Relative abundances diagnostics with SPICE, the EUV spectrometer on-board Solar Orbiter

Natalia ZAMBRANA PRADO[1] Éric BUCHLIN[1], Hardi PETER[2]

natalia.zambranaprado@ias.u-psud.fr

[1]Institut d'Astrophysique Spatiale, CNRS, Université Paris-Saclay, Orsay, FRANCE

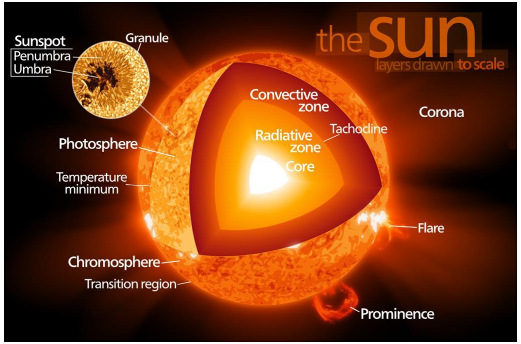
[2]Max Planck Institute for Solar System Research (MPS), Göttingen, GERMANY

Outline

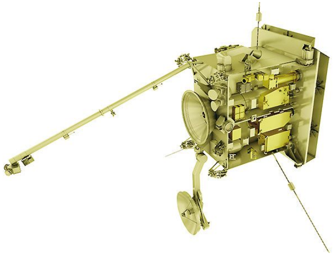
- ★ Linking the Sun to the heliosphere with Solar Orbiter
- ★ How to measure relative abundances of heavy ions
- ★ Diagnostics for SPICE/Solar Orbiter
- ★ Conclusion

Linking the Sun to the Heliosphere

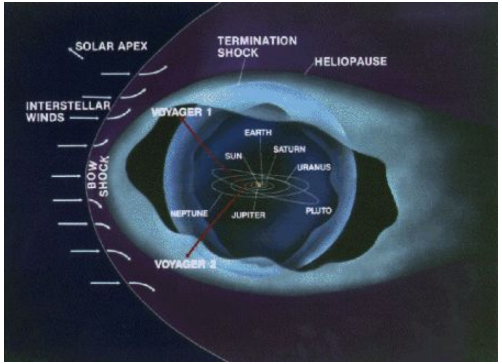
Solar Orbiter's unique combination of in-situ and remote sensing instruments will allow us to take a look at what is going on at the Sun itself and also in the heliosphere.



Internal and external layers of the Sun



Solar Orbiter



The heliosphere and the Interplanetary medium

SO can allow us to determine the **source regions of the solar wind** through **plasma composition diagnostics** which can change from structure to structure due to the FIP effect.

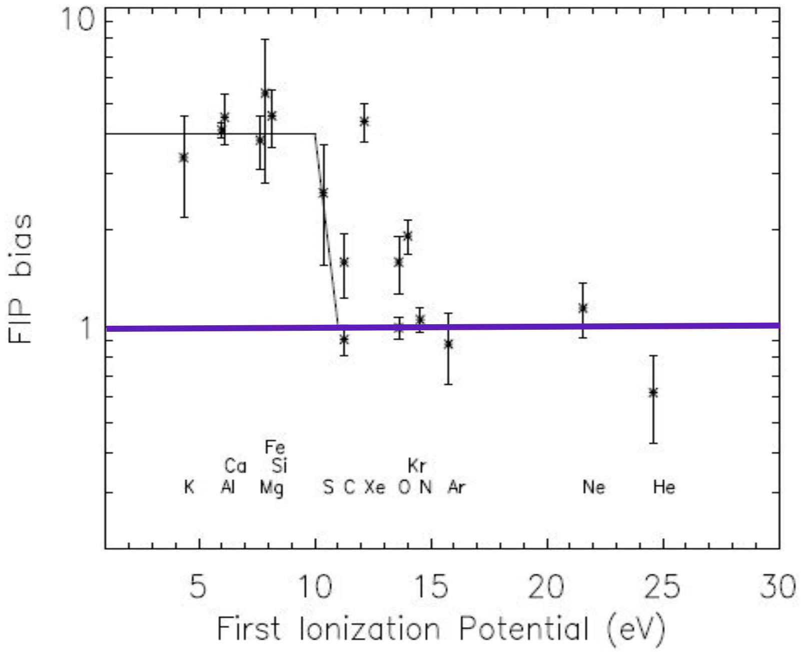
The FIP effect

In certain regions of the solar corona, e.g. active regions, we see variations in the abundances of different elements and these variations are linked to the First Ionization Potential or FIP. We call this phenomenon the FIP effect.

Quantification through the « FIP bias » :

$$f_X = \frac{Ab_X^{corona}}{Ab_X^{photosphere}}$$

where Ab_X^{region} is the elemental abundance relative to hydrogen in a given region of the solar atmosphere.



FIP bias as a function of FIP in the slow Solar Wind, von Steiger et al. (1997).

« FIP bias » frozen in the corona → **The FIP effect can allow us to trace back the source of heliospheric plasma**

Measuring relative abundances

Comparing in-situ and remote sensing composition data, coupled with modeling, will allow us to trace back the source of heliospheric plasma. Here we will focus solely on measuring relative abundances in the solar corona using UV spectrometers. In the coronal approximation, the radiance of the transition line from level i to j of ion X^{+m} can be written as an integral of the temperature :

$$I_{X^{+m},\, i\to j} = \boxed{Ab_X^{corona}} \int \boxed{C_{X^{+m},\, i\to j}(n_e, T)}\, \boxed{\mathrm{DEM}(T)}\, dT$$

Coronal abundance of element X

Contribution function
Contains all the physics involved in line formation

Differential Emission Measure
Temperature distribution of the plasma

By introducing the FIP bias and writing the integral as a scalar product (using a scalar product notation), we obtain:

$$I_{X,\, ij} = f_X \quad A_X^{\mathrm{ph}} \langle C_{X,\, ij}, \mathrm{DEM} \rangle$$

Take away message : The radiance of a spectral line of an element is **proportional** to the FIP bias of the emitting element

The Linear Combination Ratio (LCR) method

We developed a method for measuring relative abundances that is both telemetry efficient and reliable. Unlike methods based on Differential Emission Measure (DEM) inversion, the Linear Combination Ratio (LCR) method does not require a large number of spectral lines. This new method is based on optimized linear combinations of only a few UV spectral lines.

Using two sets of spectral lines, one from low FIP elements and another one of high FIP elements, we can create two radiance-like and contribution function-like quantities by doing linear combinations of the radiances and of the contribution functions of the spectral lines of each set of elements :

Low FIP elements

$$\mathscr{I}_{\mathrm{LF}} \equiv \sum_{i \in (\mathrm{LF})} \alpha_i \, \frac{I_i}{A_i^{\mathrm{ph}}}$$

$$\mathscr{C}_{\mathrm{LF}}(T) \equiv \sum_{i \in (\mathrm{LF})} \alpha_i \; C_i(T)$$

High FIP elements

$$\mathscr{I}_{\mathrm{HF}} \equiv \sum_{i \in (\mathrm{HF})} \beta_i \, \frac{I_i}{A_i^{\mathrm{ph}}}$$

$$\mathscr{C}_{\mathrm{HF}}(T) \equiv \sum_{i \in (\mathrm{HF})} \beta_i \; C_i(T)$$

The Linear Combination Ratio (LCR) method

We assume we can define an overall FIP bias for the low FIP elements f_{LF} and one for the high FIP elements f_{HF}. The ratio of these FIP biases, the relative FIP bias, will be:

$$\frac{f_{\mathrm{LF}}}{f_{\mathrm{HF}}} = \frac{\mathscr{I}_{\mathsf{LF}}}{\mathscr{I}_{\mathsf{HF}}} \left(\frac{\langle \mathscr{C}_{\mathsf{LF}}, \mathsf{DEM} \rangle}{\langle \mathscr{C}_{\mathsf{HF}}, \mathsf{DEM} \rangle} \right)^{-1}$$

The coefficients of the linear combinations are optimized such that :

$$\frac{f_{\mathrm{LF}}}{f_{\mathrm{HF}}} = \frac{\mathscr{I}_{\mathsf{LF}}}{\mathscr{I}_{\mathsf{HF}}} \boxed{\left(\frac{\langle \mathscr{C}_{\mathsf{LF}}, \mathsf{DEM} \rangle}{\langle \mathscr{C}_{\mathsf{HF}}, \mathsf{DEM} \rangle} \right)^{-1}} \approx 1$$

The **relative FIP bias** is then simply the ratio of the pseudo radiances and can be easily calculated using spectroscopic data.

All details, tests and an example of application to EIS/Hinode data can be found at Zambrana Prado & Buchlin, 2019 and the corresponding python module at fiplcr.

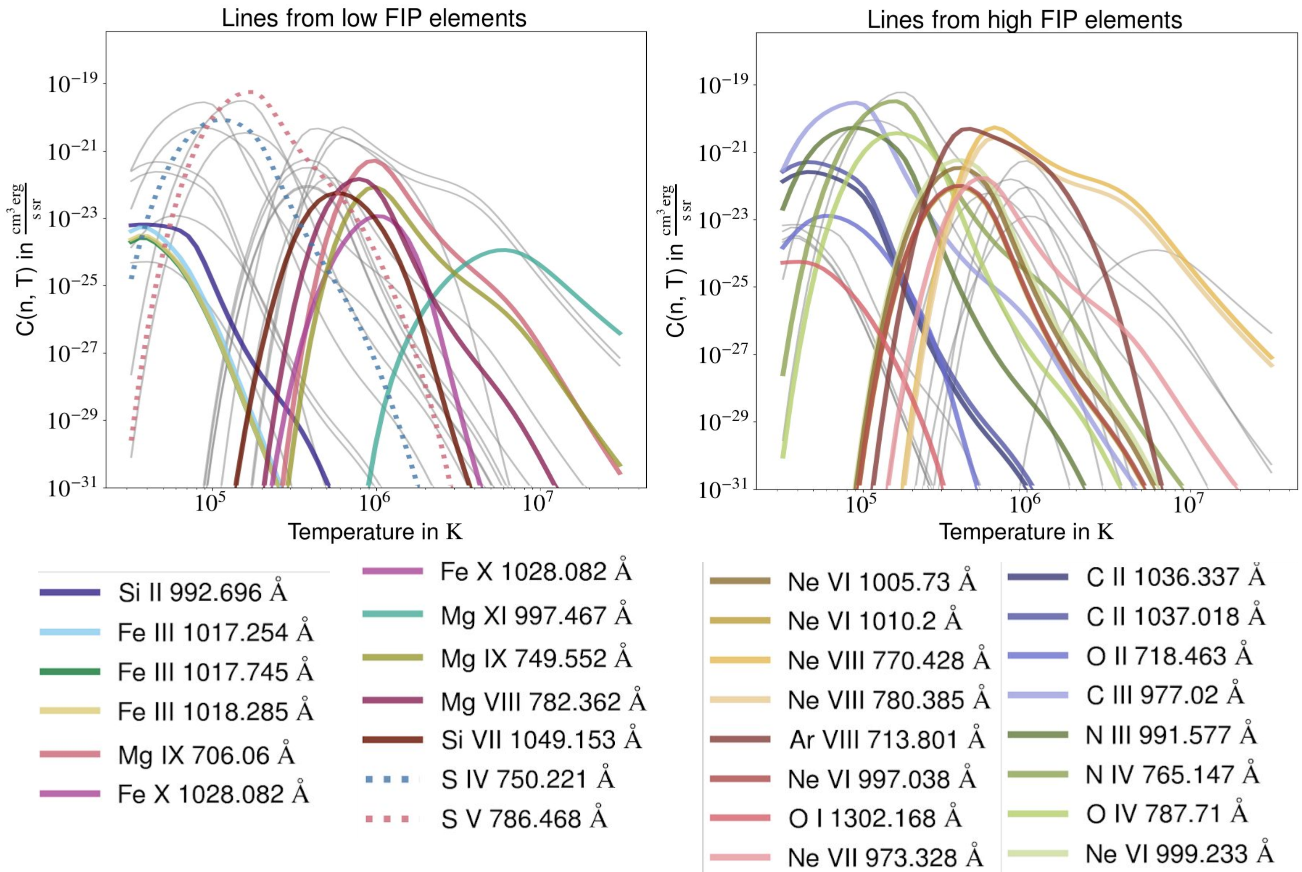
SPICE (SPectral Imaging of the Coronal Environment)

EUV Imaging Spectrometer

Wavelengths :
70.0 – 79.2 nm & 97.0 – 105.3 nm

- ★ High resolution 2D spectral images. They will allow to retrieve intensities, line profiles, line widths, composition.
- ★ Scan all heights and temperatures from the chromosphere to the flaring corona.
- ★ Need to develop a method to derive composition from observations.

Strongest observable lines with SPICE



No good line pairs for density diagnostics.

Few low FIP lines, none with a temperature peak below 4×10^5 K.

Tests with uniform abundances

We test every pair of linear combination of spectral lines by creating synthetic radiances for every line. We use a DEM cube where every pixel can have very different characteristics from the others except for its abundance, every single pixel has the same exact abundance. This means that if the linear combinations chosen are suitable for relative FIP bias determination, we would obtain a perfectly uniform relative FIP bias map.

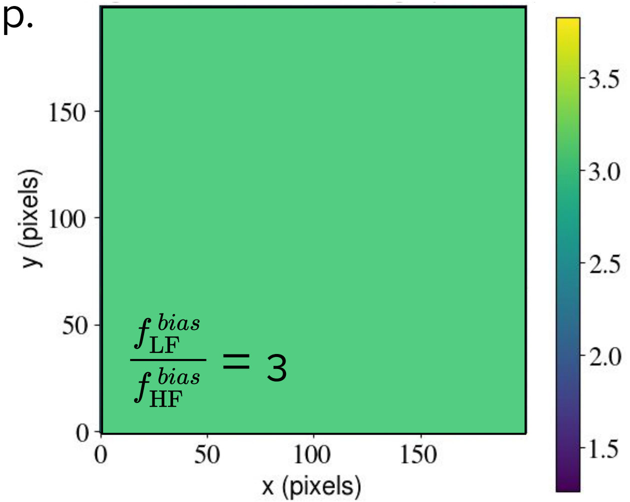
Synthetic Intensities

$$I_{X,\,ij} = f_X^{\,bias} A_X^{\rm ph} \langle C_{X,\,ij}, \mathrm{DEM} \rangle$$

LCR

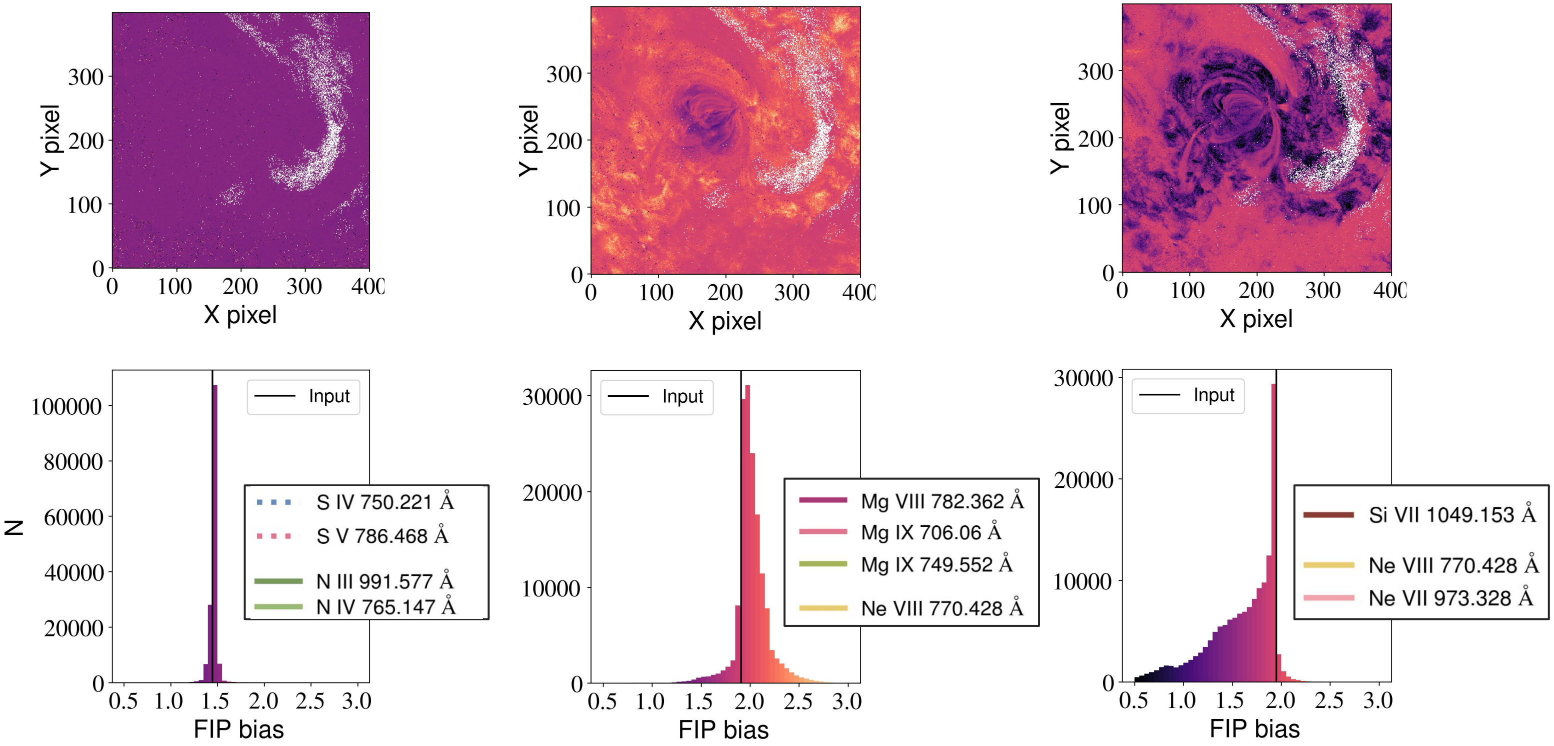
FIP bias maps

- ★ Different temperatures
- ★ Different densities
- ★ **Uniform abundances**



Relative FIP bias map obtained if the method works perfectly

Some possible relative FIP bias diagnostics



Relative FIP maps (top) and their corresponding histograms (bottom), with matching colour scales. The vertical lines in the histograms correspond to the imposed uniform values of the relative FIP bias that should ideally be retrieved.

Conclusions

- ★ It is possible to obtain **relative FIP bias maps with no prior DEM inversions**.
- ★ The tests show that **the LCR method** could be used to perform **abundance diagnostics with SPICE**.
- ★ The LCR method helps us to **prepare future observations**.

Other present and future work

- ★ Assess the **effects of noise** (including line and instrument characteristics) on relative FIP bias determination with the LCR method.
- ★ **Re-analyze past** Hinode **observations** (ISSI Team of Susanna Parenti) that were not intended for abundance measurements using the LCR method.
- ★ Assessment of **more linear combinations of lines** for **SPICE** to help connect remote and in-situ measurements.
- ★ SPICE **level 3 data product**.