Solar Orbiter/SPICE: composition studies

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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 \( (Ab^{pho}) \).

  \[
  FIP(bias) = \frac{Ab^{cor}(Mg)}{Ab^{pho}(Mg)}
  \]

  e.g. for Magnesium

- **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**

   \[
   FIP^{LR}(bias) = \frac{R^{obs}(Mg/Ne)}{R^{rec}(Mg/Ne)} = \frac{I^{obs}(Mg\ VIII\ 763\ \text{Å})/I^{obs}(Ne\ V\ 770\ \text{Å})}{I^{rec}(Mg\ VIII\ 763\ \text{Å})/I^{rec}(Ne\ V\ 770\ \text{Å})} = \frac{Ab^{cor}(Mg)}{Ab^{pho}(Mg)}
   \]
It includes:

- **2 line profiles:**
  - Ne VIII 770 Å
  - either Mg VIII 763 Å or Mg IX 706 Å
  - 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 $I(760.2 \text{ Å})/I(761.1 \text{ Å})$
    - Ne VI $I(999.2 \text{ Å})/I(1010.2 \text{ Å})$
    - Mg VIII $I(772.7 \text{ Å})/I(782.9 \text{ Å})$
  - **Step 3**: calculate $G(T_e)$ at the derived electron density ($N_e = 10^{10} \text{cm}^{-3}$)
  - **Step 4**: estimate DEM by inverting $I^{obs} = Ab \int DEM(T_e) G(T_e) dT_e$
  - **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**

**DEM analysis**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Spectroscopic Wavelength</th>
<th>Peak Temp log(T)</th>
<th>Intensity erg/cm²/s</th>
<th>QFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>718.500</td>
<td>4.70</td>
<td>0.464</td>
<td>0.464 1.000 1.679e+10 1.679e+10 2.347e+09 5.070e+08 4.567e-04</td>
</tr>
<tr>
<td>O</td>
<td>787.710</td>
<td>5.25</td>
<td>1.419</td>
<td>1.415 1.003 5.625e+10 5.600e+10 4.485e+09 1.809e+09 1.783e-02</td>
</tr>
<tr>
<td>O</td>
<td>760.230</td>
<td>5.35</td>
<td>0.101</td>
<td>0.108 0.938 3.867e+09 4.121e+09 2.751e+08 2.751e+08 1.865e+00</td>
</tr>
<tr>
<td>Ne</td>
<td>780.320</td>
<td>5.80</td>
<td>1.094</td>
<td>1.097 0.997 4.297e+10 4.310e+10 2.417e+09 5.244e+08 1.303e+01</td>
</tr>
<tr>
<td>Ne</td>
<td>770.410</td>
<td>5.75</td>
<td>2.201</td>
<td>2.322 0.948 8.315e+10 9.004e+10 3.391e+01 1.391e+01</td>
</tr>
</tbody>
</table>

\[ N_e = 10^{10} \text{ cm}^{-3} \]
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
- FIP(Mg)=7.6 eV
- FIP(Ne)=21.6 eV

- FeIII/OII
- MgVIII/NeVIII
- or MgIX/NeVIII
## Comparison of the two techniques

### Technique 1
**FIP bias from DEM**

\[
FIP_{DEM}^{bias} = \frac{I^{obs}(Mg)}{I^{rec}(Mg)}
\]

- **QS**
  \[
  FIP_{DEM}^{bias} = 4.3
  \]

- **AR**
  \[
  FIP_{DEM}^{bias} = 1.7
  \]

- **CH**
  \[
  FIP_{DEM}^{bias} = 1.8
  \]

### Technique 2
**FIP bias from LR**

\[
FIP_{LR}^{bias} = \frac{R^{obs}(Mg/Ne)}{R^{rec}(Mg/Ne)}
\]

- **QS**
  \[
  FIP_{LR}^{bias} = 4.2
  \]

- **AR**
  \[
  FIP_{LR}^{bias} = 2.9
  \]

- **CH**
  \[
  FIP_{LR}^{bias} = 2.8
  \]
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).