Elemental Abundance Variations in the Solar Atmosphere

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The Chemical Composition of the Sun (Interior) [1]

- **Convection zone**: well mixed $\Rightarrow$ photospheric abundances.
- **Radiative zone**: diffusion $\Rightarrow$ small effects ($\tau\approx 6\times 10^{13}$ yrs):
  - Thermal force (helium, metals). [e.g.: '] (More later...)
  - *(Less important)* Radiative acceleration (metals). [e.g.: Vauclair, S. (1998), Space Science Reviews, 85, 71]
Particularly important: **He**:

- After hydrogen, by far the highest abundance: $\text{He}/\text{H} \approx 10\%$.
- 4 times the mass of hydrogen.

*(More later...)*

**Special cases: Li, Be, B:**

- Fragile elements: destroyed in the solar interior.
- Interesting tool in Astrophysics (especially lithium): e.g.: stellar age indicator.

*(Outside the scope of this talk...)*
The Chemical Composition of the Sun (Photosphere) [1]

- Abundances measured in the photosphere, from spectral lines.
- Some notable exceptions: He, Ne, Ar:
  - Lines not forming in the photosphere.
  - He abundance estimated from helioseismology: \( Y = 0.242 - 0.254 \) (\( A_{\text{He}} = 0.078 - 0.088 \)). [Boothroyd, A.I., & Sackmann, I.-J. (2003), ApJ, 583, 1004]
  - Note also that these elements are largely lost by meteorites, so no meteoritic abundances either!
Usual procedures use line strengths normalized to the hydrogen-dominated background continuum ⇒ abundances relative to hydrogen.

Uncertainties: mostly due to atomic physics (transition probabilities).

- Estimated uncertainties for key elements such as C, N, and O, of the order of 0.06 dex.

- But: [O/H] lowered by 0.3 dex in recent years!


(The latter point especially relevant for measurements of abundances in the outer solar atmosphere. More later...)

The Chemical Composition of the Sun (photosphere vs. solar system)

Comparison with meteoritic abundances:


Note: Effect of migration on the bottom of the convection zone not seen! (Uncertainties on photospheric abundances too large to see a 10-15% effect...)
Remote sensing: Spectroscopy (UV, X, \(\gamma\)) → chromosphere (very little!), corona:
- UV: SOHO (CDS, SUMER, UVCS), SERTS, etc.
- X-rays: YOHKOH, etc.
- \(\gamma\)-rays: SMM/GRS, Compton/OSSE, RHESSI, etc.

In situ measurements → wind:
- Ulysses/SWICS, SOHO/CELIAS, etc.
- Lunar soils → historical record of solar wind composition!

[Wieler (1998), Space Science Reviews, 85, 303]
A force that results from the different probabilities of transferring the electron momentum to the ions in opposite directions along a temperature gradient.

The net effect is a diffusion of heavier elements towards higher temperatures.

Force density proportional to $\nabla T$. 
Interlude [2]: Theoretical Prejudices

Migration of metals:
- Outer atmosphere:
  - (?)
  - Diffusion:
    - Gravitational: DOWN
    - Thermal: UP
- Convective zone + photosphere
  - Mixing
- Radiative zone:
  - Diffusion:
    - Gravitational: DOWN
    - Thermal: DOWN

- If gravitational settling is the most effective process, one would expect the ratio of Coulomb friction term to weight, $\propto Z^2/A$, to be correlated with observed abundances in the outer atmosphere.
- Interaction with the magnetic field, could add also a dependence on the charge-to-mass ratio, $Q/M$. 
**Observations: Basics**

- **In Situ** (solar wind, mostly):
  - Fast solar wind: almost photospheric composition (almost...)
  - Slow solar wind: some elements enhanced/depleted (depends on the normalization...).
  - Solar Energetic Particle (SEP) Events: Similar to the slow wind. Also: Isotopic ratios ↔ Transport mechanisms.

- **Remote sensing** (corona, mostly):
  - Overall, similar patterns of elemental abundance variations as *in situ* measurements.
  - However, possibility of observing structures/regions perhaps not directly connected to wind plasma.
Dynamic range: H and \(^4\)He are typically measured with different detectors from other species.

- Calibration issues ensue...
- In most cases, metal abundances \textit{not} normalized to hydrogen.
- Instead: Another metal (typically: oxygen or silicon) taken as references.

On the other hand: direct measurement of mass and charge distribution of ions: little atomic physics involved.

- H and He often not observed, or difficult to interpret:
  - In most cases, metal abundances **not** normalized to hydrogen.
  - Instead: Another metal (typically: oxygen) taken as references.

- Furthermore: Atomic physics plays a big role (many cross sections needed...).

- Most reliable determinations are made from many lines of several ions \( \Rightarrow \) instrument calibration often critical.
- Line ratios methods less dependent on instrument calibration, but heavily dependent on many more assumptions and approximations.
- Problems more severe in coronal holes: Fainter lines, and less firm basic assumptions (e.g.: ionization equilibrium).

The FIP Effect

General pattern from *in situ* measurements: Elements classified according to their First Ionization Potential:

The FIP Effect: In Situ Characteristics (Solar Minimum) [1]

The 

The Ulysses mission: The solar wind outside the ecliptic plane.
The FIP Effect: In Situ Characteristics (Solar Minimum) [2]

Bi-modal distribution of the FIP effect: slow and fast wind exhibit different FIP biases.

More on the bi-modal distribution of the FIP effect:

The FIP Effect: Characteristics from Remote Sensing

- FIP effect observed in corona.
- Indication of a FIP effect even from $\gamma$-rays [e.g.: Ramaty, R., Mandzhavidze, N., Kozlovsky, B., Murphy, R.J. (1995), ApJ, 455L, 193]: already in chromosphere!
- But:
  - Different FIP biases in different structures.
  - Other processes too (Gravitational settling? Other?)
    (More later...)
The FIP Effect: Enhancement or Depletion? [1]

- Interpreting the FIP bias with respect to the photospheric abundances:
  a) Low FIP elements enhanced?
  b) High FIP elements depleted?

- Requires absolute (i.e.: relative to hydrogen) abundances.

- Difficult both from *in situ* measurements and from remote sensing (abundances usually normalized to oxygen or silicon).
The FIP Effect: Enhancement or Depletion? [2]

However:

- **SOHO/UVCS**: Ly$\beta$ $\lambda$1025, and O VI $\lambda\lambda$1032,1037 $\rightarrow$ estimates of [O/H].

- **X-rays** (e.g.: YOHKOH): continuum (mostly H-dominated bremsstrahlung) observed too $\rightarrow$ absolute abundances.

- *In situ* $^4$He/H very accurate (at least one absolute and accurate point on the FIP axis....).
A Hybrid FIP Effect?

FIP effect with absolute abundances: not so simple a picture...

Variability of the FIP Effect

Not just bimodal as in solar-minimum wind measurements:

<table>
<thead>
<tr>
<th>Structure</th>
<th>Paper</th>
<th>Height</th>
<th>Instrument</th>
<th>FIP Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal Hole</td>
<td>Doschek et al. 98 [55]</td>
<td>1.0-1.2 $R_{\odot}$</td>
<td>SUMER</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Coronal Hole</td>
<td>Feldman et al. 98 [56]</td>
<td>1.03-1.5 $R_{\odot}$</td>
<td>SUMER</td>
<td>&lt; 1.3</td>
</tr>
<tr>
<td>Coronal Hole Plume</td>
<td>Young et al. 99 [57]</td>
<td>1.0-1.1 $R_{\odot}$</td>
<td>CDS</td>
<td>1.5</td>
</tr>
<tr>
<td>Quiet Sun</td>
<td>Warren 99 [58]</td>
<td>1.05-1.35 $R_{\odot}$</td>
<td>SUMER</td>
<td>2.3±0.7</td>
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<tr>
<td>Quiet Sun</td>
<td>Laming et al. 99 [59]</td>
<td>1.1 $R_{\odot}$</td>
<td>SUMER</td>
<td>3 - 4</td>
</tr>
<tr>
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<td>Young &amp; Mason 98 [28]</td>
<td>Disk</td>
<td>CDS</td>
<td>2</td>
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<tr>
<td>EQ Streamer core</td>
<td>Raymond et al. 97 [48]</td>
<td>1.5 $R_{\odot}$</td>
<td>UVCS</td>
<td>3 - 4</td>
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<tr>
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<td>3</td>
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<td>1.02-1.19 $R_{\odot}$</td>
<td>CDS</td>
<td>1.1</td>
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<tr>
<td>Active Region</td>
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<td>1.5 $R_{\odot}$</td>
<td>CDS</td>
<td>1 - 9</td>
</tr>
<tr>
<td>Active Region</td>
<td>Rank et al. 99 [62]</td>
<td>Disk</td>
<td>CDS</td>
<td>5-9</td>
</tr>
<tr>
<td>Active Region</td>
<td>Dwivedi et al. 99 [63]</td>
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<tr>
<td>Active Region</td>
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<td>CME</td>
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<td>Prominence</td>
<td>Spicer et al. 98 [66]</td>
<td>1.5 $R_{\odot}$</td>
<td>SUMER</td>
<td>2</td>
</tr>
</tbody>
</table>

Something else than just the FIP Effect?

After all, is FIP the only parameter determining solar abundance variations in the corona/wind?

[Adapted from Raymond, J.C., et al. (1997), Sol. Phys., 175, 645]
On the Relevance of the FIP Effect on Abundance Fractionation Processes

- It is generally accepted that FIP fractionation process(es) operate around $T \sim 10^4$ K (chromosphere). [Geiss, J., (1982), Space Science Reviews, 33, 201]

- Likely: ion-neutral separation process in a partly ionized plasma.

- The key is coupling with protons: Coulomb drag forces much stronger for ions than neutrals.
  - Low-FIP elements become more easily ionized in chromosphere $\Rightarrow$ Higher coupling with proton flow.
  - High-FIP elements still partially neutral $\Rightarrow$ Weak coupling with proton flow
A Simple Cartoon...

(The role of UV ionizing radiation is also highlighted)

[From: Peter, H., (1998), Space Science Reviews, 85, ...]

Note, however, that steady-state, one-dimensional pictures probably need unrealistic boundary conditions. [e.g.: McKenzie, J.F., (2000), Solar Physics, 196, 329]

(More later...)

V. Andretta

Elemental Abundance Variations in the Solar Atmosphere
A strict relationship between abundances and FIP does not exist, nor it should...

In fact, the FIP parameter is often related, directly or indirectly, to the behaviour of atoms.

**Example**: A more relevant parameter could be the so-called standard ionization time, $\tau_{\text{st-ion}}$ [e.g.: von Steiger, R., & Geiss, J. (1989), A&A, 225, 222]
The FIP, or FIT, or Whatever Effect? [2]

Abundance biases as function of $\tau_{\text{St-Ion}}$:

[From: Geiss, J. (1998), Space Science Reviews, 85, 241]
The FIP, or FIT, or Whatever Effect? [3]

- In this case, one can talk about the First Ionization Time (FIT) effect.
- So, FIP may be not the most relevant parameter to use in the study of abundances.
- But, after all, FIP is a fundamental atomic parameter. And it is convenient, and easy to use...
- (But is it always so convenient? In stars too?)
More Theoretical Issues on FIP Abundance Fractionation

- **Mode of ionization**: photoionization (UV and EUV) usually.
- **Mode of separation**: models broadly classified by the role of the magnetic field:
  - Magnetic field playing no role:
    - Steady-state, one-dimensional models (incurring in problems with lower boundary conditions...).
    - Time-dependent...
    - ...
  - Magnetic field playing a role:
    - Neutrals diffusing across field lines (vertically or horizontally aligned).
    - Magnetic-related heating of ions.
    - ...
- Many models, very few quantitative...

**Something Interesting about Helium**

1) Highest FIP, and highest FIT $\Rightarrow$ Largely neutral in the chromosphere.

2) Small Coulomb drag factor $\Rightarrow$ Weak coupling with protons.
   - Easily depleted in the corona and solar wind...

- A challenging test (discriminating perhaps...) for elemental fractionation theories.

- In any case, needs to be taken into account: high abundance $\Rightarrow$ may contribute significantly to mass flux, energy balance, etc.
Helium in the Solar Wind

*In situ* observations of helium abundance:

More Theoretical Prejudices

What could affect helium abundance in the solar atmosphere, in addition to the Coulomb drag:

- Corona ($T=10^6$ K):
  - Gravity (DOWN)
- Transition region:
  - Thermal force (UP)
- Chromosphere ($T=10^4$ K):
  - Gravity (DOWN)
  - (Unspecified: “Dynamics”, “Turbulence”, “Magnetic Field”…)

Time scales for gravitational settling of helium atoms (at $T=7000$ K, scale height $H=200$ Km): $\tau \sim (n_{He}/4 \times 10^{10})$ days

For ions, frictional coupling with protons, and thus time scales, increase by a factor 500-1000.
Something Strange about Helium [1]

Actually, already at the top of the chromosphere should be virtually absent, in absence of some kind of “turbulent” mixing or any way to increase coupling with protons.

Something Strange about Helium [2]

- So, models tend to predict a minimum of He abundance at the top of the chromosphere or at the bottom of the transition region.

- But: Observed lines of He I and He II (formed either in chromosphere or in the lower transition region) are already much stronger than most calculations predict, even with a photospheric abundance! [e.g.: Andretta, V., Del Zanna, G., Jordan, S. (2003), A&A, 400, 737]

What do we Really Know about Elemental Fractionation in the Chromosphere?

Something is wrong with our understanding of abundance variations in the chromosphere?

(Perhaps not really surprising, given our state of understanding of the physics of the solar chromosphere...)
On Stellar FIP biases [1]

- FIP effect often observed in stars too
- Sometimes as an “inverse FIP effect”
- **But**: photospheric abundances rarely known $\Rightarrow$ Noise almost comparable to signal!
- **Also**: In the Sun, coronal FIP effect is a signature of chromospheric fractionation. What do we know about fractionation processes in stellar to justify a systematic use of the FIP parameter to order data point on a graph?
On Stellar FIP biases [2]

The effect of reference photospheric abundances:

(XMM-Newton data for λ And)

Concluding Remarks

- Solar abundances do indeed vary in the solar atmosphere.
- One of the most remarkable effects is the FIP bias.
- Other processes at work too.
- The existing data already give useful constraints on theories of the fractionation processes, but not enough even to indicate what the role of magnetic field exactly is.
- Since most of the action occurs in chromosphere, it would be nice to have some information on abundances there: but we have no reliable measurements of the chemical composition of the chromosphere, yet! (Except perhaps for prominences)
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