What is the metallicity of our reference star, the Sun?

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Introduction

The Sun as a benchmark star

The role of the Sun:
Well-studied, helioseismic constraints, neutrino fluxes, testbed for physical ingredients. The Sun is used as a reference:

- Metallicity scale,
- Enrichment laws,
- SSM framework,
- Paved the way for asteroseismology using solar-like oscillations.

Most of our models will include some ingredients that have been calibrated on the Sun. Thus, if you change the way you model the Sun, you impact stellar physics as a whole.

But how well do we know the Sun?
Solar abundances

1D Models of the 20th century

1D solar atmosphere models

Theoretical models: MARCS, Kurucz, ...

1. Hydrostatic,
2. MLT type convection,
3. LTE.

Usually, semi-empirical models were used e.g. Holweger-Müller model (1974).

Led to high abundances of C, N and O (AG89, GN93, GS98).

Pereira et al. (2009)
Revise of the abundances:
- Hydrodynamical model,
- Non-LTE corrections,
- Improved atomic data,
- Careful selection of lines,
- Use of all indicators.

⇒ 30% reduction of $Z_{\odot}$!
The solar modelling problem

A brief history of Standard Solar Models

Before 2004, high metallicity solar models ($Z = 0.0182$):

1. Correct position of the BCZ,
2. Correct Helium abundance in the CZ,
3. Sound Speed profile relative differences of up to 0.006.


But: slow degradation as physical ingredients were updated.

From 2004, downward revision of the solar $Z$:

1. Wrong position of the BCZ,
2. Wrong Helium abundance in the CZ,
3. Sound Speed profile relative differences of up to 0.02.
Discussions of the revised abundances

Study by Caffau et al. 2011: Higher C,N,O abundances, closer to the “old values”.

What causes the discrepancies?

- Selection of lines, blends, molecular lines.

If the same inputs are used, the same results are obtained.

What about meteorites? Differentiation, they are not substitutes to photospheric abundances! (N.Grevesse, private communication)
The problem of Neon: No photospheric lines.
⇒ Inferences from coronal lines, solar wind, ... Variations with activity!

- Difficult measurements,
  Ne/H unaccessible,
  Ne/O measured,
- Antia & Basu (2004): increase of 400% to solve the “solar problem”.
- Landi & Testa 2015 + Young 2018: increase of 40% of Ne/O.
Helioseismology

The solar modelling problem as seen in seismology:

Current state of the issue, for various abundance and opacity tables...

Base of the solar convective zone

\[ \times 10^{-3} \]

\[ \begin{align*}
&\text{AGSS09 – OPAL} \\
&\text{AGSS09 – OPLIB} \\
&\text{GS98 – OPAL} \\
&\text{AGSS09 – OPAS} \\
&\text{AGSS09 Ne – OPAL}
\end{align*} \]

Position \( r/R \)
Constraints from seismic inversions:

Inversions can only constrain variables from the \textit{acoustic structure}: \( \rho \), \( c^2 \) or \( \Gamma_1 = \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_S \) for example.

However, assuming an E.O.S, one has:

\[
\frac{\delta \Gamma_1}{\Gamma_1} = \left( \frac{\partial \ln \Gamma_1}{\partial \ln P} \right)_{\rho,Y,Z} \frac{\delta P}{P} + \left( \frac{\partial \ln \Gamma_1}{\partial \ln \rho} \right)_{P,Y,Z} \frac{\delta \rho}{\rho} + \left( \frac{\partial \ln \Gamma_1}{\partial Y} \right)_{P,\rho,Z} \delta Y \\
+ \left( \frac{\partial \ln \Gamma_1}{\partial Z} \right)_{P,\rho,Y} \delta Z,
\]

thus allowing for inversions of \( Y \), the helium abundance, or \( Z \), the metallicity.

Initial attempts in Takata and Shibahashi (2001) using density and $\Gamma_1$ kernels.

Impossibility to conclude because of the errors bars. However, the conclusion mentions that the three last point are consistent with a 30% reduction of the solar metallicity.
This inversion (Buldgen et al. 2017c) favours a low metallicity (as in Vorontsov et al. 2013).
Potential solutions to the solar modelling problem I (Buldgen et al. 2019, in prep.)

Combination of: Neon increase from Landi & Testa (2015) and Young et al. (2018), extra-mixing and opacity modification (from A. Pradhan)
A few illustration of the potential impact of the solar problem

1. Solar reference for the chemical abundances,
2. Revision of key ingredients: opacity, EOS, screening factor (Mussack & Däppen 2011, Bailey et al. 2015),
3. Transport of chemicals (see talk by R. Hirschi),
4. Angular momentum transport processes (see talk by P. Eggenberger),
5. Impact on asteroseismic modelling and characterization of stellar populations in the Galaxy (see talk by C. Chiappini).

The role of calibrator of the Sun implies that changing its ingredients impacts a wide range of stellar models.
In conclusion


What about the BCZ: Extensively studied (see e.g. Hughes 2007 and references therein)

Is that it? No: Microscopic diffusion, EOS improvements, convection, instabilities, early history (see also Zhang et al. 2019)...

What is clear? Stop using GN93 and GS98. (listen to Nicolas Grevesse)

The solar problem is not purely an issue of abundances, rather an issue of other modelling ingredients. No significant variations found in 2015 by AGSS. Its impact reaches beyond the range of solar models.
Thank you for your attention!
Other approach: build a seismic model and try to see what its properties may be (Buldgen et al. In prep).

Help lift some degeneracies and drive revisions of physical ingredients.
Opacity kernels

Vinyoles et al. (2017)
Allow for a static analysis of the required changes in opacity to match helioseismic constraints.

- Based on Tripathy & Christensen-Dalsgaard (1998).
- Assumes linear behaviour with respect to small $\kappa$ perturbation.
Conclusions and prospects

The current state of the issue
Conclusions and prospects

The current state of the issue
Conclusions and prospects

The current state of the issue

Base of the solar convective zone
Conclusions and prospects

Combining seismic information I

Combining: \( A, S_{5/3}, c^2, Y \), position of BCZ, \( m_{CZ} \)... (Buldgen et al. submitted to A&A)

Combining seismic information II

**Combination of:** Neon increase from Landi & Testa (2015) and Young et al. (2018), extra-mixing and opacity modification (from A. Pradhan)
It seems: Opacity increase too high and perhaps too steep + wrong $\nabla T$ transition in overshooting region (improve on Christensen-Dalsgaard 2011) (Work by Rempel et al. 2004, Zhang et al. 2012)
Inferring $Z$ from helioseismic data - Tests

Tests on artificial data (same $\nu$, same $\sigma_\nu$) to ensure accuracy.
Add additional free parameters and constraints to the solar models to expand the calibration procedure. (Ayukov & Baturin 2013, 2017)
Conclusions and prospects

Considered opacity modification

\[ f_k \]

\[ \log T \]
Other classical diagnostics

<table>
<thead>
<tr>
<th>Helioseismic measurements</th>
<th>$r_{\text{Conv}}/R_\odot$</th>
<th>$Y_{\text{Conv}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM (AGSS09, Free, OPAL)</td>
<td>0.720</td>
<td>0.236</td>
</tr>
<tr>
<td>SSM (AGSS09, Free, OPLIB)</td>
<td>0.718</td>
<td>0.230</td>
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<tr>
<td>SSM (AGSS09, Free, OPAS)</td>
<td>0.717</td>
<td>0.232</td>
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<tr>
<td>SSM (GN93, Free, OPAL)</td>
<td>0.711</td>
<td>0.245</td>
</tr>
<tr>
<td>SSM (GN93, Free, OPLIB)</td>
<td>0.708</td>
<td>0.240</td>
</tr>
</tbody>
</table>
Conclusions and prospects

Standard Models with new opacities - Frequency ratios

- $r_{02}, r_{13} \Rightarrow \text{AGSS09 favoured!}$
- $c^2$ inversions still favour GN93.
- BCZ wrong for both AGSS09 and GN93.
- $Y_S$ very low for AGSS09.

$\Rightarrow$ Need new diagnostics.
Conclusions and prospects

Inversions of the convective parameter for Standard Solar Models

The compensation is related to the heavy-element mixture.
Inversions of the convective parameter for Standard Solar Models

Conclusions and prospects
The compensation is also related to the temperature gradient.
Conclusions and prospects

Relative differences OPLIB-OPAL

![Graph showing relative differences between OPLIB and OPAL](image)
Metallicity Inversions for the Solar Envelope

Metallicity kernels can thus be derived to estimate $Z$ in the envelope.
Conclusions and prospects

Appendices Helioseismology - Kernel fits

![Graph showing baseline fit and kernel function](image)

- **Base of the solar convective zone**
- **AGSS09-OPLIB (SOLA)**
- **Averaging Kernel**
- **Target Function**

Position $r/R$
Entropy inversions hint directly at inaccuracies in the radiative zone.
Parameters of the solar models with modified opacities and additional mixing used in this study

<table>
<thead>
<tr>
<th>$(r/R)_{BCZ}$</th>
<th>$(m/M)_{CZ}$</th>
<th>$Y_{CZ}$</th>
<th>$Z_{CZ}$</th>
<th>$Y_0$</th>
<th>$Z_0$</th>
<th>Opacity</th>
<th>Abundances</th>
<th>Diffusion</th>
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<td>OPAL+Poly</td>
<td>AGSS09Ne</td>
<td>Thoul</td>
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<tr>
<td>0.7129</td>
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<td>Paquette</td>
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<td>Thoul+$D_{Turb}$</td>
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<td>AGSS09Ne</td>
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<td>AGSS09Ne</td>
<td>Thoul+Ov – Rad</td>
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<td>AGSS09Ne</td>
<td>Thoul+Ov – Ad</td>
</tr>
</tbody>
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