Helioseismology and the solar abundance problem

Katie Mussack
Los Alamos National Laboratory
The solar abundance problem can be attacked on several fronts

- Spectroscopic analysis determines atmospheric abundances
- New spectral measurements can be taken
- Solar models can be adapted to modify interior of model Suns
- Abundances can be inferred through seismology

Here:
- Attack on all fronts
- Focus on the role of seismology
Helioseismology was used to determine He abundance in the convection zone

Split up the adiabatic sound speed gradient:

\[
\frac{dc^2}{dr} = \frac{Gm}{r^2} \left\{ 1 - \gamma_1 \left\lbrack 1 + \left( \frac{\partial \ln \gamma_1}{\partial \ln p} \right)_s \right\rbrack \right\}
\]

Into:

\[
W = \frac{r^2}{Gm} \frac{dc^2}{dr}
\]

\[
\Theta = 1 - \gamma_1 \left\lbrack 1 + \left( \frac{\partial \ln \gamma_1}{\partial \ln p} \right)_s \right\rbrack
\]

Däppen & Gough, 1984
Simple assumptions were used to model solar interior

- One-dimensional
- Initial homogeneous composition
- Negligible mass loss or accretion
- Neglect rotation and magnetic fields
- Simple surface boundary conditions
- No additional mixing or structural changes
  - convective overshoot
  - shear from differential rotation
  - meridional circulation
  - waves or oscillations
Reanalyzed solar optical spectrum

Used updated techniques
- improved atomic physics
- 3D hydrodynamical model atmosphere

Confidence in new analysis
- Good agreement with observed line profiles and line bisectors
- Different lines give similar abundances (i.e.: O)

<table>
<thead>
<tr>
<th></th>
<th>AG89</th>
<th>GN93</th>
<th>GS98</th>
<th>AGS05</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>8.56 ±0.04</td>
<td>8.55 ±0.05</td>
<td>8.52 ±0.06</td>
<td>8.39 ±0.05</td>
</tr>
<tr>
<td>N</td>
<td>8.05 ±0.04</td>
<td>7.97 ±0.05</td>
<td>7.92 ±0.06</td>
<td>7.78 ±0.06</td>
</tr>
<tr>
<td>O</td>
<td>8.93 ±0.04</td>
<td>8.87 ±0.04</td>
<td>8.83 ±0.06</td>
<td>8.66 ±0.05</td>
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<tr>
<td>Ne</td>
<td>8.09 ±0.10</td>
<td>8.07 ±0.06</td>
<td>8.08 ±0.06</td>
<td>7.84 ±0.06</td>
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<tr>
<td>Z/X</td>
<td>0.0274 ±0.0016</td>
<td>0.0244 ±0.0014</td>
<td>0.0231 ±0.0018</td>
<td>0.0165 ±0.0011</td>
</tr>
</tbody>
</table>

AG89 = Anders & Grevesse (1989)
GN93 = Grevesse & Noels (1993)
GS98 = Grevesse & Sauval (1998)
AGS05 = Asplund, Grevesse, & Sauval (2005)
Lower abundances result in worse agreement with helioseismic constraints

- Sound-speed discrepancy up to 1.4% below CZ
- CZ too shallow
- CZ helium abundance too low

Guzik & Mussack, 2010
What’s the problem?

- “Solar abundance problem”
  - New abundances inconsistent with helioseismic constraints

- “Solar model problem”
  - Agreement with observed line profiles & bisectors
  - Different lines give similar abundances
  - Sun now similar to comparable neighbors

- Perhaps both models and abundances need to be refined
## 2008-2009: Intermediate abundance values proposed

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Z</th>
<th>Z/X</th>
</tr>
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<tbody>
<tr>
<td>1989</td>
<td>Anders &amp; Grevesse</td>
<td>0.0201</td>
<td>0.0274</td>
</tr>
<tr>
<td>1993</td>
<td>Grevesse &amp; Noels</td>
<td>0.0179</td>
<td>0.0244</td>
</tr>
<tr>
<td>1998</td>
<td>Grevesse &amp; Sauval</td>
<td>0.0170</td>
<td>0.0231</td>
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<tr>
<td>2001,</td>
<td>Holweger (compiled by Turck-Chièze et al. 2004)</td>
<td>0.0155</td>
<td>0.0210</td>
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<tr>
<td>2005</td>
<td>Asplund et al.</td>
<td>0.0122</td>
<td>0.0165</td>
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<tr>
<td>2009</td>
<td>Asplund et al.</td>
<td>0.0134</td>
<td>0.0181</td>
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<tr>
<td>2008,</td>
<td>COBOLD</td>
<td>0.0154</td>
<td>0.0209</td>
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<tr>
<td>2009</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Coronal X-ray measurements offer a potential solution

- **Measure neon abundance: Ne Kα line**
  - Coronal X-rays near temperature minimum
  - Weak line, but isolated & unblended

- **Measure oxygen abundance: O Kα line**
  - Coronal X-rays just above temperature minimum
  - Essentially uncontaminated & observable

- **Drawback: wait for observations**
  - Sensitive X-ray spectrometer needs to be funded and built

Drake & Ercolano, 2007 & 2008
Changes to solar models have been explored

- Opacities – increase below CZ (11-20%)
- Abundances – increase within uncertainty limits
- Ne abundance – increase up to x3
- Diffusive settling – increase at CZ base
- Evolution – early accretion of lower Z material
- Tachocline – mixing
- Various combinations

It is difficult to match both the new abundances and the helioseismic constraints for CZ He, CZ depth, and sound-speed profile.
Some modifications improve sound-speed agreement

Opacity increases

Diffusion and abundance increases

Ne, Ar, + some CNO enhancement

Diffusion changes
Accretion of low-Z material shows potential

- Maintain an interior similar to GN93 with lower Z near surface
  - [Graph showing Y vs. R (R_{sun})]
  - [Graph showing Z vs. R (R_{sun})]

- Improves interior of Sun, not near CZ base
  - [Graph showing c difference (Sun - Model)/Sun vs. R (R_{sun})]
  - [Graph showing Observed minus Calculated Frequency (kHz) vs. Frequency (kHz)]

Guzik & Mussack, 2010
Including mass loss in solar models can improve the agreement

- Mass loss can improve sound-speed agreement and O-C frequencies

- Hot, bright early Sun

Li destroyed at $T=2.8\times10^6$ K
Mass-loss + intermediate abundances is even better

Li destroyed at $T=2.8\times10^6$ K
Convective overshoot was proposed as a way to improve agreement

- Overshoot did not provide much improvement

- Extra overshoot made the problem worse

Guzik & Mussack, 2010
Model changes can be evaluated using sound-speed differences, O-C frequencies, and small separations.
Dynamic screening introduces a correction to p-p reaction rates in the solar core

Static reaction rate calculation:

\[
\langle \sigma v \rangle_{\alpha\beta} \propto \int_0^\infty \exp \left( -\frac{E}{kT} - \frac{b}{\sqrt{E}} \right) dE
\]

With energy dependent screening:

\[
\langle \sigma v \rangle_{\alpha\beta} \propto \int_0^\infty \frac{E}{E - U_o(E)} \exp \left( -\frac{E}{kT} - \frac{b}{\sqrt{E - U_o(E)}} \right) dE
\]

\[G(E) = E - U\]
\[H(E) = \frac{E}{G(E)}\]
\[J(E) = \exp \left[ -\frac{E}{kT} - \frac{b}{\sqrt{G(E)}} \right]\]
\[F(E) = H(E)J(E)\]

Energy dependence reduces the screening correction to \(\sim 1\)

Mussack & Dappen, 2011
Dynamic correction to screening improves sound-speed agreement in the solar core
Mass loss + dynamic screening may help

- Mass loss improves model below the base of the convection zone
- Dynamic screening correction improves model in the core
- Work in progress: combine mass loss and dynamic screening correction in a solar model (Suzannah Wood)
Dark matter may also improve agreement in the core

- Explored solar models with WIMP masses low enough and cross sections high enough to influence solar structure
- Included WIMPs in solar model by modifying the opacity
- Models rule out WIMP masses <10 GeV

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Cumberbatch et al., 2010
Abundance can also be inferred using seismology

\[
\Theta, W
\]

\[
\tau / \tau_s
\]

Acoustic radius: \( \tau = \int c^{-1} dr \)

Gough, 2006
Total Z and individual abundances can be evaluated through the ionization bumps in W and \( \Theta \)

**EFF Models at 4.6Gy**

Acoustic radius: \( \tau = \int c^{-1} dr \)

Standard Mix:
- O = .4987
- C = .2254
- Fe = .0795
- Si = .0565
- N = .0549
- Mg = .0436
- Ne = .0335
- Al = .00403
- Na = .00197
- Ar = .00180
Seismic inversion can be used to evaluate models with different abundances

- Use $W$ and $\Theta$ kernels to find $\delta W$

$$\frac{\delta \omega^2}{\omega^2} = \int_0^R \left( K_{W,\Theta} + K_{\Theta,W} \right) \delta W \, dr$$

- Calibrate abundances in models to match solar $W$
Where are we now?

- **Intermediate abundance values are more agreeable**
  - COBOLD, 2008-2009: $Z = 0.0154$
  - AGSS, 2009: $Z = 0.0134$

- **Modifications of solar models make some improvement in agreement**
  - Mass loss
  - Accretion

- **Further investigation is needed**
  - Seismic determination of abundances in the CZ
  - Models with mass loss + dynamic screening or dark matter
  - Other adjustments to models
  - Data from solar atmosphere
Douglas continues to influence seismic investigations of abundances

- “Sources of uncertainty in direct seismological measurements of the solar helium abundance”, Kosovichev, Christensen-Dalsgaard, Däppen, Dziembowski, Gough, Thompson, 1992
- “On the influence of treatment of heavy elements in the equation of state on the resulting values of the adiabatic exponent”, Däppen, Gough, Kosovichev, Rhodes, 1993
- “The Sun is not severely deficient in Heavy Elements”, Christensen-Dalsgaard & Gough, 2004
- “Effect of He ionization on stellar eigenfrequencies”, Houdek & Gough, 2004
- “Asteroseismic signature of He ionization”, Houdek & Gough, 2007
Thank you
Katie Mussack
Los Alamos National Laboratory, XTD-2
mussack@lanl.gov