Elemental Abundance Variations in the Solar Atmosphere

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

- Convection zone: well mixed ⇒ photospheric abundances.
- Radiative zone: diffusion ⇒ small effects ($\tau \approx 6 \times 10^{13}$ yrs):
  - Gravitational settling (helium, metals). [e.g.: Thoul, A.A., Bahcall, J.N., & Loeb, A. (1994), ApJ, **421**, 828]
  - Thermal force (helium, metals). [e.g.: ''] *(More later...)*
  - *(Less important)* Radiative acceleration (metals). [e.g.: Vauclair, S. (1998), Space Science Reviews, **85**, 71]

The Chemical Composition of the Sun (Interior) [2]

- Particularly important: He:
  - After hydrogen, by far the highest abundance: He/H ≈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_{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!

The Chemical Composition of the Sun (Photosphere) [2]

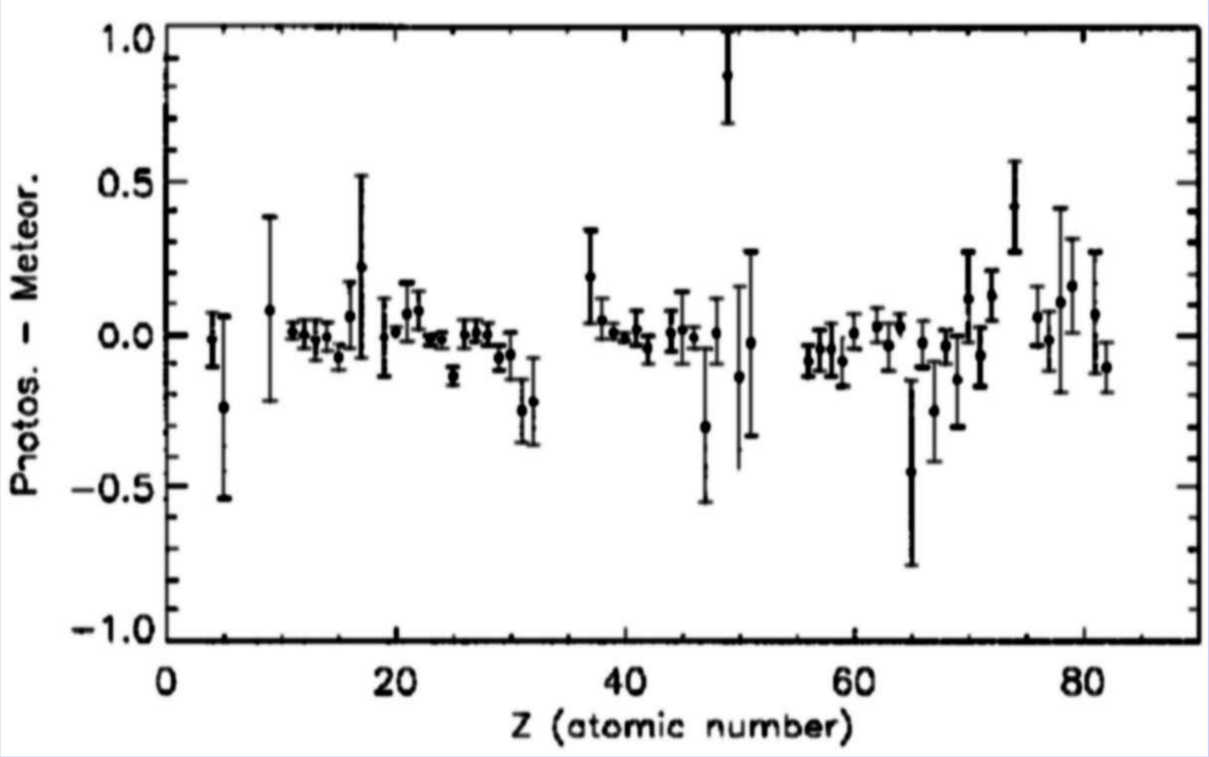
- Usual procedures use line strengths normalized to the hydrogen-dominated background continuum
  $\Rightarrow$ abundances relative to hydrogen.
- Uncertainties: mostly due to atomic physics (transition probabilities).
  - Estimated uncertainties for key elements such as C, N, and O, of the order of 0.06 dex.
  - But: [O/H] lowered by 0.3 dex in recent years!

[Grevesse, N., & Sauval, A.J. (1998), *Space Science Reviews*, **85**, 161; Allende Prieto, et al. (2002), *ApJ*, **556**, L63]

(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:



[From: Grevesse, N. & Sauval, A.J. (1998), *Space Science Reviews*, **85**, 161]

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...)

The Chemical Composition of the Sun (Outer atmosphere; Wind)

- Remote sensing: Spectroscopy (UV, X, γ) → chromo-sphere (very little!), corona:
  - UV: SOHO (CDS, SUMER, UVCS), SERTS, etc.
  - X-rays: YOHKOH, etc.
  - γ-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]

Interlude [1]: What is Thermal Diffusion?

- 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 ∇T.

Interlude [2]: Theoretical Prejudices

Migration of metals:

- Outer atmosphere:
  - (?)
  - Diffusion:

    Gravitational: DOWN

    Thermal: UP
- Convective zone + photo-sphere
  - 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.

In situ Observations: Some Issues

- Dynamic range: H and ^{4}He are typically measured with different detectors from other species.
  - Calibration issues ensue...
  - In most cases, metal abundances 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.

Remote Sensing: Some Issues [1]

- 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...).

Remote Sensing: Some Issues [2]

- Most reliable determinations are made from many lines of several ions ⇒ 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).

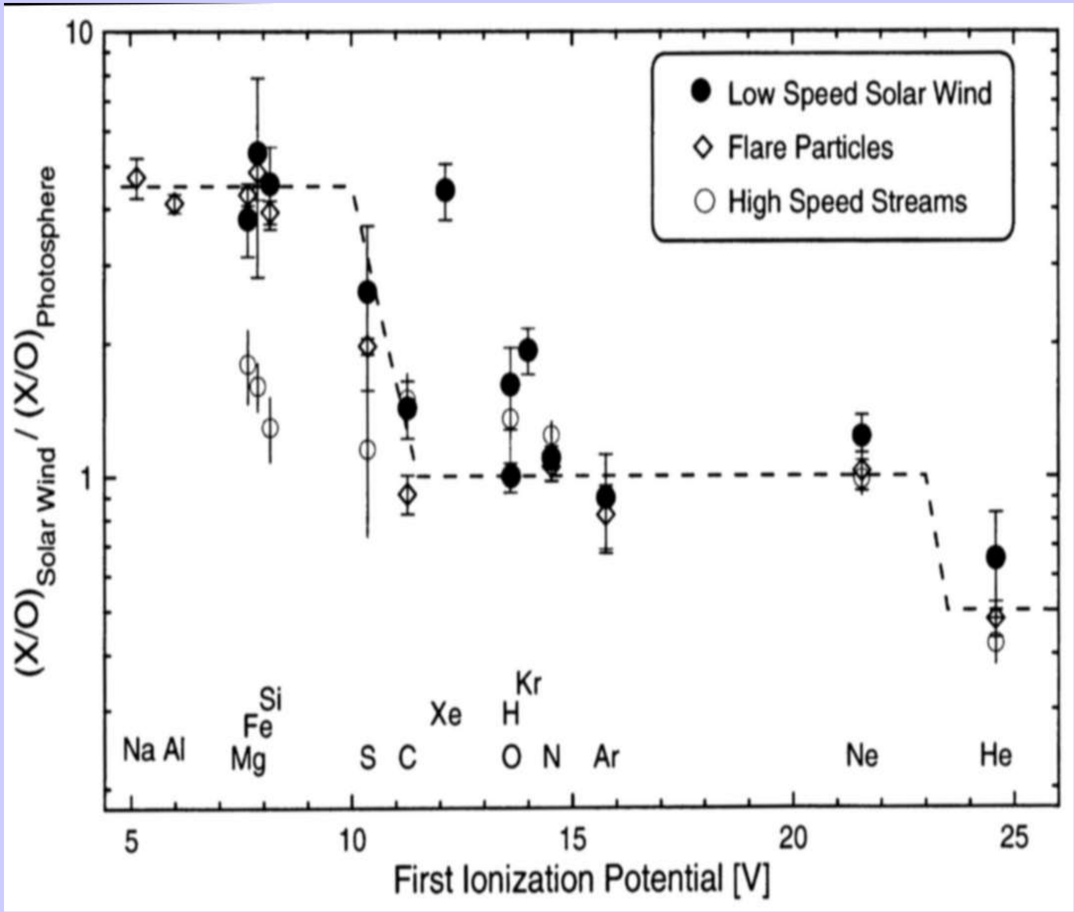
[Problems reviewed in, e.g.:

Del Zanna, G., Bromage, B.J.I, & Mason, H.E. (2001), *AIP Conf. Proc.*, **598**, 59;

Del Zanna, G., Landini, M., & Mason, H.E. (2002), *A&A* **385**, 968]

The FIP Effect

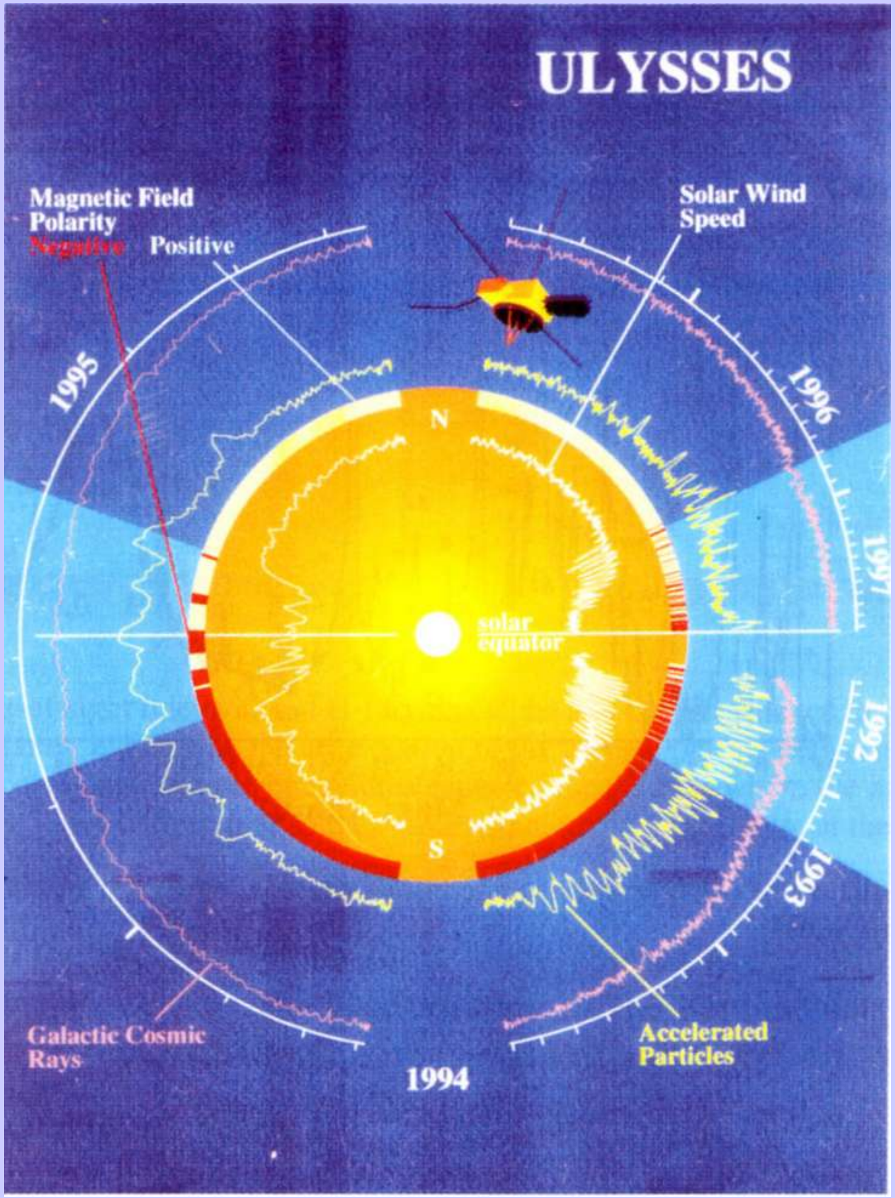
General pattern from *in situ* measurements: Elements classified according to their **F**irst **I**onization **P**otential:



[From: Geiss, J. (1998), Space Science Reviews, **85**, 241]

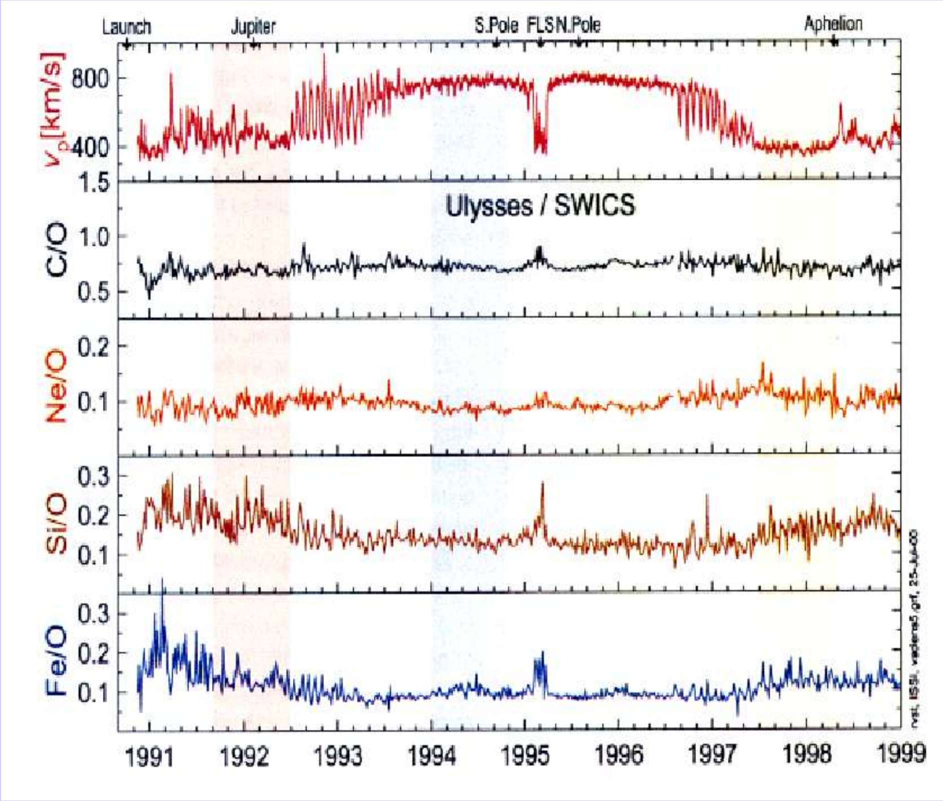
The FIP Effect: In Situ Characteristics (Solar Minimum) [1]

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.

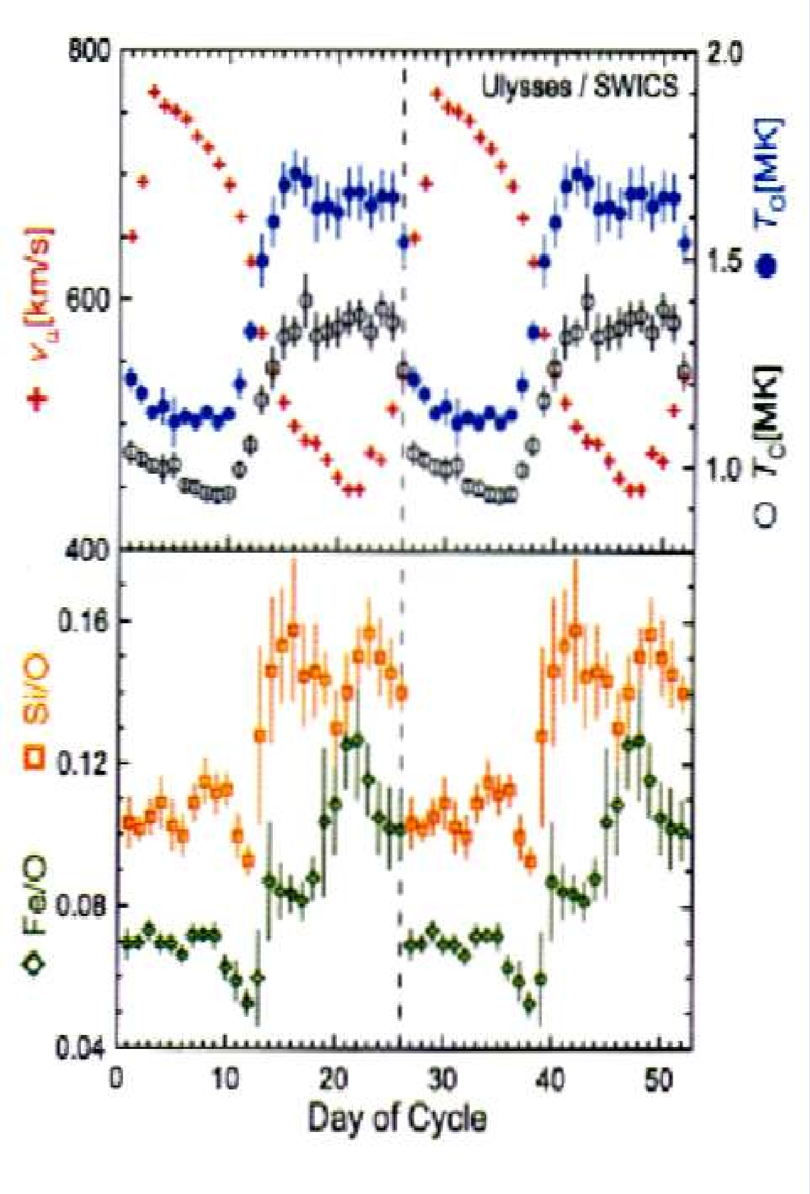


[From: von Steiger, R., et al. (2000), Journal of Geophysical Research, **105**, A12]

The FIP Effect: In Situ Characteristics (Solar Minimum) [3]

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

[From: von Steiger, R., et al. (2000), Journal of Geophysical Research, **105**, A12]



The FIP Effect: Characteristics from Remote Sensing

- FIP effect observed in corona.
- Indication of a FIP effect even from γ-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).

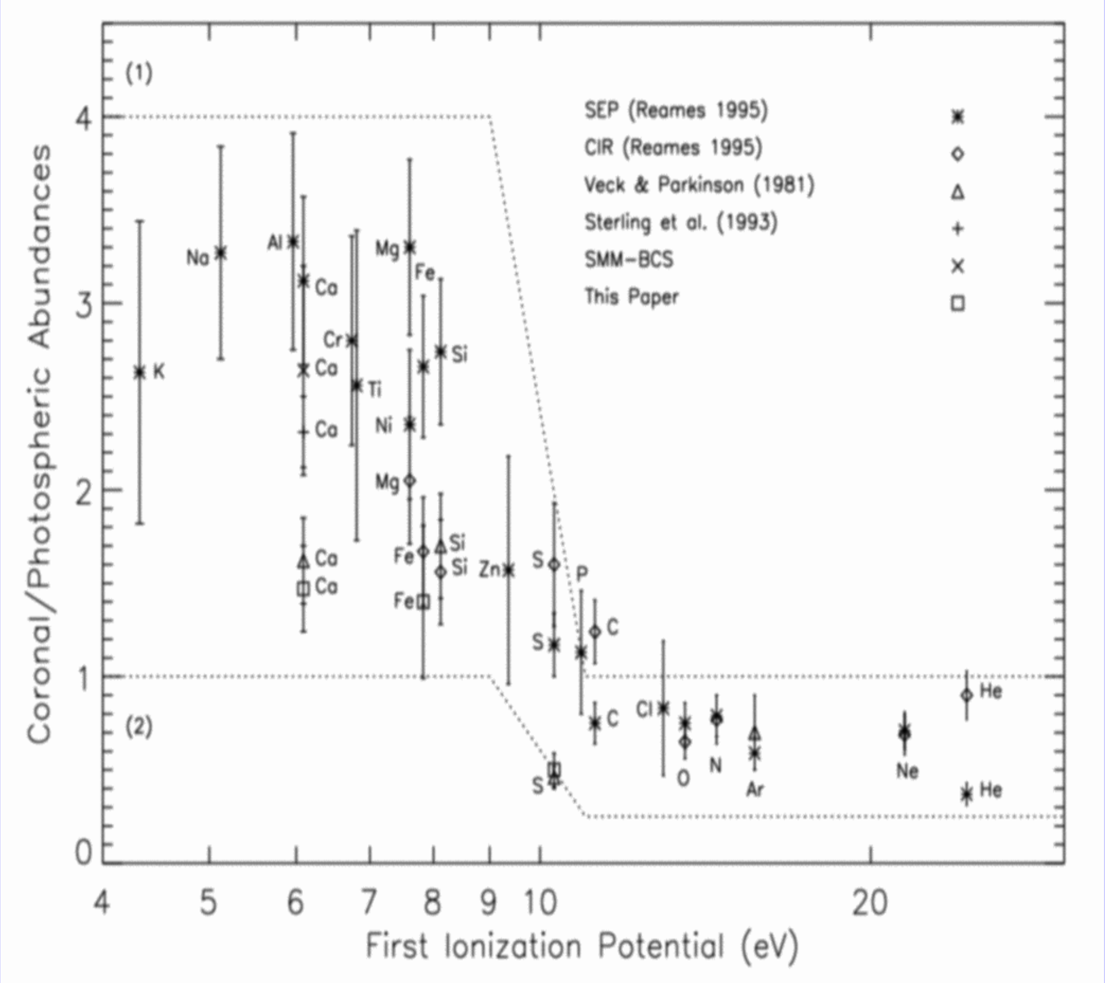
The FIP Effect: Enhancement or Depletion? [2]

However:

- SOHO/UVCS: Lyβ λ1025, and O VI λλ1032,1037 → estimates of [O/H].
- X-rays (e.g.: YOHKOH): continuum (mostly H-dominated bremsstrahlung) observed too → 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...



[From: Fludra, A., & Schmelz, J.T. (1999), *A&A*, **348**, 286]

Variability of the FIP Effect

Not just bimodal as in solar-minimum wind measurements:

Structure	Paper	Height	Instrument	FIP Bias
Coronal Hole	Doschek et al. 98 [55]	1.0-1.2 $R_\odot$	SUMER	< 2
Coronal Hole	Feldman et al. 98 [56]	1.03-1.5 $R_\odot$	SUMER	< 1.3
Coronal Hole Plume	Young et al. 99 [57]	1.0-1.1 $R_\odot$	CDS	1.5
Quiet Sun	Warren 99 [58]	1.05-1.35 $R_\odot$	SUMER	2.3 ± 0.7
Quiet Sun	Laming et al. 99 [59]	1.1 $R_\odot$	SUMER	3 - 4
Quiet Sun	Young & Mason 98 [28]	Disk	CDS	2
EQ Streamer core	Raymond et al. 97 [48]	1.5 $R_\odot$	UVCS	3 - 4
EQ Streamer legs	Raymond et al. 97 [48]	1.5 $R_\odot$	UVCS	3 - 4
EQ Streamer base	Feldman et al. 99 [56]	1.03-1.5 $R_\odot$	SUMER	4
EQ Streamer	Parenti et al. 00 [61]	1.6 $R_\odot$	UVCS	3
EQ Streamer base	Parenti et al. 00 [61]	1.02-1.19 $R_\odot$	CDS	1.1
Active Region	Young & Mason 98 [28]	1.5 $R_\odot$	CDS	1 - 9
Active Region	Rank et al. 99 [62]	Disk	CDS	5-9
Active Region	Dwivedi et al. 99 [63]	1.04-1.11 $R_\odot$	SUMER	8
Active Region	Ko et al. 01 [64]	1.3-1.7 $R_\odot$	UVCS	4
CME	Ciaravella et al. 97 [65]	1.5 $R_\odot$	UVCS	1
Prominence	Spicer et al. 98 [66]	1.5 $R_\odot$	SUMER	2

[From Raymond, J.C. et al. (2001), AIP Conf. Proc., **598**, 49]

Something else than just the FIP Effect?

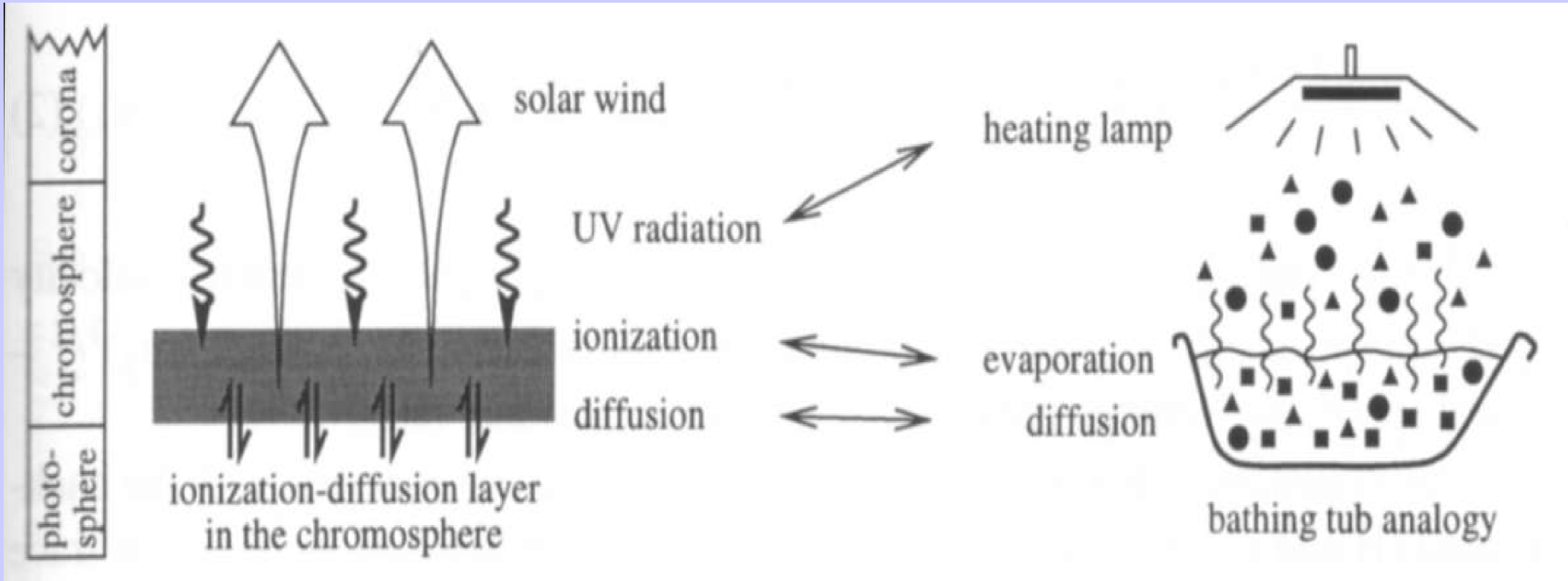
After all, is FIP the only parameter determining solar abundance variations in the corona/wind?

[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]

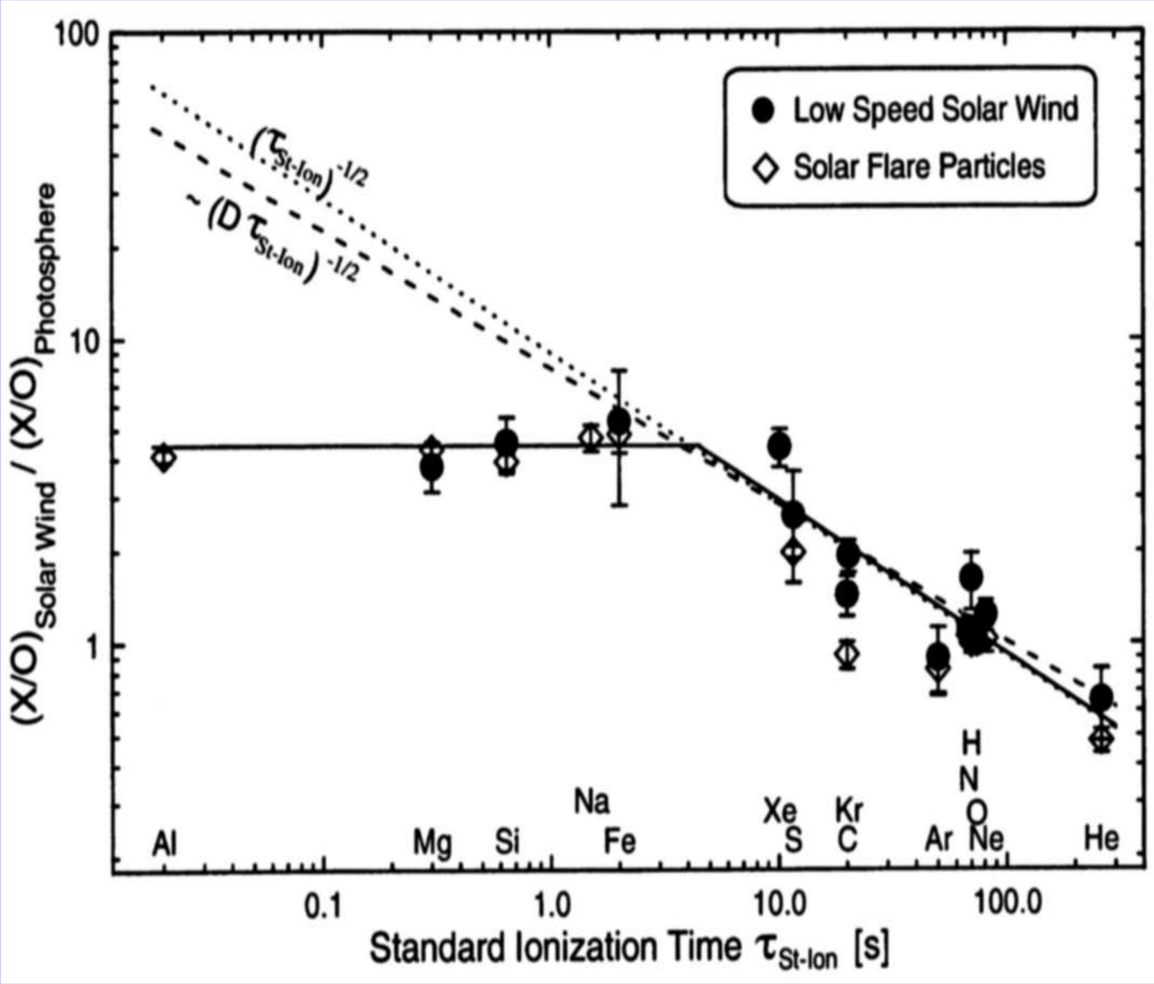
(More later...)

The FIP, or FIT, or Whatever Effect? [1]

- A strict relationship between abundances and FIP does not exist, nor it should...
- In fact, the FIP parameter is often related, directly or in-directly, to the behaviour of atoms.
- Example: A more relevant parameter could be the so-called standard ionization time, $\tau_{st\text{-}ion}$ [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 $\tau_{St\text{-}Ion}$:



[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...

[A review: Hénoux, J.-C. (1998), Space Science Reviews, **85**, 241]

Something Interesting about Helium

1) Highest FIP, and highest FIT ⇒ Largely neutral in the chromosphere.

2) Small Coulomb drag factor ⇒ Weak coupling with protons.

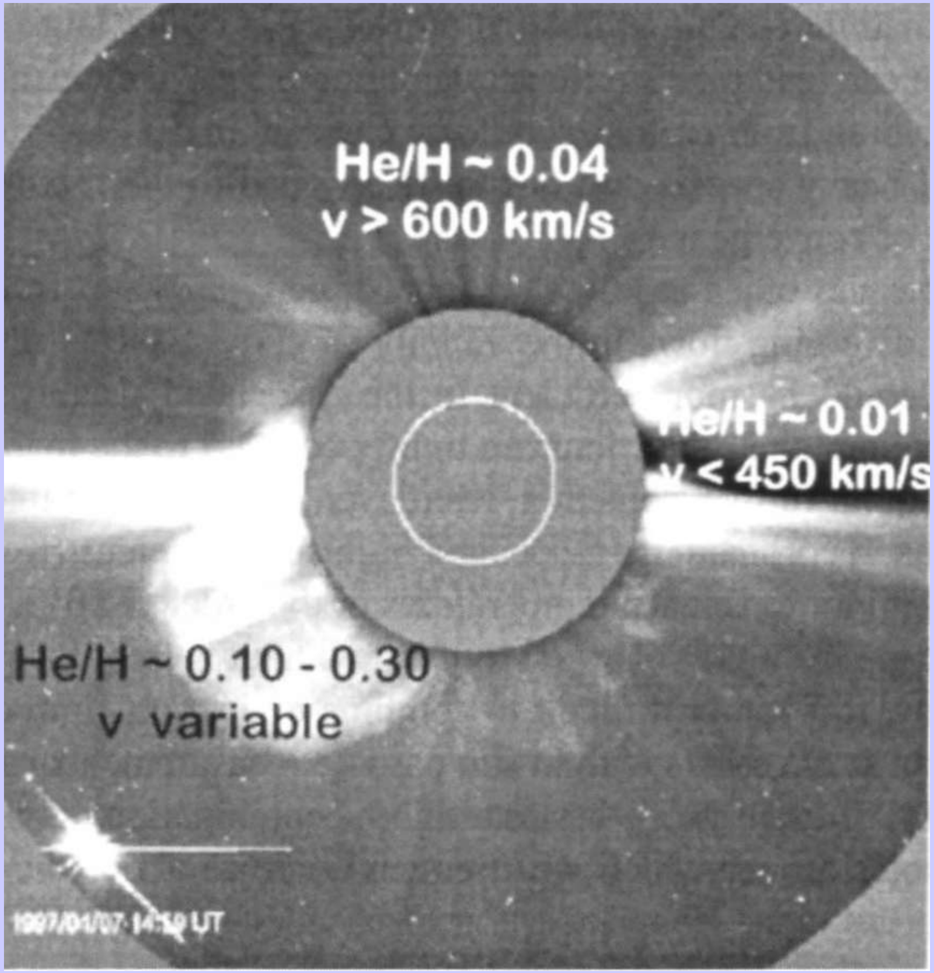
   - ➔ Easily depleted in the corona and solar wind...

- A challenging test (discriminating perhaps...) for elemental fractionation theories.
- In any case, needs to be taken into account: high abundance ⇒ may contribute significantly to mass flux, energy balance, etc.

Helium in the Solar Wind

In situ observations of helium abundance:

[From: Bochsler, P. (1998), Space Science Reviews, **85**, 291]



More Theoretical Prejudices

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

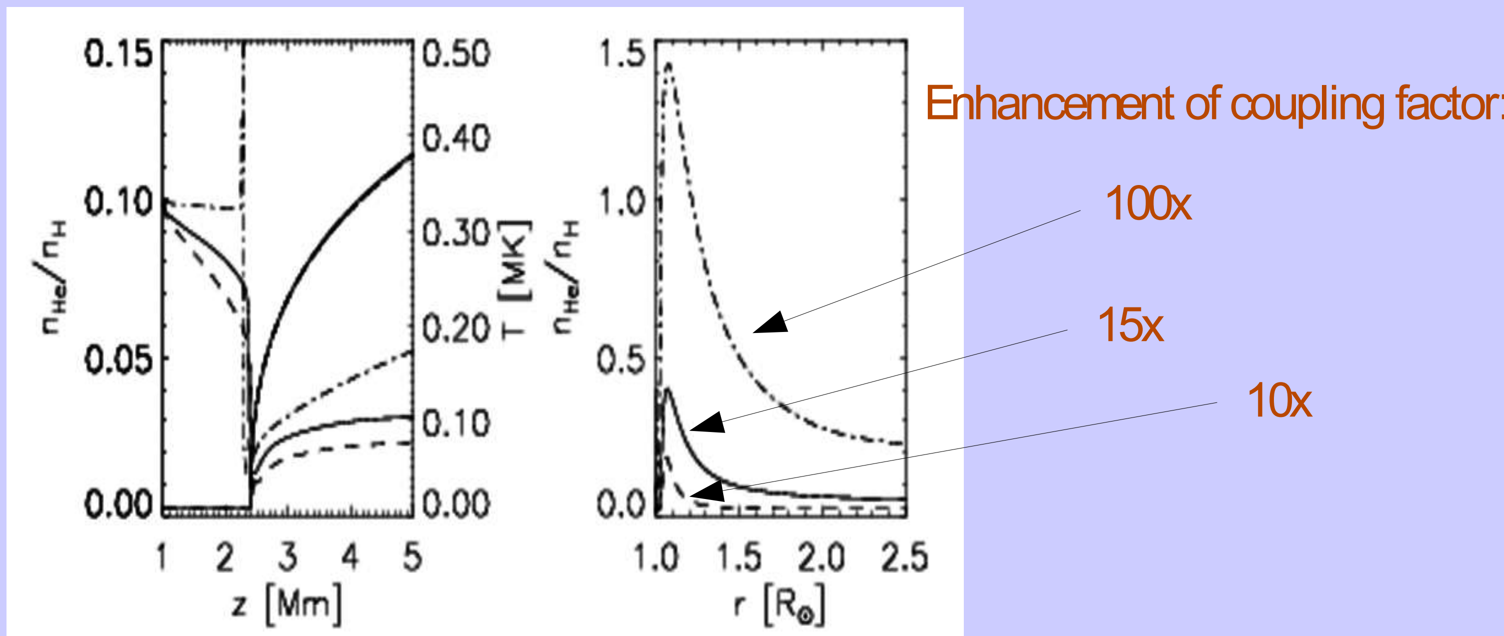
- Corona (T=10^6 K):
  Gravity (DOWN)
- Transition region:
  Thermal force (UP)
- Chromosphere (T=10^4 K):
  Gravity (DOWN)
  (Unspecified: “Dynamics”, “Turbulence”, “Magnetic Field”...)

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



[From: Hansteen, V.H., Leer, E., & Holzer, T. E. (1997), *ApJ*, **482**, 498]

(Findings confirmed by Lie-Svendsen, Ø., Hansteen, V. H., Leer, E. (2003), *ApJ*, **596**, 621)

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.
- <u>But</u>: Observed lines of He I and He II (formed either in chromosphere or in the lower transition region) are already <u>much stronger</u> than most calculations predict, even with a photospheric abundance! [e.g.: Andretta, V., Del Zanna, G., Jordan, S. (2003), *A&A*, **400**, 737]
- <u>Also</u>: γ-ray measurements in flares hint that [He/O] $\gtrsim$photospheric in some places in chromosphere. [Mandzhavidze, N., Ramaty, R., Kozlovsky, B. (1999), *ApJ*, **518**, 918]

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

Something is wrong with our understand-ing of abundance variations in the chromosphere?

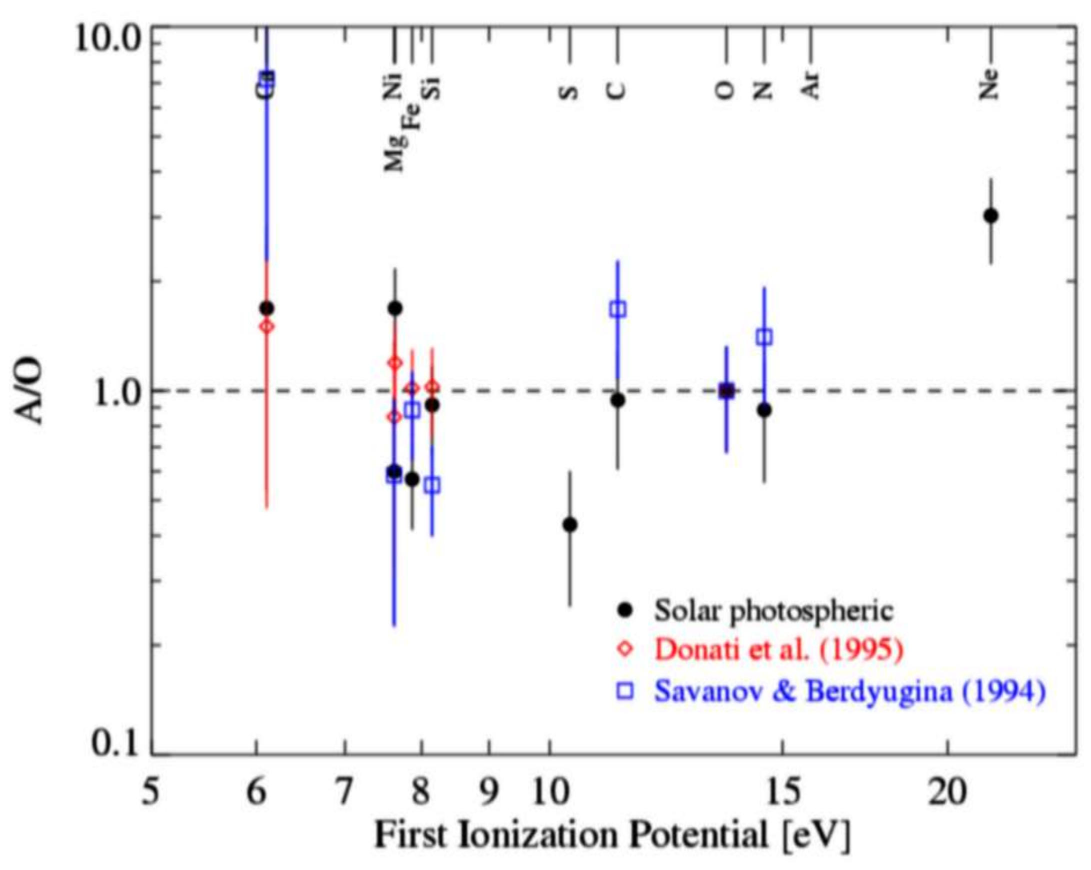
(Perhaps not really surprising, given our state of under-standing of the physics of the solar chromosphere...)

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)

[From: Audard, M., et al. (2003), *A&A*, **398**, 1137]

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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