The solar composition problem

The Standard Solar Model (SSM) treats the absolute and relative elemental abundances as an input. The old G98 admixture yields concordance between models and helioseismic and solar neutrino data. A significant overall in solar model atmospheres, see e.g. AGSS09 model, has led to a downward revision in photospheric heavy element abundances by up to 30-40% for important species such as oxygen.

- Is there something wrong or unaccounted in solar models?
- Is the chemical evolution not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?
- Are properties of the solar matter (e.g. opacity) correctly described?
- Is this discrepancy pointing at new physics (e.g. WIMPs in the solar core)?

The internal structure of SSMs using the lower solar surface metallicity of AGSS09met does not reproduce the helioseismic constraints:

Table: 
<table>
<thead>
<tr>
<th>Species</th>
<th>Observed</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>7.83 ± 0.05</td>
<td>7.92 ± 0.06</td>
</tr>
<tr>
<td>O</td>
<td>8.60 ± 0.05</td>
<td>8.4 ± 0.16</td>
</tr>
<tr>
<td>Ne</td>
<td>7.86 ± 0.01</td>
<td>7.84 ± 0.02</td>
</tr>
<tr>
<td>Si</td>
<td>7.51 ± 0.01</td>
<td>7.66 ± 0.01</td>
</tr>
<tr>
<td>S</td>
<td>7.15 ± 0.02</td>
<td>7.26 ± 0.02</td>
</tr>
<tr>
<td>Fe</td>
<td>7.45 ± 0.04</td>
<td>7.40 ± 0.03</td>
</tr>
</tbody>
</table>

The internal structure of SSMs using the lower solar surface metallicity of AGSS09met does not reproduce the helioseismic constraints:

\[ \Phi (\text{Ne}) = \Phi (\text{Fe}) \]

In synthesis, inferences from modern 3D hydrodynamic models of the solar atmosphere lead to predictions in strong disagreement with observational constraints.

The role of metals in the Sun

A change of the solar composition produces a modification of the opacity profile of the Sun. The source term \( \delta \alpha (\tau) \) drives the modification of the solar properties is given by the sum of two contributions:

\[ \delta \alpha (\tau) = \delta \alpha (\tau)_{\text{outer}} + \delta \alpha (\tau)_{\text{core}} \]

- The intrinsic opacity change \( \delta \alpha (\tau)_{\text{outer}} \) represents the fractional variation of the opacity along the SSM profile. It is given, in our approach, by:
  \[ \delta \alpha (\tau)_{\text{outer}} = \frac{1}{\tau} \ln \frac{\alpha_{\text{SM}}}{\alpha_{\text{SM}}} \]

- The composition opacity change \( \delta \alpha (\tau)_{\text{core}} \) is produced by admixture modification and can be calculated as:
  \[ \delta \alpha (\tau)_{\text{core}} = \sum_{i} \frac{\Delta \alpha_{i}}{\sum_{i} \Delta \alpha_{i}} \frac{\Delta \alpha_{i}}{\sum_{i} \Delta \alpha_{i}} \]

Are there other effects that can provide the required opacity change?

Wrong opacity calculations? → the required variations seem large with uncertainties
Different distribution of metals in the Sun → According to the standard assumptions, metals are nearly homogeneous in the Sun (elemental diffusion is expected to be a small effect at the solar center). Is this an oversimplified picture of chemical evolution?
Is this discrepancy pointing at new physics?

A quantitative analysis

To combine observational infos, we need an estimator that is non-biased and can be used as a figure-of-merit for solar models with different composition. We define:

\[ x^2 = \sum_{i=1}^{n} \left( \frac{Q_i - Q_{i,\text{obs}}}{\sigma_i} \right)^2 \]

where:

\[ \sigma_i = \text{f} \left( \delta \alpha (\tau)_{\text{outer}}, \delta \alpha (\tau)_{\text{core}}, \text{ errors} \right) \]

We consider 34 obs. quantities:

\[ \left\{ Q_i \right\} = \left\{ \delta \Phi (\text{Fe}), \delta \Phi (\text{Ne}), \delta \Phi (\text{He}), \delta \Phi (\text{Na}), \delta \Phi (\text{Mg}), \delta \Phi (\text{Al}), \delta \Phi (\text{Si}), \delta \Phi (\text{S}), \delta \Phi (\text{Ar}), \delta \Phi (\text{Ca}), \delta \Phi (\text{Fe}), \delta \Phi (\text{Ni}), \delta \Phi (\text{Cu}), \delta \Phi (\text{Zn}), \delta \Phi (\text{Ga}), \delta \Phi (\text{Ge}), \delta \Phi (\text{As}), \delta \Phi (\text{Se}), \delta \Phi (\text{Br}), \delta \Phi (\text{Kr}), \delta \Phi (\text{Xe}), \delta \Phi (\text{Ba}), \delta \Phi (\text{La}), \delta \Phi (\text{Ce}), \delta \Phi (\text{Nd}), \delta \Phi (\text{Sm}), \delta \Phi (\text{Eu}), \delta \Phi (\text{Gd}), \delta \Phi (\text{Tb}), \delta \Phi (\text{Dy}), \delta \Phi (\text{Ho}), \delta \Phi (\text{Er}), \delta \Phi (\text{Tm}), \delta \Phi (\text{Yb}), \delta \Phi (\text{Lu}), \delta \Phi (\text{Hf}), \delta \Phi (\text{Ta}), \delta \Phi (\text{W}) \right\} \]

We take the surface abundances (wet hydrogen) as parameters:

\[ \eta_i = \frac{\Phi_i}{\Phi_i(\text{SM})} \]

We infer the best-fit composition by minimizing the \( x^2 \):

\[ x^2 = \chi^2 = \sum_{i=1}^{n} \chi^2_i = \sum_{i=1}^{n} \chi^2_i \]

A two parameter analysis - continued

- The SSM implementing AGSS09met is excluded at a high confidence level (\( x^2 / d.o.f. = 176.7/32 \)).
- There is a substantial agreement between the info provided by the various observational constraints. The quality of the fit is quite good (\( x^2 / d.o.f. = 39.6/32 \)).
- The best-fit abundances are consistent at 1σ with G989. The errors on the inferred abundances are smaller than what is obtained by obs. determinations.
- The CNO neutrino fluxes are expected to be ~50% larger than predicted by AGSS09met (this result depend on the assumed heavy element grouping).

A three parameter analysis (\( \delta Z_{\text{CN}}, \delta Z_{\text{Ne}}, \delta Z_{\text{He}} \))

Prior: Neon-to-oxygen ratio forced at the AGSS09met value with 30% accuracy

The importance of CNO neutrinos

Even a low accuracy CNO neutrino flux measurement, providing a direct determination of the metallicity of the solar core, permits to remove the degeneracy between opacity and composition effects:

\[ 1 + \delta \Phi = \left( 1 + x_{\text{CN}} \right) \left( 1 + \delta \Phi_{\text{CNO}} \right) \]

Total number of catalysts for CN-cycle

At present, we only have a loose upper limit on CNO neutrino fluxes:

\[ x_{\text{CN}} = \frac{\delta \Phi_{\text{CNO}}}{\Phi_{\text{CNO}}} \]

Determines the central temperature

Will it be possible to detect CNO neutrinos? Very difficult, in practice. Not improbable, in principle...