The Solar Oxygen Abundance Problem

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Who Cares?

- The Sun is used as the ‘standard ruler’ for studying chemistry
- Need to know the solar composition to high accuracy

(Asplund et al. 2009)
Meteoritic Abundances

- Mass spectroscopy of meteorites can give high precision for almost every element and isotopes (Suess & Urey 1956)
Methods

Meteoritic Abundances

- Mass spectroscopy of meteorites can give high precision for almost every element and isotopes (Suess & Urey 1956)
  - Volatile elements have been depleted to some extent
- Meteorites are an inaccurate tool to measure primordial abundances
- Abundance ratios measured relative to some other element
Photospheric Abundances

- Photospheric abundances via spectroscopy
  - (Nearly) pristine
  - Shallow enough for convection to not bring fusion products to the surface (von Steiger et al. 2001)
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- Virtually no information about isotopic abundances are observed; inferred through models

- Not precise enough to rival meteors
The Problem

The Calm Before the Storm

\[
\log \epsilon_X = 12 + \log \left( \frac{N(X)}{N(H)} \right)
\]

<table>
<thead>
<tr>
<th>Element</th>
<th>Photosphere</th>
<th>Meteorites</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>12.00</td>
<td>[12.00]</td>
</tr>
<tr>
<td>He</td>
<td>[10.990 ± 0.035]</td>
<td>[10.99]</td>
</tr>
<tr>
<td>O</td>
<td>8.930 ± 0.035</td>
<td>[8.93]</td>
</tr>
<tr>
<td>C</td>
<td>8.56 ± 0.04</td>
<td>[8.56]</td>
</tr>
<tr>
<td>Fe</td>
<td>7.67 ± 0.03</td>
<td>7.51 ± 0.01</td>
</tr>
<tr>
<td>Ne</td>
<td>[8.09 ± 0.10]</td>
<td>[8.09 ± 0.10]</td>
</tr>
<tr>
<td>N</td>
<td>8.05 ± 0.04</td>
<td>[8.05]</td>
</tr>
<tr>
<td>Si</td>
<td>7.55 ± 0.05</td>
<td>7.55 ± 0.02</td>
</tr>
<tr>
<td>Mg</td>
<td>7.58 ± 0.05</td>
<td>7.58 ± 0.02</td>
</tr>
<tr>
<td>S</td>
<td>7.21 ± 0.06</td>
<td>7.27 ± 0.05</td>
</tr>
<tr>
<td>Ni</td>
<td>6.25 ± 0.04</td>
<td>6.25 ± 0.02</td>
</tr>
</tbody>
</table>

(Anders & Grevesse 1989)
Anders & Grevesse (1989) had an oxygen abundance of
\[ \log \epsilon_O = 8.93 \pm 0.04 \]
- Obtained by a 1D hydrostatic model to fit oxygen lines, including
  \([O \, i] \ 630.0 \text{ nm}\)
- Assumed LTE line formation

Using non-LTE line formation gives an abundance 0.2 lower; supported by observation (Kiselman & Nordlund 1995)
The Problem

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The Storm

- Allende Prieto et al. (2001) used a 3D hydrodynamical model on [O I]
  - Showed that the [O I] is blended with a Ni I line
  - Lowers the abundance significantly to $\log \epsilon_O = 8.69 \pm 0.05$
- Asplund et al. (2004) extended the method to account for O I and OH lines
  - $\log \epsilon_O = 8.66 \pm 0.05$
[O I] and Ni I Blending

(Allende Prieto et al. 2001)
The study of the interior of the Sun using solar oscillations

- Standing acoustic waves used to measure:
  - Radial distribution of pressure (Basu et al. 2000)
  - Position of the base of the convection zone
  - Helium abundance (Antia & Basu 1994)
  - Rotation speed as a function of depth (Schou et al. 1998)
Abundances via Helioseismology

1. Studying the convection zone
   - Model atmospheres are consistent with the old abundance (Basu & Antia 1997)
   - Seismic constraints give $\log \varepsilon_O = 8.87$ (Delahaye & Pinsonneault 2006)

2. Structure of the core
   - Models using the old abundance agree with BiSON data (Basu et al. 2007)
   - New abundance does not satisfy seismic constraints (Chaplin et al. 2007)

3. Ionization zone and the equation of state
   - $W(r)$ data agreed with the old abundance (Antia & Basu 2006)
Reconciliation?

- Asplund et al. (2006) are convinced that their results are correct
  - Believe that their results are more realistic
  - Abundances are more consistent with each other than in a 1D analysis
  - Koesterke et al. (2008) showed that 3D model abundances are of the same quality as 1D models
- Socas-Navarro & Norton (2007) reconstructed the thermal and magnetic structure of the solar atmosphere
  - LTE: $\log \varepsilon_O = 8.93$
  - non-LTE: $\log \varepsilon_O = 8.63$
Abundance Sensitivity

- Socas-Navarro (2015) investigated the sensitivity of these models to the oxygen abundance
  - Compared three different models with three different iron abundances
  - The best fit was \( \log \epsilon_{Fe} = 7.50, \log \epsilon_{O} = 8.90, \log \epsilon_{Ni} = 6.15 \)
  - The second best fit was
    \( \log \epsilon_{Fe} = 7.50, \log \epsilon_{O} = 8.95, \log \epsilon_{Ni} = 6.10 \)
  - Adding a perturbation in optical depths \( \log(\tau_{500}) = (-1, 1) \) of \( \pm 50 \) K changed oxygen to 8.78
  - Other factors are continuum reference, wavelength calibration, wavelength shift, line broadening
Abundance Sensitivity

(Socas-Navarro 2015)
Helioseismology

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- It is possible, through tweaking the model, to get the full range of oxygen abundances
The Future

???
The Future

“The question is: is it really a problem or does it open a new field of research?”

(Asplund et al. 2006)
References I

Asplund, M., Grevesse, N., & Sauval, A. J. 2006, CoAst, 147, 76
References II