A quantitative analysis of the solar composition problem

University of L'Aquila

F.L. Villante – Universita' dell'Aquila and INFN-LNGS

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Gran Sasso

Theory Group

The solar composition problem

The Standard Solar Model (SSM) treats the absolute and relative elemental abundances as an input. The old GS98 admixture yields concordance between models and helioseismic and solar neutrino data. A systematic overhaul in solar model atmospheres, see e.g. AGSS09met admixture, has led to a **downward revision** in photospheric heavy element abundances by up to 30-40% for important species such as oxygen.

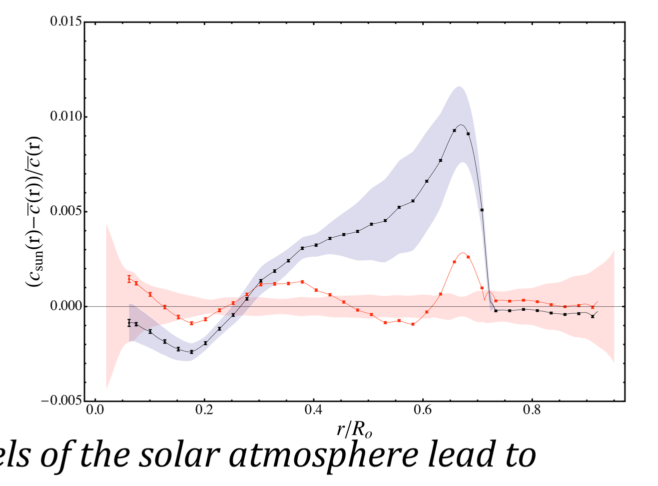
Element	AGSS09met	GS98	δz_i
C	8.43 ± 0.05	8.52 ± 0.06	0.23
N	7.83 ± 0.05	7.92 ± 0.06	0.23
O	8.69 ± 0.05	8.83 ± 0.06	0.38
Ne	7.93 ± 0.10	8.08 ± 0.06	0.41
Mg	7.53 ± 0.01	7.58 ± 0.01	0.12
Si	7.51 ± 0.01	7.56 ± 0.01	0.12
S	7.15 ± 0.02	7.20 ± 0.06	0.12
Fe	7.45 ± 0.01	7.50 ± 0.01	0.12
Z/X	0.0178	0.0229	0.29

$$[I/H] \equiv \log\left(N_I/N_H\right) + 12$$

- *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:

	AGSS09met	GS98	Obs.
Y_s	$0.2319\,(1 \pm 0.013)$	$0.2429\,(1 \pm 0.013)$	0.2485 ± 0.0035
$R_b/R_\odot$	$0.7231\,(1 \pm 0.0033)$	$0.7124\,(1 \pm 0.0033)$	0.713 ± 0.001
Φ_{pp}	$6.03\,(1 \pm 0.005)$	$5.98\,(1 \pm 0.005)$	$6.05(1^{+0.003}_{-0.011})$
Φ_{Be}	$4.56\,(1 \pm 0.06)$	$5.00\,(1 \pm 0.06)$	$4.82(1^{+0.05}_{-0.04})$
Φ_{B}	$4.59\,(1 \pm 0.11)$	$5.58\,(1 \pm 0.11)$	$5.00(1 \pm 0.03)$
Φ_{N}	$2.17\,(1 \pm 0.08)$	$2.96\,(1 \pm 0.08)$	≤ 6.7
Φ_{O}	$1.56\,(1 \pm 0.10)$	$2.23\,(1 \pm 0.10)$	≤ 3.2



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

A quantitative analysis

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

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta Q - \sum_I \xi_I \, C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right].$$

see Fogli et al. 2002

where:

$$\delta Q = \frac{Q_{obs} - Q}{Q}$$

- U_Q Uncorrelated (observational) errors
- $C_{Q,I}$ Correlated (systematical) uncertainties

We include **10 syst. error** sources: $\{I\} = \{\mathtt{opa};\, \mathtt{age};\, \mathtt{diffu};\, \mathtt{lum};\, S_{11},\, S_{33},\, S_{34},\, S_{17},\, S_{e7},\, S_{1,14}\}$

We consider **34 obs. quantities**: $\{\delta Q\} = \{\delta\Phi_B,\, \delta\Phi_{Be},\, \delta Y_b,\, \delta R_b,\, \delta c_1,\, \delta c_2,\, \ldots,\, \delta c_{30}\}$

^{7}Be and ^{8}B neutrino fluxes; Surface helium and convective radius; Sound speed data points (Basu et al, 2009)

We take the **surface abundances** (wrt hydrogen) as free parameters: $z_j \equiv Z_{j,b}/X_b$

We infer the **best-fit composition** by minimizing the χ^2: $\chi^2 \equiv \chi^2_{obs} + \chi^2_{syst} = \sum_Q \tilde{X}_Q^2 + \sum_I \tilde{\xi}_I^2$

__Note:__ This approach is completely equivalent to the standard covariance matrix approach. However:

- *It is more easily implemented numerically*
- *It allows to trace the individual contributions to the χ^2*
- *The distribution of pulls can be used to highlight tensions in SSM.*

$$\tilde{X}_Q \equiv \frac{\delta Q_{obs} - \sum_I \tilde{\xi}_I \, C_{Q,I}}{U_Q}$$

It is not possible (nor useful) to consider all the abundances as free parameters. For this reason, we group metals according to the method by which their abundances are determined:

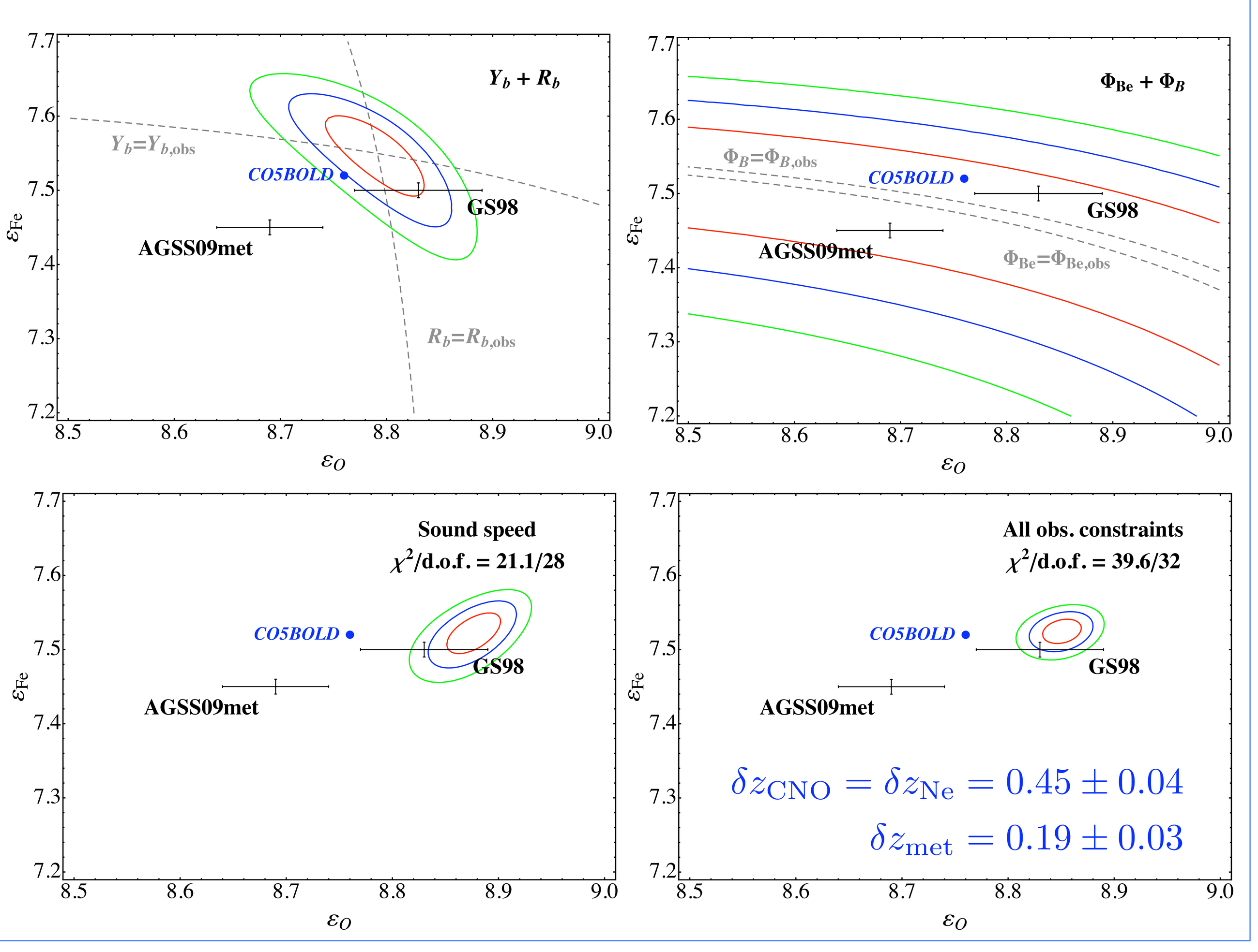
$$1 + \delta z_{CNO} \equiv \frac{z_C}{\bar{z}_C} = \frac{z_N}{\bar{z}_N} = \frac{z_O}{\bar{z}_O} \quad \textit{(photosphere)}$$

$$1 + \delta z_{Ne} \equiv \frac{z_{Ne}}{\bar{z}_{Ne}} \quad \textit{(chromosphere and corona)}$$

$$1 + \delta z_{Heavy} \equiv \frac{z_{Mg}}{\bar{z}_{Mg}} = \frac{z_{Si}}{\bar{z}_{Si}} = \frac{z_S}{\bar{z}_S} = \frac{z_{Fe}}{\bar{z}_{Fe}} \quad \textit{(meteorites)}$$

A two parameter analysis ($\delta Z_{CNO} = \delta Z_{Ne}$)

- Results are presented by using the astronomical scale for logarithmic abundances ε_i in order to facilitate comparison with obs. data.
- The coloured lines are obtained by cutting at 1, 2, 3 σ confidence levels.
- The data points show the obs. values (and 1σ errors) for oxygen and iron abundances in the AGSS09met, GS98 and CO5BOLD compilations.

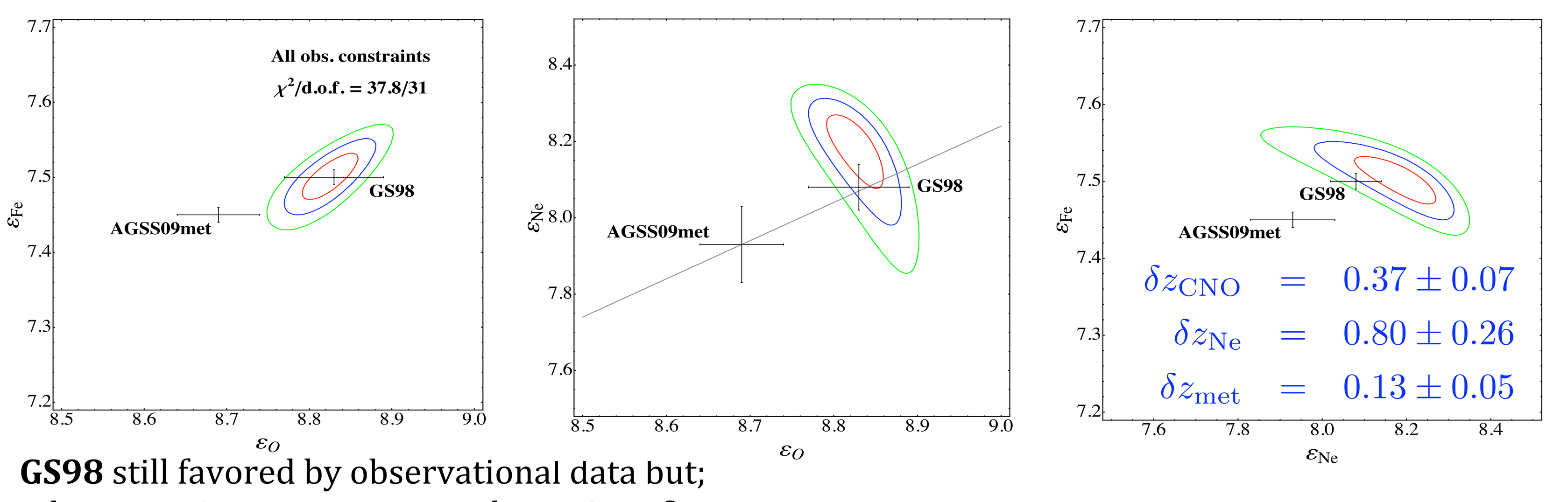


A two parameter analysis - *continued*

- The SSM implementing **AGSS09met** is **excluded** at an high confidence level (**χ^2/d.o.f. = 176.7/32).**
- There is a substantial agreement between the infos provided by the various observational constraints. The quality of the fit is quite good (**χ^2/ d.o.f. = 39.6/32**).
- The best-fit abundances are **consistent** at 1σ with **GS98**. 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 heavly element grouping).

A three parameter analysis(δZ_{CN}, δZ_{Ne}, δZ_{Heavy})

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



GS98 still favored by observational data but;
- degeneracies appear among the various δz_i;
- obs.data do not effectively constrain the Ne/O ratio

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 δκ(r)** that drives the modification of the solar properties is given by the **sum of two contributions: $\delta\kappa(r) = \delta\kappa_I(r) + \delta\kappa_Z(r)$.**

- The **intrinsic opacity change $\delta\kappa_I(r)$** represents the fractional variation of the opacity along the SSM profile. It is given, in our approach, by:

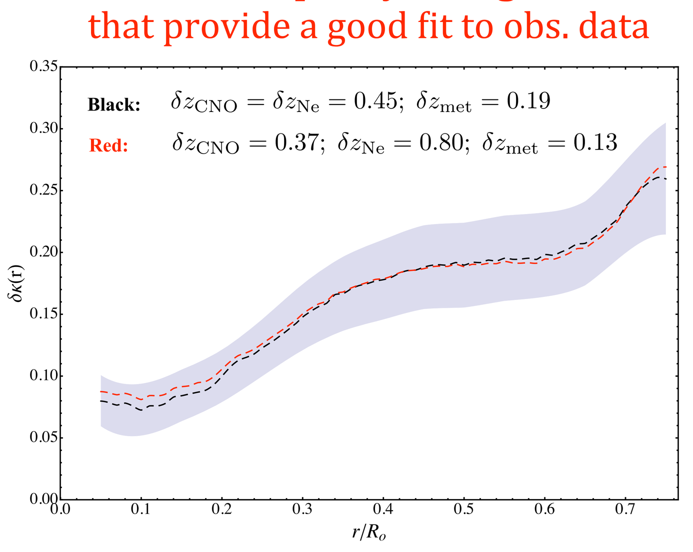
$$\delta\kappa_I(r) = \tilde{\xi}_{opa}\, \delta\kappa_{opa}(r)$$

Opacity profile uncertainty

- The **composition opacity change $\delta\kappa_Z(r)$** is produced by admixture modification and can be calculated as:

$$\delta\kappa_Z(r) \simeq \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j}\, \delta z_j$$

The **effective opacity change** for SSMs that provide a good fit to obs. data



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

Wrong **opacity** calculations? → the required variations seems large wrt uncertainties

Different **distribution of metals** in the Sun? → According to the standard assumptions, metals are nearly omogeneous in the sun (elemental diffusion is responsible for a slight increase at the solar center). Is this an oversimplified picture of chemical evolution?

Is this discrepancy pointing at **new physics?**

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:

$$1 + \delta\Phi_\nu = (1 + \delta X_{CN}) \left[1 + \int dr\, K_\nu(r)\, \delta\kappa(r) \right]$$

$$X_{CN} \equiv X_C/12 + X_N/14$$

Total number of catalysts for CN-cycle

Determines the central temperature

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

ν flux	GS98	AGSS09	Solar
^{13}N ($10^8\,cm^{-2}\,s^{-1}$)	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
^{15}O ($10^8\,cm^{-2}\,s^{-1}$)	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.3
^{17}F ($10^6\,cm^{-2}\,s^{-1}$)	$5.52(1 \pm 0.17)$	$3.04(1 \pm 0.16)$	≤ 59

Will it be possible to detect CNO neutrino? *Very difficult, in practice. Not impossible, in principle .....*

See eg.F.L. Villante et al. – Phys.Lett. B701 (2011) 336

If the detected fluxes were consistent with those predicted by using AGSS09met admixture:
→ Opacity calculations are wrong by a factor much larger than the presently estimated uncertainties.

If they were consistent with the expectations from our analysis (i.e. ~50% larger than predictions):
→ the AGSS09met surface abundances are wrong and/or the chemical evolution paradigm of SSM is not correct.

Both these results would have enormous implications for stellar evolution.

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