Does the Sun have a subsolar metallicity?
Main partners in crime

Solar modelling:
Mats Carlsson (Oslo)
Remo Collet (MPA)
Wolfgang Hayek (MPA)
Åke Nordlund (Copenhagen)
Regner Trampedach (Boulder)

Solar abundances:
Nicolas Grevesse (Liege)
Jorge Melendez (Porto)
Tiago Pereira (ANU)
Ivan Ramirez (MPA)
Jacques Sauval (Brussels)
Patrick Scott (Stockholm)
Solar abundances

The solar chemical composition is a fundamental yardstick for almost all astronomy

Some compilations:
Russell (1929)
Unsöld (1948)
Suess & Urey (1956)
Goldsmith et al. (1960)
Anders & Grevesse (1989)
Grevesse & Sauval (1998)
Lodders (2003)
Asplund et al. (2005, 2009)
Solar system abundances

Meteorites
Mass spectroscopy
Very high accuracy
Element depletion

Solar atmosphere
Solar spectroscopy
Modelling-dependent
Very little depletion
3D solar atmosphere models

Ingredients:
- Radiative-hydrodynamical
- Time-dependent
- 3-dimensional
- Simplified radiative transfer
- LTE

Essentially parameter free

For the aficionados:
- Stagger-code (Nordlund et al.)
- MHD equation-of-state (Mihalas et al.)
- MARCS opacities (Gustafsson et al.)
- Opacity binning (Nordlund)
Temperature structure

Atmospheric temperature structure is critical

Our 3D model performs remarkably well
Spectral line formation

Line profiles vary tremendously across the solar surface.

3D model describes observations very well without free parameters.
More observational tests

3D stellar models outperforms all tested 1D model atmospheres (Pereira et al. 2009a,b; 2010)
Solar abundances revisited

- Asplund, Grevesse, Sauval, Scott, 2009, ARAA, 47, 481 + series of A&A papers
- Realistic model for the solar atmosphere
- Detailed spectrum formation calculations
- Improved atomic and molecular input data
- Careful selection of lines

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>8.56+/-0.06</td>
<td>8.43+/-0.05</td>
<td>-26%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>8.05+/-0.04</td>
<td>7.83+/-0.05</td>
<td>-40%</td>
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<tr>
<td>Oxygen</td>
<td>8.93+/-0.03</td>
<td>8.69+/-0.05</td>
<td>-42%</td>
</tr>
</tbody>
</table>

Note: logarithmic scale with H defined to have 12.00
Oxygen
Oxygen diagnostics

- Discordant results in 1D: $\log O \sim 8.6-8.9$
- Excellent agreement in 3D: $\log O = 8.69 \pm 0.05$
- Asplund et al. (2009)

<table>
<thead>
<tr>
<th>Lines</th>
<th>MARCS</th>
<th>Holweger-Mueller</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O I]</td>
<td>8.69 +/- 0.05</td>
<td>8.73 +/- 0.05</td>
<td>8.70 +/- 0.05</td>
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<tr>
<td>O I</td>
<td>8.62 +/- 0.05</td>
<td>8.69 +/- 0.05</td>
<td>8.69 +/- 0.05</td>
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<tr>
<td>OH, dv=0</td>
<td>8.78 +/- 0.03</td>
<td>8.83 +/- 0.03</td>
<td>8.69 +/- 0.03</td>
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<tr>
<td>OH, dv=1</td>
<td>8.75 +/- 0.03</td>
<td>8.86 +/- 0.03</td>
<td>8.69 +/- 0.03</td>
</tr>
</tbody>
</table>

Two often-used 1D model atmospheres
[O I]: blends

Allende Prieto et al. 2001:
Blend with Ni: -0.19 dex

Johansson et al. 2003:
gf-value of Ni I blend measured experimentally

Scott et al. 2009:
New solar Ni abundance

Asplund et al. 2009, Pereira et al. 2009:
log O = 8.69±0.05

(Similar results for other [OI] lines)
High-excitation O I lines are sensitive to non-LTE effects
Non-LTE - LTE ≈ -0.2 dex

Pereira et al. 2009a:
Use observed center-to-limb variations to determine poorly known H collisions

Asplund et al. 2009a:
\[ \log \text{O} = 8.69 \pm 0.05 \]

Note: \( S_H \) only makes sense for a given model atom and atmosphere
**OH lines: 3D effects**

Molecular lines are very temperature sensitive

3D model: different mean $T(\tau)$ and $T$ inhomogenities

- Vibration-rotation lines:
  - $\log O=8.69\pm0.03$

- Pure rotation lines:
  - $\log O=8.69\pm0.03$

Asplund et al. 2009a
Carbon diagnostics

- Discordant results in 1D: log C~8.4-8.7
- Excellent agreement in 3D: log C=8.43±0.05
- C/O=0.55±0.07
- Asplund et al. (2009)

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<th>3D</th>
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</thead>
<tbody>
<tr>
<td>[C I]</td>
<td>8.38</td>
<td>8.41</td>
<td>8.41</td>
</tr>
<tr>
<td>C I</td>
<td>8.39+/-0.04</td>
<td>8.45+/-0.04</td>
<td>8.42+/-0.05</td>
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<tr>
<td>CH, dv=1</td>
<td>8.44+/-0.04</td>
<td>8.53+/-0.04</td>
<td>8.44+/-0.04</td>
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<tr>
<td>CH, A-X</td>
<td>8.43+/-0.03</td>
<td>8.51+/-0.03</td>
<td>8.43+/-0.03</td>
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<tr>
<td>C₂, Swan</td>
<td>8.46+/-0.03</td>
<td>8.51+/-0.03</td>
<td>8.46+/-0.03</td>
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<tr>
<td>CO, dv=1</td>
<td>8.55+/-0.02</td>
<td>8.60+/-0.01</td>
<td>8.44+/-0.01</td>
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<tr>
<td>CO, dv=2</td>
<td>8.58+/-0.02</td>
<td>8.69+/-0.02</td>
<td>8.44+/-0.01</td>
</tr>
</tbody>
</table>
Independent studies

3D-based solar analysis by CO5BOLD collaboration
Caffau, Ludwig, Steffen, Freytag et al.

<table>
<thead>
<tr>
<th>Element</th>
<th>Caffau et al. (2008, 2009a,b)</th>
<th>Asplund et al. (2009a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>8.50+/-0.11</td>
<td>8.43+/-0.05</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>7.86+/-0.12</td>
<td>7.83+/-0.05</td>
</tr>
<tr>
<td>Oxygen</td>
<td>8.76+/-0.07</td>
<td>8.69+/-0.05</td>
</tr>
</tbody>
</table>

Very good agreement when same input data are used
• Selection of lines
• Equivalent widths
• Non-LTE corrections
(Caffau et al. do not consider molecular lines)
Solar Fe abundance

3D model:

\[ \log{\text{Fe I}} = 7.51 \pm 0.05 \]
\[ \log{\text{Fe II}} = 7.50 \pm 0.04 \]

Holweger & Müller:

Fe I trend with \( \chi_{ex} \)

Fe I and Fe II offset
Asplund et al. (2009, ARAA): 3D-based analysis of all elements Statistical and systematic errors included in total uncertainties
(Some) Implications

- Significantly lower solar metal mass fraction $Z$
  - $Z=0.0213$ (Anders & Grevesse 1989)
  - $Z=0.0143$ (Asplund et al. 2009)

- Alters cosmic yardstick
  - $[X/H]$, $[X/Fe]$ etc

- Makes Sun normal compared with surroundings
  - Young stars in solar neighborhood
  - Local interstellar medium

- Changes stellar structure and evolution
  - Wrecks havoc with helioseismology
Trouble in paradise

- Wrong sound speed
- Wrong depth of convection zone: $R=0.723$ vs $0.713\pm0.001$
- Wrong surface helium abundance: $Y=0.235$ vs $0.248\pm0.004$

Solar interior models with new abundances are in conflict with helioseismology.
Possible solutions

- Missing opacity?  
  - Possibly?
- Underestimated element diffusion?  
  - Unlikely
- Accretion of low-Z material?  
  - Unlikely
- Internal gravity waves?  
  - Possibly
- Underestimated solar Ne abundance?  
  - Unlikely
- Erroneous solar abundances?  
  - Hopefully not
- Combination of some of the above?  
  - Contrived?
Is the Sun unusual?

Melendez et al. 2009:

11 solar twins + Sun observed with Magellan/MIKE:

- $R = 65,000$
- S/N $\approx 450$
- $\Delta T_{\text{eff}} < 75\text{K}$
- $\Delta \log g < 0.1$
- $\Delta [\text{Fe/H}] < 0.1$

Extremely high precision achieved:

$\leq 0.01$ dex in $[\text{X/H}]$, $[\text{X/Fe}]$
Signatures of planet formation

Correlation with condensation temperature highly significant (probability $<10^{-6}$ to happen by chance)

$\approx 0.08 \text{ dex} \approx 20\%$
The Sun is unusual

Only a minority of our solar twins resemble the Sun
Confirmation of trend

Ramirez et al. (2009):
Observations of 22 solar twins with McDonald 2.7m
R=60,000, S/N~200
~0.02 dex accuracy in [X/Fe]

Note: opposite definition!
Re-analyzing previous studies

Ramirez et al. (2010):
Signature exists also in previous stellar samples but disappears at high [Fe/H]
⇒ Metallicity-dependence of planet formation

Data from Neves et al. 2009

Solar analogs from literature

Average (R03,A04,N09,B10)
Scenario

**Sun**: planet formation locked up refractories but less of volatiles during accretion phase

**Solar twins**: less planet formation and thus more refractories than Sun

Iron gradient in the inner solar system
Terrestrial or giant planets?

How much dust-cleansed gas accretion is required?

Assume gas accretion once solar convection zone reached ≈ present size (~0.02 Mₒ):
Refractions ≈2*10²⁸ g ≈4 M⊕

Rocky planets: ~8*10²⁷ g ≈1.3 M⊕
Cores of giant planets: ≈30 M⊕?

Characteristic temperature of ~1200 K only encountered at <<1 AU in proto-planetary disks
Time-scale problems

Ages of proto-planetary disks typically ≤10 Myr

\[ M_{cz} \approx 0.02 M_\odot \text{ only } >30 \text{ Myr} \]

\[ M_{cz} \approx 0.4 M_\odot \text{ at } \sim 10 \text{ Myr} \]

Sun had unusually long-lived disk?
Smaller convection zone in hydrodynamical models?

Wuchterl (2004):

Baraffe et al. (2010):

Hydrostatic

Episodic accretion
Stars with/without giant planets

Analysis of solar-like stars followed with radial velocity monitoring (HARPS)

Fraction of stars resembling the Sun:
⇒ With hot Jupiters: ~0%
⇒ Without hot Jupiters: ~70%
⇒ Stars in general: ~20%

Close-in giant planets prevent long-lived disks and/or formation of terrestrial planets?

An ideal candidate for terrestrial planet searches
Galactic archaeology

Implications for Galactic archaeology:
• Identify stars with planets!
• High resolution + S/N
• Many elements (oxygen!)
• Improve stellar analysis
  - 3D, non-LTE, parameters

Disk substructure and chemical tagging
\(\Delta(\text{Thick-thin}) \approx 0.1 \text{ dex}\)
\(\Delta(\text{Thin}) \approx 0.01 \text{ dex}\)?
⇒ Planet signature larger!

Reddy et al. (2006)

≈ 0.08 dex
Near-field cosmology

HERMES @ AAT 4m
R=30k & S/N~100 spectra of $10^6$ stars for “chemical tagging”:
⇒ Reconstruct chemical, dynamical and SF history of Milky Way
⇒ Identify solar siblings

Observe $>10,000$ dwarfs @ R=50k and S/N>200 to search for planet signature!
Summary

• **Solar chemical composition**
  - New abundances for all elements
  - Low C, N, O and Ne abundances

• **Precision stellar spectroscopy**
  - Sun is unusual
  - Signatures of planet formation

• **Galactic archeology**
  - Complicates finding solar siblings
  - Planet formation as a mask