Low-Z solar model: sound speed profile under the convection zone

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Abstract. With the low solar heavy elements abundances published in 2004 discrepancy in sound speed profile between models and inversions became much larger than with older, higher abundances. We consider structure and source of the discrepancy. The most important source of discrepancy is shallow convection zone but making it deeper with localized opacity modifications does not lead to desired sound speed profile. Special opacity changes can produce models with sound speed profile which is close to inversion but these changes look fairly artificial. Enhanced heavy element diffusion improves agreement on He abundance but not on sound speed profile. We present solar models which include aforementioned effects or their approximations.

1. Introduction
Helioseismology provides means to verify models of the solar internal structure. The most important data used for this purpose are the sound speed profile, the convection zone depth \( R_{cz} \) and the helium abundance in the convection zone \( Y_{cz} \). These are results of helioseismic inversion; in this work we’re using compilation [1].

Since 1996 ([2]) until 2004 an agreement between models and inversions was quite remarkable. In 2004 solar composition was redetermined using new atmosphere models ([3], [4]); data were revised in 2009 ([5]). New abundances of many elements heavier than helium appeared to be significantly lower. Solar models computed with low abundances showed much worse agreement with inversion. We study low-Z problem and possible ways to obtain helioseismically consistent solar model with low-Z abundances.

Details of our model calculations are described in [6]. All low-Z models use AGSS09 ([5]) abundances and are calibrated to value of \( Z/X = 0.0181 \) which corresponds AGSS09.

2. Artificially enhanced diffusion
Enhanced diffusion was suggested by Asplund as a solution for low-Z problem ([3]) and later was investigated by many authors, including Basu and Antia ([7]), Montalban et al. ([8]), Bahcall et al. ([9]), Guzik et al. ([10]) and others. It was found that sound speed and convection zone (CZ) depth discrepancies can be significantly reduced in models with enhanced diffusion, but such models have rather low \( Y_{cz} \). Even selective changes in diffusion rates ([10]) cannot produce model which gives good agreement on sound speed, \( Y_{cz} \) and \( R_{cz} \).

In this work we enhance \( Z \) diffusion rate and don’t change He diffusion rate. Let us remind that final model of the evolutionary track is adjusted to have predetermined \( Z/X \) (0.0181 for [5]). If we assume helioseismic calibration for \( Y_{cz} \approx 0.25 \), composition of the present Sun’s envelope
### Table 1. Solar models

| Model    | Mixture | $Y_{cz}$   | $Z_{cz}$   | $Z/X$       | $R_{cz}$   |
|----------|---------|------------|------------|-------------|------------|
| 721-0001 | GN93    | 0.242674   | 0.018045   | 0.024409    | 0.71509    | high-Z, standard |
| 721-0100 | AGSS09  | 0.232267   | 0.013666   | 0.018123    | 0.72664    | low-Z, standard  |
| 721-0113 | AGSS09  | 0.249826   | 0.013353   | 0.018123    | 0.73095    | enhanced Z diffusion |
| 721-0102 | AGSS09  | 0.224431   | 0.013805   | 0.018123    | 0.72506    | no Z diffusion at all |
| 721-0208 | AGSS09  | 0.259377   | 0.013183   | 0.018123    | 0.72421    | monotonic opacity change |
| 721-0237 | GN93    | 0.230775   | 0.018328   | 0.024409    | 0.72508    | low-Z opacity in high-Z model |
| 721-0238 | AGSS09  | 0.243617   | 0.013464   | 0.018123    | 0.71770    | high-Z opacity in low-Z model |
| 721-0319 | AGSS09  | 0.233292   | 0.013647   | 0.018123    | 0.71293    | opacity correction near boundary CZ |
| 721-0320 | AGSS09  | 0.254679   | 0.013267   | 0.018123    | 0.71034    | opacity corrections |
| 721-0347 | AGSS09  | 0.248932   | 0.013369   | 0.018123    | 0.71302    | opacity corrections |

becomes fixed; equation $X + 0.25 + X \cdot 0.0181 = 1$ gives $X = 0.7367$, $Z = 0.0133$. With so low $Z$ in convection zone, enhanced Z diffusion increases $Z$ below CZ boundary and partially restores model’s structure. Our standard model with AGSS09 abundances (721-0100) has $X = 0.7541$, $Y = 0.232$, $Z = 0.0136$ in the CZ (Table 1). Increasing Z diffusion rate leads to decrease of $Z$ in the envelope and, since $Z/X$ is fixed, $X$ is decreased and therefore $Y_{cz}$ is increased. To obtain model with $Y_{cz} = 0.25$ we have to increase Z diffusion rate by 200% (721-0113 on Fig. 1).

Enhanced Z diffusion partially compensates overall decrease in $Z$ caused by switching to low-Z abundances. To reach proper $Y_{cz}$ we have to go about halfway to full compensation in $Z$ below convection zone (Fig. 2).

Sound speed profile is not greatly affected by enhanced diffusion in the model calibrated to $Z/X$ (Fig. 3; all sound speed comparisons are made against inversion [1]). The visible effects are probably caused by change of CZ depth. Therefore model with enhanced Z diffusion can have good $Y_{cz}$ but not the proper sound speed profile and $R_{cz}$. In fact, such diffusion makes CZ even shallower than in standard low-Z model. This may look strange because we’re increasing $Z$

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**Figure 1.** Helium abundance and convection zone boundary position. Circles—standard models with different composition, triangles—models with enhanced Z diffusion. Rectangle—results of helioseismic inversion ([1])
Figure 2. Models with enhanced Z diffusion; Z near convection zone boundary

Figure 3. Sound speed comparison for models with enhanced heavy element diffusion

(and opacity) directly below CZ. However increasing opacity in the center makes CZ shallower (see 3.4 below), and since Z increase in the center is even larger than in the radiative zone this effect apparently suppresses Z increase in the radiative zone.

On the other hand, if we decrease Z diffusion rate or even disable Z diffusion, we get better (but still small) CZ depth and improper $Y_{cz}$ and sound speed profile (Fig. 1, 3).

3. Opacity modifications

Opacity change was one of the first ideas to solve the low-Z problem. Basu and Antia ([7]) have found that opacity increase of about 19% near the CZ boundary improves density profile. Montalban ([8]) has suggested 14% opacity increase. Bahcall et al. ([9]) have made an extensive study and found that 11% increase in opacity in the region $T = 2 \times 10^6$ K helps to restore agreement. However not all of these works used models calibrated to exact value of $Z/X$, and we are not aware of any model with low-Z abundances which reproduces sound speed, $Y_{cz}$ and $R_{cz}$.

Our models are calculated with OPAL opacities, 19-component interpolation scheme ([6]) and AGSS09 mixture. Introduced opacity modification factors are simple temperature-dependent functions.

3.1. Effect of low-Z abundances on opacity

To estimate the effect of low-Z composition on opacity, we have calculated opacity values for the solar conditions. Two calculations were made and compared. Both use the same temperature and density values taken from model with AGSS09 composition. X and total Z values, however, are taken from the two models with different mixtures. Thus we eliminate temperature and density dependence and consider only effect of chemical composition on the opacity at the conditions in the present Sun. Fig. 4 shows that low-Z effect on opacity is 3% decrease in the center and 17% near the bottom of the convection zone. This result is close to the plot published in [9].

We can introduce opacity correction resembling this profile. This correction is plotted on Fig. 4 as a function of $\log T$; simple polynomial approximation is used. Correction in the atmosphere is excluded, but detailed computations confirm that it does not affect sound speed profile below the convection zone (only convection theory parameter $\alpha$ is affected by opacity in this region). Model with high-Z abundances and such opacity correction (721-0237) can help to understand the role of the opacity in model. It has sound speed profile very close to the proper
low-Z model (721-0100). Density comparison plot is similar.

Comparison of opacity itself in these models (interpolated to the same radius points) shows differences about 4% (compare with correction amplitude of about 17%), so we did not achieve full compensation. Given that opacity correction can reproduce sound speed profile it is instructive to check how these models (721-0100 with AGSS09 and 721-0237 with GN93+opacity correction) differ in other parameters. The radiative interior did not change much. What we see is change in Z and change of convection parameter $\alpha$. $X$ and $Y$ are almost fully compensated by opacity change, unlike $Z$. In other words, if we decrease opacity according low-Z abundances we get a model which is very close to original but has low $Z$ everywhere.

This correction can be also applied in opposite direction, i.e. increase of opacity in the low-Z model (721-0238). This gives sound speed profile close to the high-Z sound speed profile (Fig. 5). Fit to helioseismic sound speed profile can improved further by adding more local corrections (721-0320; Fig. 10).

3.2. Global opacity correction

Several models were computed with opacity uniformly increased everywhere by 5%, 10%, 15%, 20%. The effect on $R_{cz}$ is noticeably small, and sound speed profile is almost unchanged even with 20% opacity increase (Fig. 6). This is somewhat surprising. It seems global opacity increase leads to overall decrease in $Z$ (to keep opacity approximately at the same values) and, since $Z/X$ is fixed in CZ, $X$ also decreases. This in turn increases $Y$. Therefore global correction can help with low $Y$ in low-Z models, but does not change $R_{cz}$ and sound speed profile. This is illustrated by Fig. 7; models with such opacity correction have nearly the same $R_{cz}$.

3.3. Opacity correction localized at lower CZ boundary

Opacity correction localized near CZ boundary was also analyzed. Such correction affects only region near CZ boundary (Fig. 8). Model 721-0319 (AGSS09 composition; 24% increase in opacity; Fig. 9) has proper convection zone depth, but sound speed looks good only directly below CZ; in the deeper layers it is unchanged. Therefore such correction can produce model with proper CZ depth but sound speed in the radiative zone is not helioseismically consistent. Helium abundance in the envelope is almost unaffected by such correction.
3.4. Corrections localized in the core and radiative zone

To obtain model with helioseismically consistent sound speed profile we applied a set of opacity corrections localized in the core and radiative zone. Trial-and-error technique was used to search for appropriate set; result was judged by model’s sound speed profile. It was found that simplest opacity change in fact is not monotonic; opacity is to be significantly decreased in central regions. Model with such correction has proper sound speed and $R_{cz}$ but low $Y$ abundance in the envelope. Since global opacity correction can change $Y_{cz}$, we can add 19% global correction to obtain helioseismically consistent model (721-0347; Fig. 10, 11).

It was also found that increasing opacity in the core makes convection zone shallower while increasing opacity below CZ makes CZ deeper. The switching point lies at $\lg T = 6.7$ in our models; figure is not included due to space constraints.

4. Conclusions

As expected, no natural solution for low-Z problem has been found. We have attempted to apply enhanced heavy element diffusion and several kinds of opacity correction. Opacity corrections are able to bring the model into agreement with helioseismic data (sound speed profile, convection zone depth and helium abundance in the envelope). The required correction amplitude is quite

Figure 6. Sound speed profile in models with monotonic global opacity change

Figure 7. Models with global opacity change (triangles) on $Y - R_{cz}$ plane

Figure 8. Sound speed in models with opacity correction localized near CZ boundary

Figure 9. Opacity correction in model 721-0319
large and reaches 30% in the vicinity of the CZ base (Fig. 11). However our current high-Z model also has sound speed profile which significantly deviates from inversion, so high-Z model also needs opacity correction but required amplitude is approximately two times smaller than for low-Z model.

Models with opacity corrections near CZ base demonstrate that core and radiative zone in low-Z models are in disagreement with inversions and cannot be improved simply by changing CZ depth.

In author’s opinion a solution to low-Z problem may be either in error of abundances and/or opacities or in existence of some mechanism which creates a gradient in chemical composition between deep layers of the convection zone and atmosphere.

Acknowledgements
This work was supported by ISTC grant 3755.

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