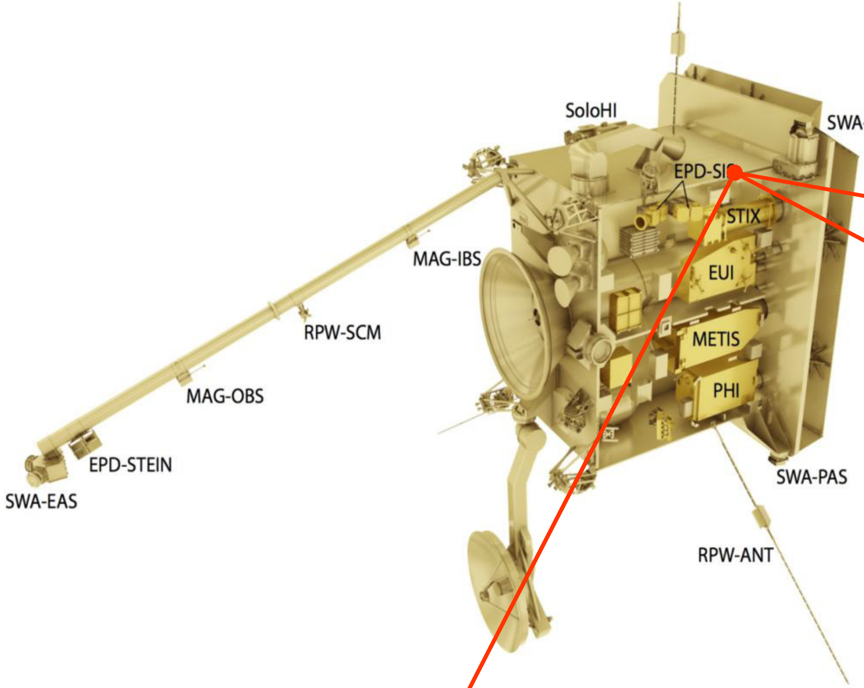
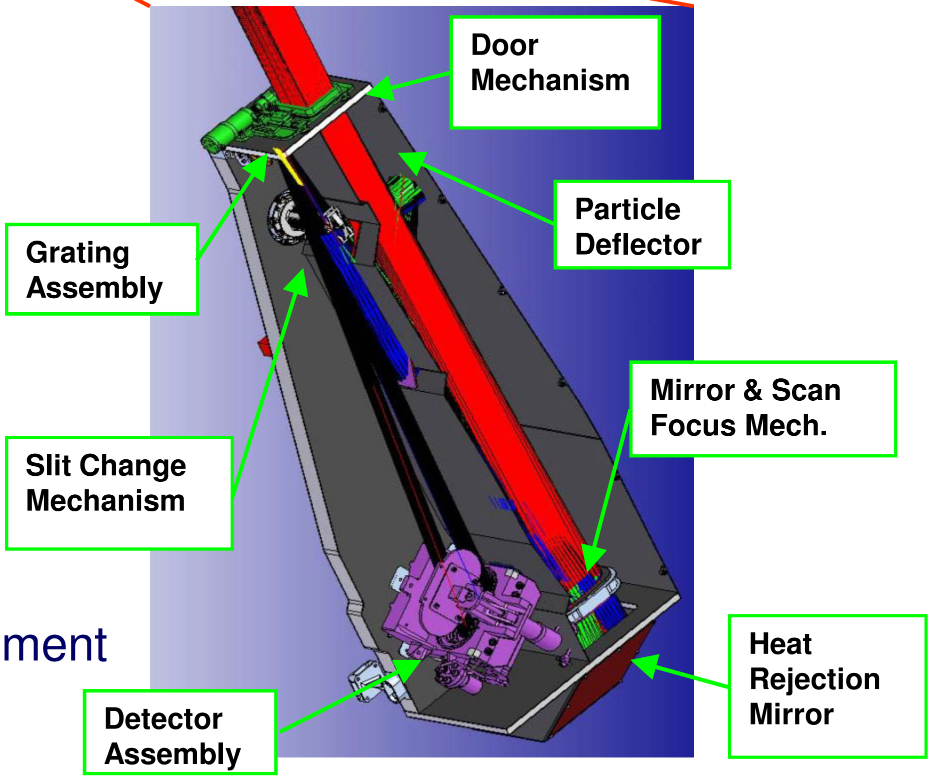
Solar Orbiter/SPICE:
composition studies

Alessandra Giunta

Solar Orbiter/SPICE





SPICE

SPectral Investigation of Coronal Environment

Introduction to SPICE …

- SPICE is the high resolution imaging spectrometer on-board Solar Orbiter (launch due in 2018).
- It will record EUV spectra from the Sun in two bands: 703.9 -790.2 Å and 972.5-1049.2 Å.
- Selection of lines covering temperatures from chromosphere to flaring corona ($2x10^4$-10^7 K).

… and science goals

- Solar wind origin.
- Composition of plasma.
- Coronal Mass Ejection onsets and early propagation.
- An understanding of energetic particles (their source and acceleration in magnetic reconnection regions).
- EUV emission and magnetic field.
- Connectivity to in-situ observations.
- Microflares, wave propagation, jets.

Composition of plasma…

- The analysis of elemental composition of the solar atmosphere is one of the goal of Solar Orbiter/*SPICE.*

Issues

- Abundances of elements with low (<10 eV) First Ionisation Potential (FIP) (e.g. Mg, Fe) are enhanced in the corona, while high (>10 eV) FIP elements (e.g. O, Ne) have the same abundance in the photosphere and corona.
- FIP pattern seen in solar atmosphere, solar wind and solar energetic particles.

…and atomic physics

- SPICE will allow observations up to the relatively dense solar upper chromosphere/ lower transition region and will be oriented to dynamic conditions.

Issues

- The use of zero-density approach (Giunta et al. 2015) and inappropriate simplification of the theoretical atomic models (Giunta et al. 2012) can lead to misinterpretation in comparing measurements and theory.

⇩

Accurate studies using the Generalised Collisional-Radiative (GCR) modelling and the most up-to-date atomic data will allow a precise investigation of the FIP effect in the solar atmosphere and relate it to the in situ measurement on Solar Orbiter.

Target

***Solar Orbiter science question 1.1*:**
What are source regions of the solar wind and heliospheric magnetic field?

- Can we determine elemental composition in the solar atmosphere with SPICE?
- Do we see the FIP effect, does it vary spatially or in time?
- How can we compare SPICE abundance measurements with in-situ measurements:

  - how do we determine whether/when the solar observations are magnetically connected to the location of the spacecraft?

  - do we see the same FIP pattern on the Sun and in-situ (Solar Wind plasma Analyser/Heavy Ion Sensor, SWA/HIS, Energetic Particle Detector, EPD)?

Can we determine elemental composition in the solar atmosphere with SPICE?

- ***What can we derive in practice?***

  - relative elemental abundances

  - FIP bias maps

- ***Requirements***:

  - lines which arise from high FIP and low FIP elements and with close temperature of formation

  - lines for solar plasma diagnostics (electron temperature, electron density, emission measure)

  - a (*semi-automatic*) method to derive FIP bias maps

Composition study techniques

- FIP bias

  It is the *ratio between the abundance of an element in the corona (Ab^{cor}) and the abundance of the same element in the photosphere (Ab^{pho})*.

  e.g. for Magnesium $FIP(bias) = \frac{Ab^{cor}(Mg)}{Ab^{pho}(Mg)}$

- FIP bias maps

  It is the *spatial distribution* along Solar-X and Solar-Y *of the FIP bias values*.

  From a theoretical point of view, the FIP bias can be derived by spectroscopic techniques. Two methods are the following:

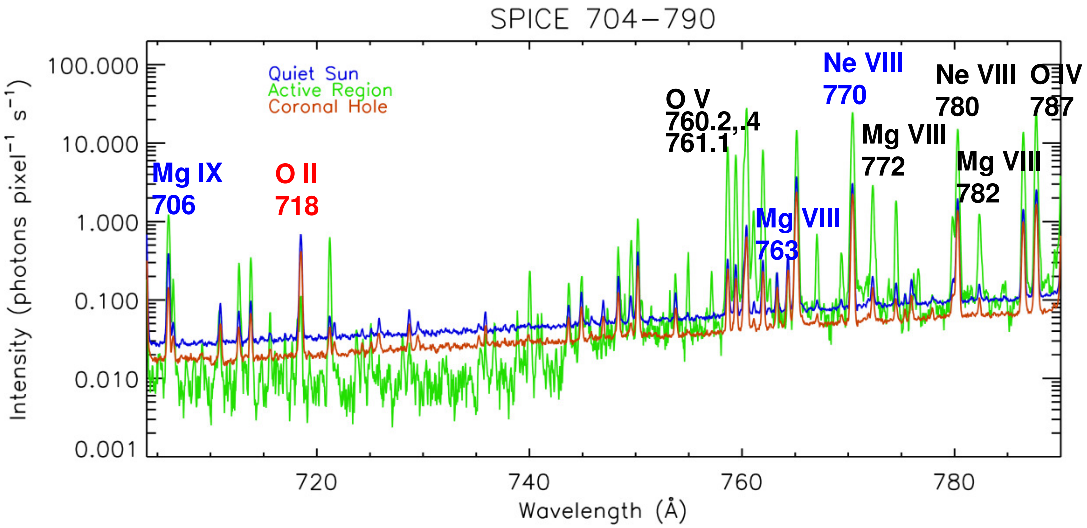
  1. Differential Emission Measure (DEM) technique

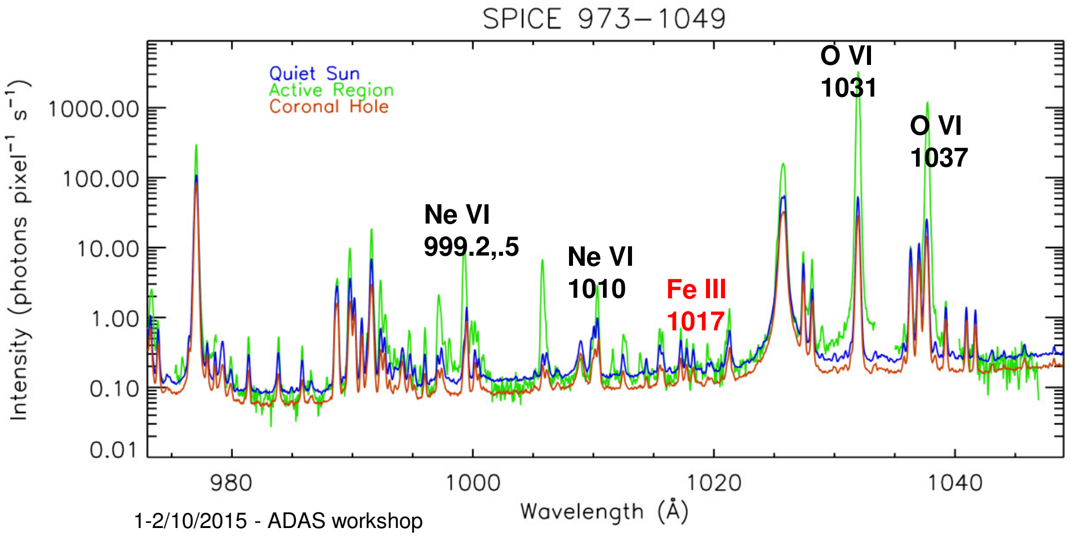
$$FIP^{DEM}(bias) = \frac{I^{obs}(Mg\,VIII\ 763\ \text{Å})}{I^{rec}(Mg\,VIII\ 763\ \text{Å})} = \frac{Ab^{cor}(Mg)}{Ab^{pho}(Mg)}$$

  2. Line Ratio (LR) technique

$$FIP^{LR}(bias) = \frac{R^{obs}(Mg/Ne)}{R^{rec}(Mg/Ne)} = \frac{I^{obs}(Mg\,VIII\ 763\ \text{Å})/I^{obs}(Ne\,VIII\ 770\text{Å})}{I^{rec}\ (Mg\,VIII\ 763\ \text{Å})/I^{rec}(Ne\,VIII\ 770\text{Å})} = \frac{Ab^{cor}(Mg)}{Ab^{pho}(Mg)}$$

SPICE composition mapping study





It includes:

- ***2 line profiles***:

  - Ne VIII 770 Å
  - either **Mg VIII 763 Å** or Mg IX 706 Å

  or

  - O II 718 Å
  - Fe III 1017.24 Å

- ***13 intensities***:

  - *lines for density diagnostics*:
    O V 760.2 Å,760.1 Å (O'Shea 2000)
    Ne VI 999.2 Å, 1010 Å (Laming 1997)
    Mg VIII 772 Å, 782 Å (Laming 1997)

  - *lines for DEM* – **high FIP only**:
    O II 718 Å, O IV 787 Å, O V 760.2 Å, (O VI 1031 Å, 1037 Å), Ne VI 999.2 Å, Ne VIII 780.3 Å

FIP bias from DEM: method

- ***Needs***
  - observed intensities I^{obs}
  - contribution functions $G(T_e)$
  - elemental abundances for O and Ne (taken from Phillips 2008)

- ***Procedure***
  - *Step 1*: select lines from elements with high FIP only (O and Ne)
  - *Step 2*: derive electron density N_e from the following line ratios

    O V I(760.2 Å)/I(761.1 Å)

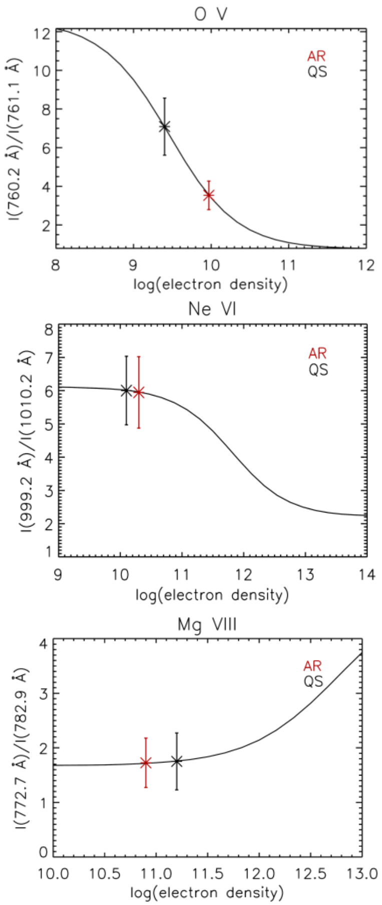
    Ne VI I(999.2 Å)/I(1010.2 Å)

    Mg VIII I(772.7 Å)/I(782.9 Å)
  - *Step 3*: calculate $G(T_e)$ at the derived electron density $(N_e = 10^{10} cm^{-3})$
  - *Step 4*: estimate DEM by inverting $I^{obs} = Ab \int DEM(T_e)\ G(T_e)\mathrm{d}T_e$
  - *Step 5*: predict intensity of Mg VIII 763 Å (or Mg IX 706 Å) from the DEM obtained in *Step 4*
  - *Step 6*: evaluate FIP bias as a ratio between the observed and predicted intensity of the Mg line

FIP bias from DEM: example

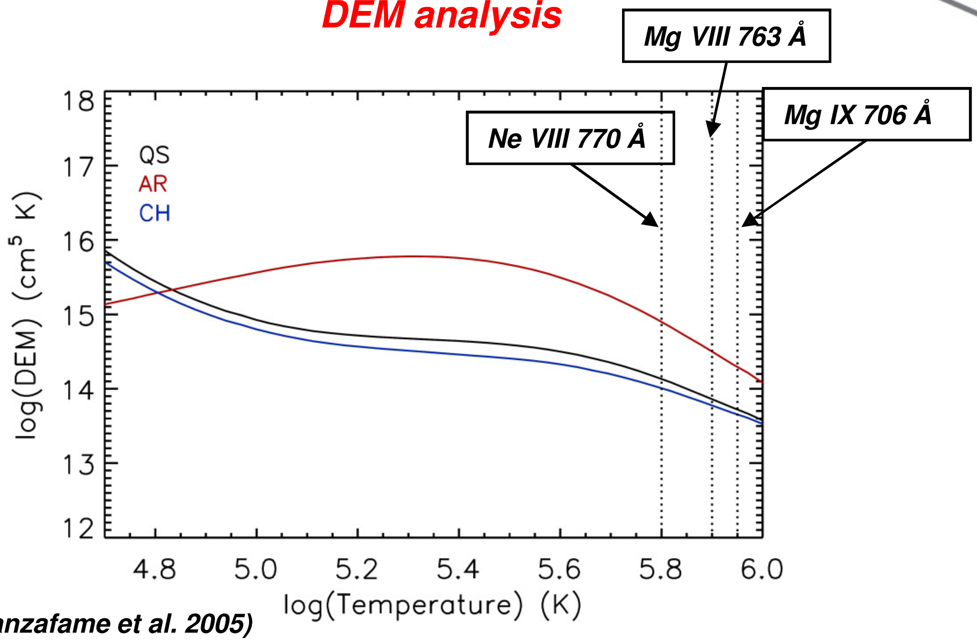
Observed spectra from SUMER atlas for Quiet Sun (QS), Active Region (AR) and Coronal Hole (CH) (Curdt et al. 2001).

Density diagnostics



$$\boxed{N_e = 10^{10} cm^{-3}}$$

DEM analysis



QS DEM – ADAS601 (Lanzafame et al. 2005)

SINGLE LINES

ION	SPECTROSCOP. WAVELENGTH	PEAK TEMP log(T)	RECONSTR. INTENSITY erg/cm2/s	OBSERVED INTENSITY erg/cm2/s	QFR	RECONSTR. INTENSITY ph/cm2/s	OBSERVED INTENSITY ph/cm2/s	EPS	SIG	DEV
O + 1	718.500	4.70	0.464	0.464	1.000	1.678e+10	1.679e+10	2.347e+09	5.070e+08	4.567e-04
O + 3	787.710	5.25	1.419	1.415	1.003	5.625e+10	5.609e+10	4.485e+09	1.809e+09	1.783e-02
O + 4	760.230	5.35	0.101	0.108	0.938	3.867e+09	4.121e+09	2.751e+08	2.751e+08	1.865e+00
Ne+ 5	999.230	5.60	0.207	0.192	1.076	1.039e+10	9.659e+09	6.494e+08	5.073e+08	4.547e+00
Ne+ 7	780.320	5.80	1.094	1.097	0.997	4.297e+10	4.310e+10	2.417e+09	5.244e+08	1.303e-01

PREDICTED INTENSITIES

ION	SPECTROSCOP. WAVELENGTH	PEAK TEMP log(T)	RECONSTR. INTENSITY erg/cm2/s	OBSERVED INTENSITY erg/cm2/s	QFR	RECONSTR. INTENSITY ph/cm2/s	OBSERVED INTENSITY ph/cm2/s	DEV
Ne+ 7	770.410	5.75	2.201	2.322	0.948	8.535e+10	9.004e+10	3.391e+01
Mg+ 7	763.180	5.90	0.003	0.005	0.548	1.009e+08	1.840e+08	3.716e+00

FIP bias from LR

Needs

Couples of lines with close temperature of formation and which arise from a low FIP element and a high FIP element.

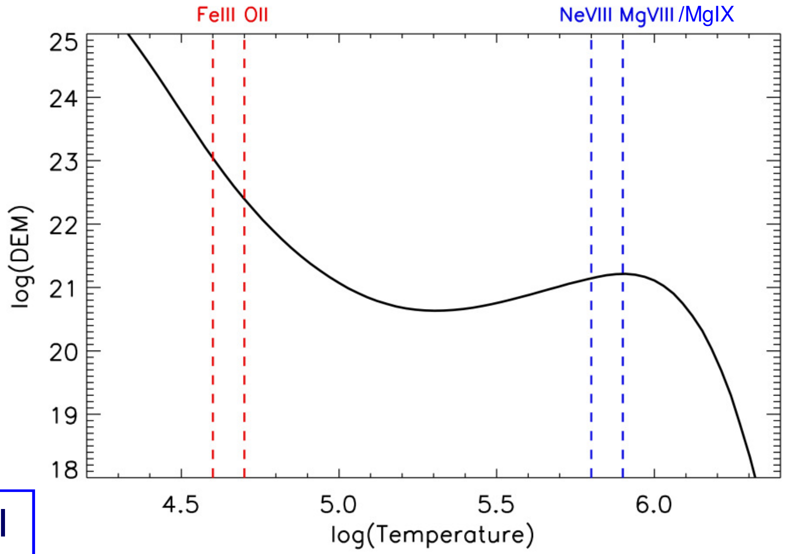
Potential from SPICE

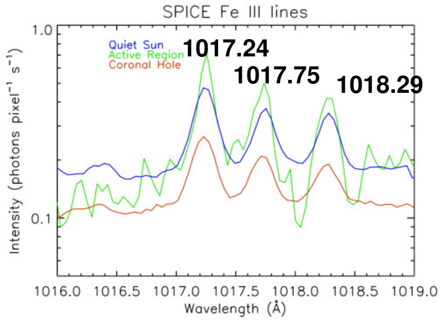
FIP(Fe)=7.9 eV
FIP(O)=13.6 eV

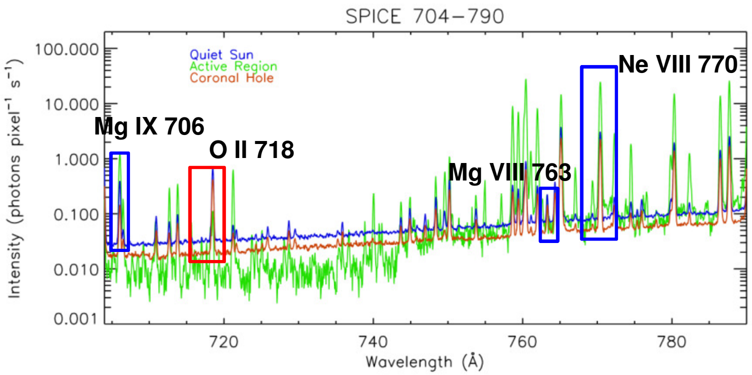
FeIII/OII

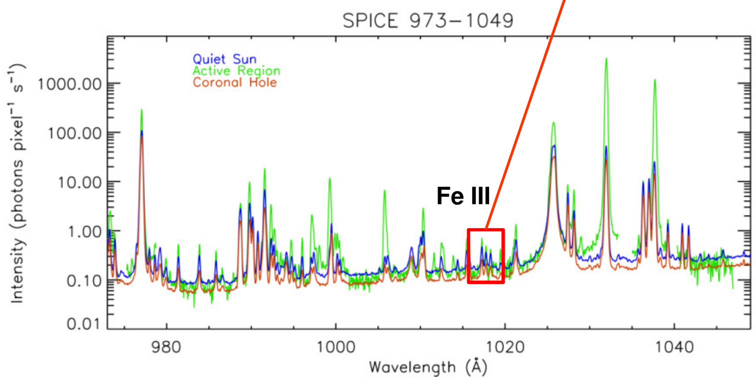
FIP(Mg)=7.6 eV
FIP(Ne)=21.6 eV

MgVIII/NeVIII
or
MgIX/NeVIII









Comparison of the two techniques

Technique 1

FIP bias from DEM

$$FIP^{DEM}(bias) = \frac{I^{obs}(Mg)}{I^{rec}(Mg)}\bigg]_{QS} = 1.8$$

$$FIP^{DEM}(bias) = \frac{I^{obs}(Mg)}{I^{rec}(Mg)}\bigg]_{AR} = 4.3$$

$$FIP^{DEM}(bias) = \frac{I^{obs}(Mg)}{I^{rec}(Mg)}\bigg]_{CH} = 1.7$$

Technique 2

FIP bias from LR

$$FIP^{LR}(bias) = \frac{R^{obs}(Mg/Ne)}{R^{rec}(Mg/Ne)}\bigg]_{QS} = 2.9$$

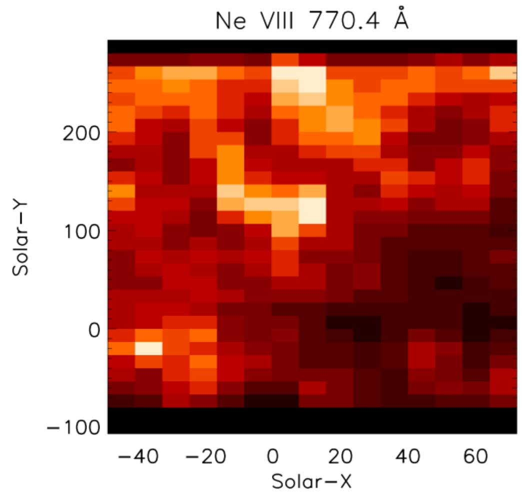
$$FIP^{LR}(bias) = \frac{R^{obs}(Mg/Ne)}{R^{rec}(Mg/Ne)}\bigg]_{AR} = 4.2$$

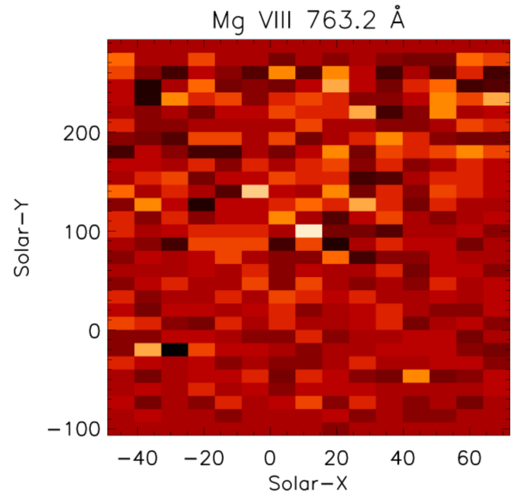
$$FIP^{LR}(bias) = \frac{R^{obs}(Mg/Ne)}{R^{rec}(Mg/Ne)}\bigg]_{CH} = 2.8$$

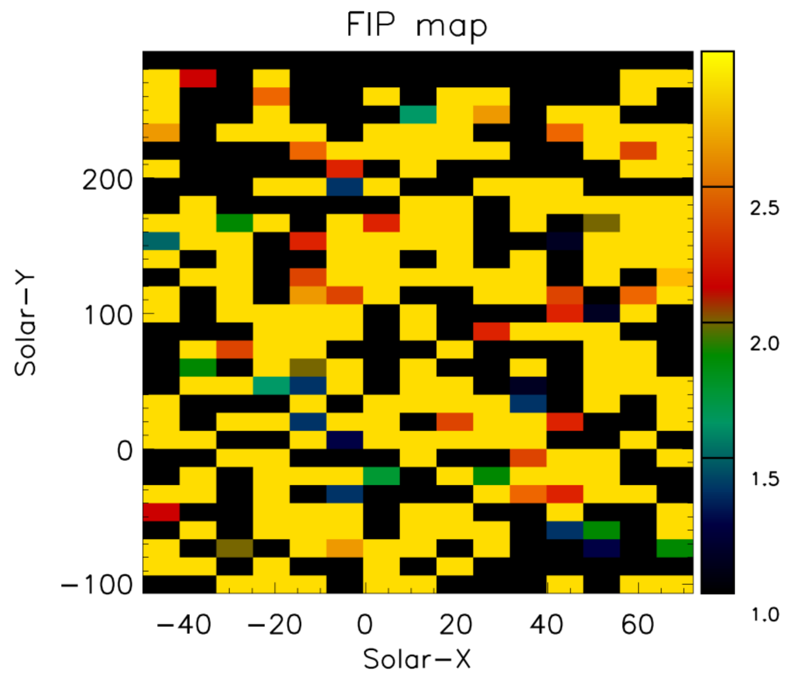
FIP bias map: illustrative example

- Line Ratio technique
  using Mg VIII 763 Å and Ne VIII 770 Å

- *Simulated SPICE intensities taken from SUMER **spatial resolved observations** of April 2009*







Conclusions and future work

- The SPICE potential to derive FIP bias maps, using different techniques, will give higher confidence in the interpretation of the results.
- Mg and Fe are essential for SPICE composition maps.

- ***Next steps***:

  - completion of GCR modelling for Mg and Fe with extension to *ic* resolution and inclusion of ion impact;
  - to automate the two techniques in order to provide a quicker and reproducible estimate of the FIP bias, using a variety of observations from different regions of the Sun;
  - to derive additional physical quantities (e.g. proton rate) which allow further linkage with in-situ and magnetic field observations (Brooks et al. 2015).