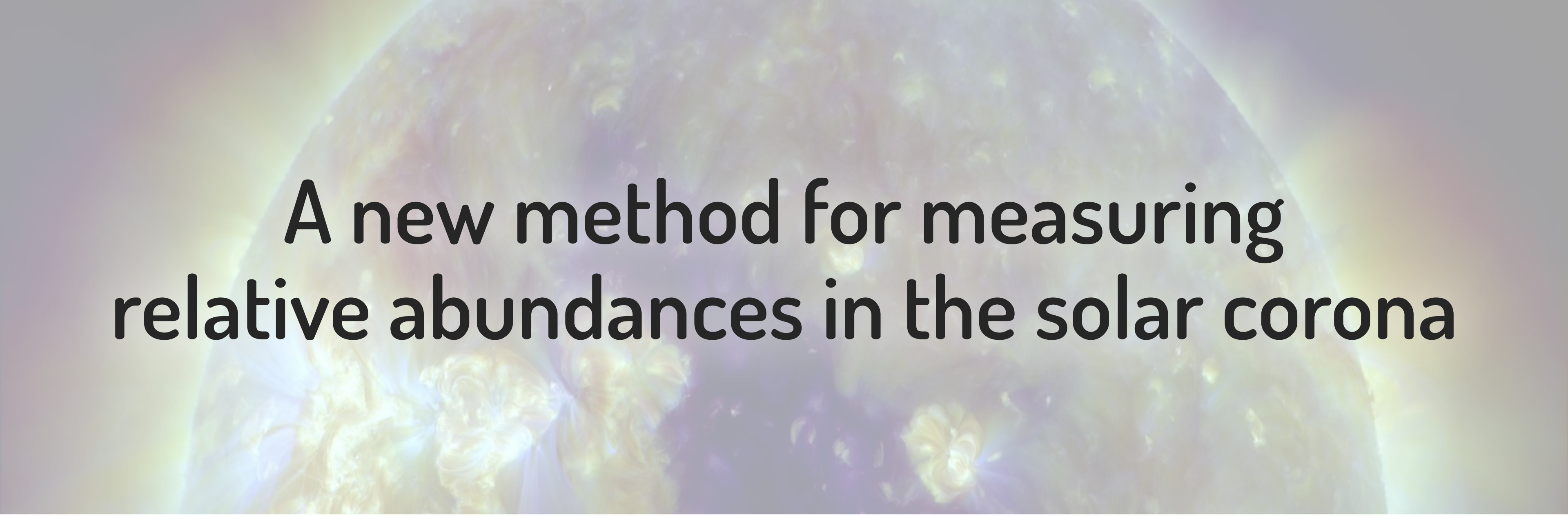

A new method for measuring relative abundances in the solar corona

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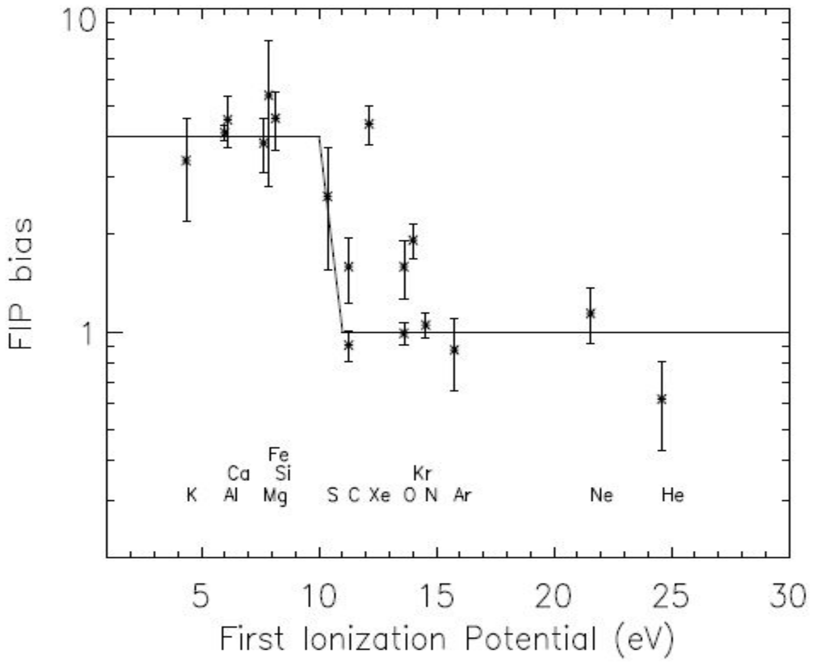
The FIP effect

Fractionation of the coronal composition as a function of the First Ionization Potential.

« FIP bias » : $f_X = \dfrac{Ab_X^{corona}}{Ab_X^{photosphere}}$

- ★ FIP : First Ionization Potential
- ★ Ab_X^{region} : elemental abundance relative to hydrogen in a given region of the solar atmosphere

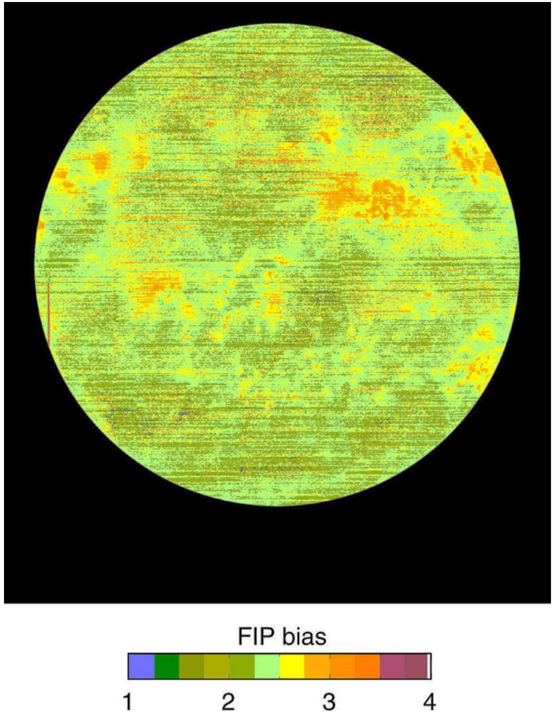


FIP bias as a function of FIP in the slow Solar Wind, von Steiger et al. (1997).

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

Linking the Sun to the Heliosphere

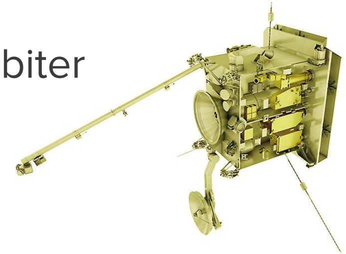
« FIP bias » frozen in the corona → **The FIP effect can allow us to trace back the source of heliospheric plasma**



FIP bias map of the Solar corona, D. Brooks et al, 2014

UV spectroscopy (remote sensing)

Solar Orbiter



In-situ measurements

FIP bias maps in the corona

Comparisons

Abundance measurements in the Solar Wind

Measuring relative abundances

In the coronal approximation, the radiance of the transition line from level i to j of ion X^{+m} is :

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

Coronal abundance of element X

Contribution function

Differential Emission Measure

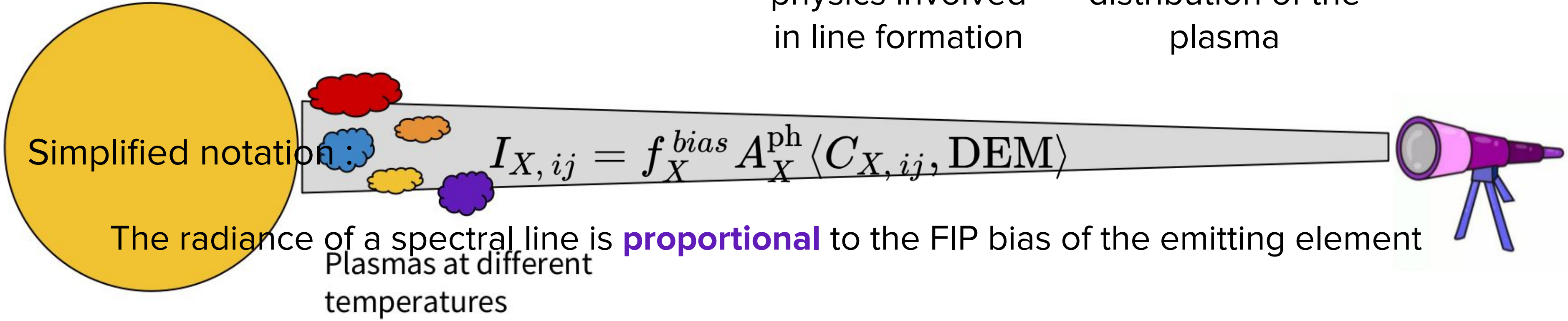
Contains all the physics involved in line formation

Temperature distribution of the plasma

Simplified notation :

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

The radiance of a spectral line is **proportional** to the FIP bias of the emitting element



Measuring relative abundances

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

$$\frac{f_{X_{\rm LF}}^{\,bias}}{f_{X_{\rm HF}}^{\,bias}} = \frac{I_{\rm LF}}{I_{\rm HF}} \left(\frac{A_{X_{\rm LF}}^{\rm ph}}{A_{X_{\rm HF}}^{\rm ph}} \frac{\boxed{\langle C_{\rm LF},}\boxed{\mathrm{DEM}\rangle}}{\boxed{\langle C_{\rm HF},}\boxed{\mathrm{DEM}\rangle}} \right)^{-1}$$

Two Line Ratio (2LR)

- ✅ Fast and simple
- ✅ Easy to automate
- ❌ Inaccurate unless contribution functions match perfectly

Following DEM inversion

- ❌ Inverse problem difficult to constrain
- ❌ Complicated to automate
- ✅ More accurate

The game plan

What we have

Spectroscopic observations

How

A new FIP bias measuring method with:

- ★ No DEM Inversion
- ★ Optimized linear combinations of spectral lines

What we want to do

- ★ Create accurate FIP bias maps systematically and semi-automatically
- ★ Re-analyze past observations
- ★ Design observations : which lines should we use ?

The Linear Combination Ratio (LCR) method

Spectral lines of **low FIP** elements

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

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

Spectral lines of **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 **relative FIP bias** is $\frac{f_{\mathrm{LF}}^{bias}}{f_{\mathrm{HF}}^{bias}} = \frac{\mathscr{I}_{\mathsf{LF}}}{\mathscr{I}_{\mathsf{HF}}} \boxed{\left(\frac{\langle \mathscr{C}_{\mathsf{LF}}, \mathsf{DEM}\rangle}{\langle \mathscr{C}_{\mathsf{HF}}, \mathsf{DEM}\rangle}\right)^{-1}}$ **≈1**

We **minimize** $\phi(\alpha,\beta) = \sqrt{\sum_{j\in(\mathsf{DEM}_j)_j} \left| \frac{\langle \mathscr{C}_{\mathsf{LF}}, \mathsf{DEM}_j\rangle}{\langle \mathscr{C}_{\mathsf{HF}}, \mathsf{DEM}_j\rangle} - 1 \right|^2}$ for a set of reference DEMs

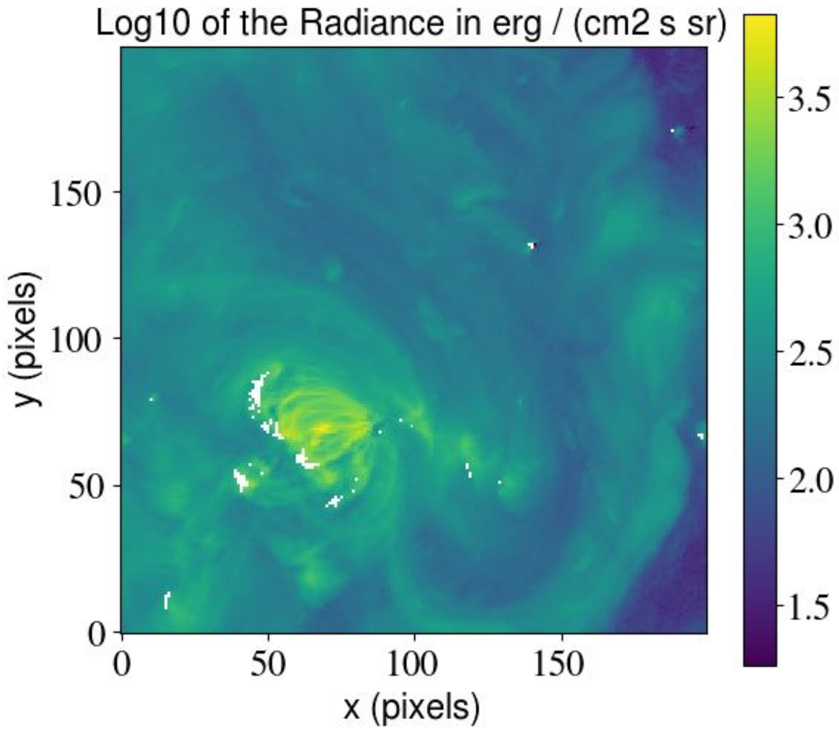
Tests on uniform FIP bias maps

Synthetic intensities

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

2LR vs LCR

FIP bias maps

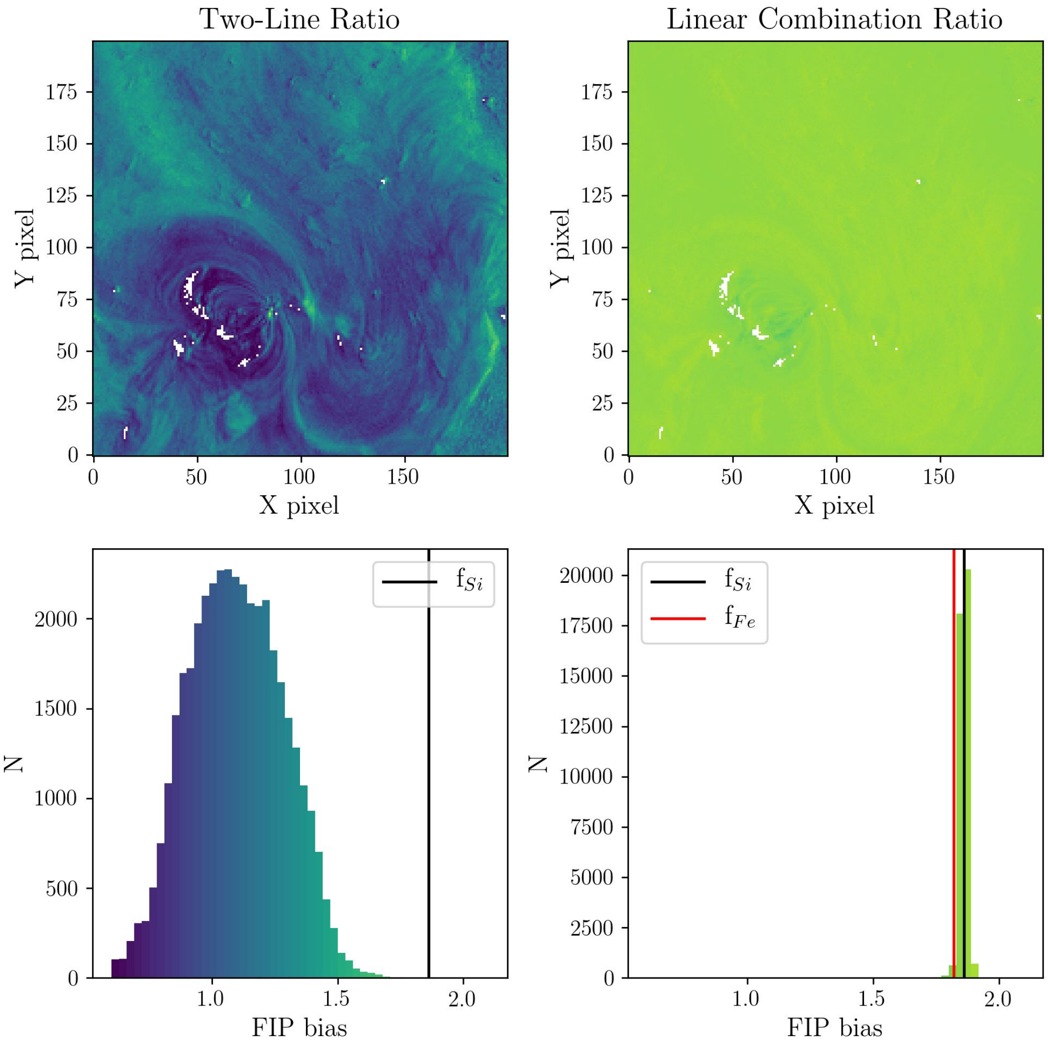


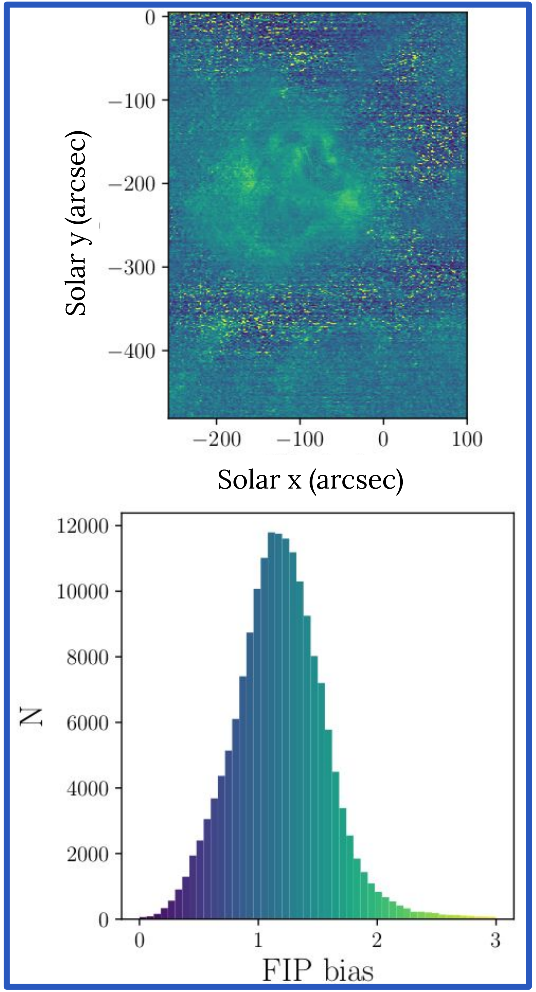
Fe xii 195.119 Angstroms

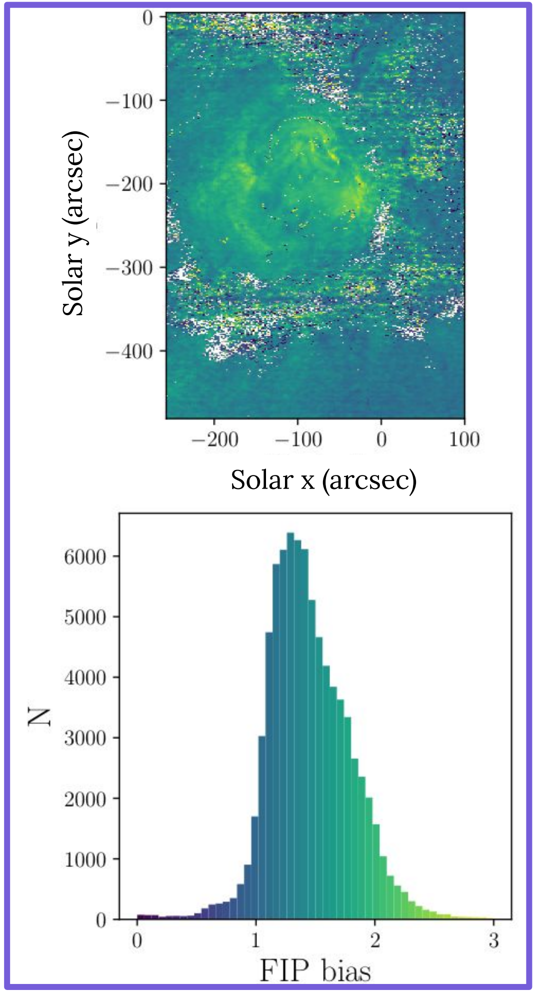
Tests on uniform FIP bias maps

Maps for relative FIP bias (ground truth: uniform, ≈ 1.8)

Histograms of values in maps







Data courtesy of D. Baker

In practice : Hinode/EIS

Application of the LCR method to spectroscopic observations of a sigmoidal anemone-like Active Region inside an equatorial Coronal Hole, previously studied in Baker et al. (2013).

Following DEM inversion

$$\frac{f_{\mathrm{Si}}}{f_{\mathrm{S}}}$$

Linear combinations

$$\frac{f_{\mathrm{Si\ \&\ Fe}}}{f_{\mathrm{S}}}$$

★ Similar structures with enhanced or depleted relative FIP bias in both maps.

Conclusions

★ The tests show that **the LCR method performs well,** and **does not require prior DEM inversion**.

★ The LCR method could be useful to **re-analyze past observations** that were not intended for abundance measurements.

★ It could help us **prepare future observations**.

Present and Future work

★ Re-analyze past EIS/Hinode observations (ISSI Team of Susanna Parenti).

★ Assessment of **linear combinations of lines** for the UV spectrometer **SPICE** on board Solar Orbiter to help connect remote and in-situ measurements from SWA/HIS.

★ Could become a SPICE **level 3 data product**.

Thank you for listening