team "Linking the Sun to the Heliosphere using Composition Data and Modelling" led by Susanna Parenti. CHIANTI is a collaborative project involving George Mason University, the University of Michigan (USA) and the University of Cambridge (UK). This work used data provided by the MEDOC data and operations centre (CNES / CNRS / Univ. Paris-Sud), `http://medoc.ias.u-psud.fr/`.

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