

# HOW DOES THE CHANGE ON SOLAR ABUNDANCES AFFECT LOW DEGREE MODES?

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## ABSTRACT

The most recent determination of the solar chemical composition by, has been done using time-dependent, 3D hydrodynamical model of the solar atmosphere [1], instead of the classical 1D hydrostatic models. This new determination exhibits a significant decrease on C, N, O abundances compared to their previous values. Solar models using these new abundances are not consistent with helioseismological measurements. However, the increase on neon abundance reduces the inconsistency [2]. We investigate the change on solar abundances using low degree p-mode characteristics which are strong constraints of the solar core. As a result, none of the models match the observations. We also show the influence of the solar abundances on g-modes frequencies which are strongly related to the solar core properties.

## 1. INTRODUCTION

The observed solar p-modes have been used to probe several layers of the interior of the Sun through helioseismological determinations of its properties. Among others, seismic sound speed, and density are used to constrain the interior of the Sun except the surface layers and the core. The seismic surface helium abundance and the depth of the convection zone bring constraints to the surface and the limit between radiative and convective zones. The small number of p-modes (only low degree p-modes) able to reach the solar core is not sufficient to probe in detail this region. However, the solar core is crossed by thousands of g-modes, capable to bring a very precious information from this region, but not yet observed because of their confinement under the convection zone. The determination of their properties is very important.

The new revision of solar chemical abundances [1] leads to an inconsistency between solar models and helioseismology (see, for instance, [3]; [2]; [4]). We study the sensitivity of the solar core properties, through g-modes and low degree p-modes, to the change on solar mixture.

According to [2] we change the neon abundance in order to improve the discrepancy between the new solar model and helioseismic determinations.

We have constructed several solar models using different sets of chemical abundances and the corresponding opacities using the CESAM code. We tried to constrain our solar models to small frequency separations in low degree p-mode frequency range, in addition to the already used constraints (seismic sound speed, surface helium abundance and convection zone depth). The g-mode and low-degree p-mode frequencies have been calculated for each model.

## 2. SOLAR MODELING

We have computed a set of solar models with different sets of heavy element abundances by using the stellar evolution code CESAM (Code d'Evolution Stellaire Adaptatif et Modulaire), [5]. Models are calibrated for a solar age  $t = 4.6$  Gyr at the solar radius, the solar luminosity ( $R_{\odot} = 6.959910^{10}$  cm,  $L_{\odot} = 3.84610^{33}$  erg/s, [6]) and the solar surface metallicity  $Z/X$  of the various mixtures. All the models include the microscopic diffusion of the chemical elements. OPAL opacity tables<sup>1</sup>, calculated for each mixture, and opacity tables at low temperatures ( $T < 6000K$ ), as in [7], have been used. Nuclear reaction rates are from NACRE compilation (1999). We use OPAL equation of state tables and assume the convection treatment as in [8]. Table 1 summarizes the characteristics of the solar models at both the surface and the core, their chemical composition is given, as well.

The change in the abundances affects essentially the opacity estimations from the core to the surface as it is seen in Figure 1. The contribution of neon to the opacity is shown by the big difference between  $0.4R_{\odot}$  and  $0.7R_{\odot}$  as noticed in [9].

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<sup>1</sup><http://www-pat.lnl.gov/Research/OPAL/>

	M-GN	M-AGS	M3	M4	M5	M6
$A(Ne)$	8.08	7.84	8.10	8.29	8.47	8.24
$(Z/X)_S$	0.0245	0.0166	0.0179	0.0192	0.0212	0.0210
$Y_S$	0.2437	0.2279	0.2328	0.238	0.2442	0.2420
$r_{ZC}$	0.7133	0.7292	0.7236	0.718	0.7117	0.7149
$T_c^7$	1.574	1.549	1.555	1.559	1.565	1.566
$P_0$	35.08	35.66	35.48	35.28	34.72	35.13

Table 1. Global characteristics for the solar models.  $A(Ne)$  is the Neon abundance in dex,  $(Z/X)_S$  is the surface metallicity,  $T_c^7 = T_c * 10^{-7}$ ,  $T_c$  the central temperature in Kelvin.  $P_0$  is the characteristic period (in minutes) of low degree gravity modes. The different models are calibrated with the following solar abundances: M-GN: [10] (GN; hereafter); M-AGS: [1] (AGS; hereafter); M3, M4, M5: AGS with the indicated change of the Neon abundance; M6 : AGS in which the neon and different abundances have been changed ( $A(C,N,O)=A(C,N,O)_{AGS}+0.05$ ,  $A(Si,Mg)=A(Si,Mg)_{AGS}+0.02$  and  $A(Ar)=A(Ar)_{AGS}+0.40$ ).

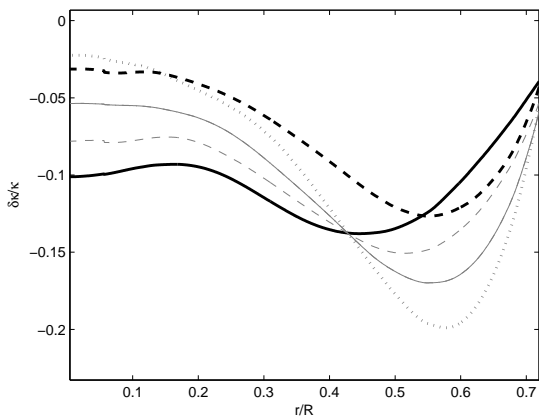


Figure 1. Relative differences between the opacities associated with the abundances of the different models and those associated with GN abundances: M-AGS (full heavy line), M3 (light dashed line), M4 (light full line), M5 (light dotted line), M6 (heavy dashed line). The differences are estimated along a solar path for given radius, density, temperature and chemical composition.

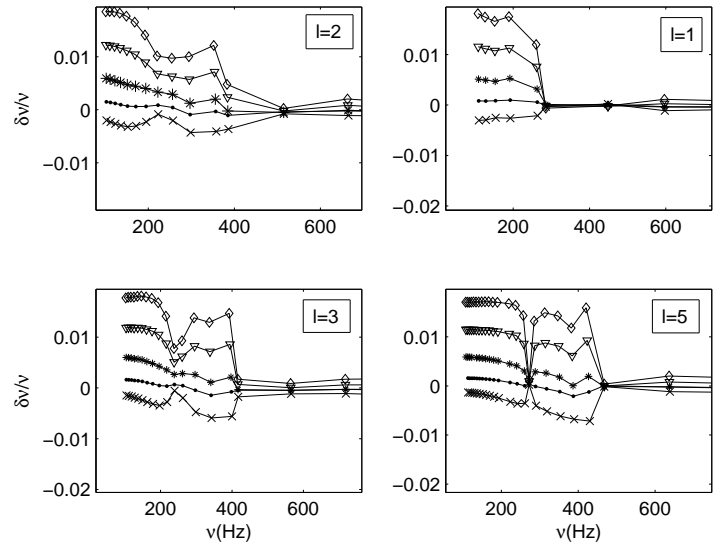


Figure 2. Relative differences between the frequencies of the reference model M-GN and the models: M-AGS ( $\diamond$ ), M3 ( $\nabla$ ), M4(\*), M5 ( $\times$ ), M6( $\cdot$ )

### 3. GRAVITY MODES

Adiabatic frequencies of all the models have been computed in the frequency range from 100 to 4000  $\mu\text{Hz}$  and for low degrees ( $0 < \ell < 6$ ). We are first considering modes on the frequency range [ $100\mu\text{Hz}$ ,  $500\mu\text{Hz}$ ] and  $0 < \ell < 6$  including both g-modes and mixed modes. The period of low frequency gravity modes are proportional to the characteristic period  $P_0$  ( $P_0 = 2\pi^2 / \int_0^{r_{ZC}} (N/r) dr$ , where  $N$  is the Brunt-Väissälä frequency). This period is given for all the computed models in Table 1. The lowest  $P_0$  difference between the reference model M-GN and the other models is obtained for M6, leading to the closest model g-modes frequencies. The frequency differences between the M-GN model and some other models are given in the Figure 2. The biggest shift in the frequencies with the change in the model is given between M-GN and M-AGS, it goes down 1.5% for low g-modes frequencies. This difference decreases for all the models after  $200\mu\text{Hz}$  and reaches its lowest value around  $250\mu\text{Hz}$ . Consequently, the g-modes around  $250\mu\text{Hz}$  are the less sensitive modes to the change in the models. The lowest shift in the frequencies compared to the reference model is given for M6 which is the closest model to M-GN.

### 4. HELIOSEISMOLOGICAL CONSTRAINTS

Figures 3 and 4 show, respectively, the comparison of the seismic sound speed, and the seismic helium abundance and the depth of the convection zone to those of the

computed models. The first comparison shows the worse concordance between the model using Asplund et al. abundances (AGS) and the seismic model. Indeed, their sound speed relative difference peaks at 1.5% under the convection zone. Models M3, M4, M5 bring an idea of how big the neon abundance increase has to be in order to reduce the discrepancy. We have estimated this augmentation to 0.4-0.5Dex, which is in accordance with [2]. On the other hand, the larger the neon abundance is, the larger surface helium abundance  $Y_S$  (the smaller the convection zone depth  $r_{ZC}$ ) is. Nevertheless, none of the models is in accordance, simultaneously, with the 3 seismic values (sound speed,  $Y_S$  and  $r_{ZC}$ ). In the aim to bring closer all these parameters to the ones of the models, we constructed the model M6 in which the neon abundance is increased by 0.4dex in addition to slightly increases of other heavy elements. We notice that  $Y_S$  and  $r_{ZC}$  of the M6 model have been enhanced but not enough to reach the observations.

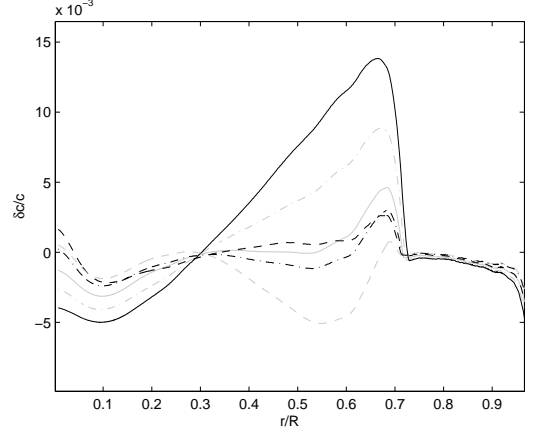


Figure 3. Relative sound speed differences between the Sun and the models. M-GN dark dashed, M-AGS dark full, M3 light dashed-dotted, M4 light full, M5 light dashed, M6 dark dashed-dotted.

We also consider the small low degree frequency spacings which are very sensitive to the core. In order to compare our theoretical results to observational ones, we use the latest results given in [12] and those given in [13] in the measurement of low degree solar frequencies from GOLF experiment. In so doing, we examine the small frequency spacings  $\delta\nu_{02}$ ,  $\delta\nu_{13}$  and  $\delta\nu_{01}$  which are combinations of acoustic modes penetrating differently towards the center and thus very sensitive to the central part of the solar interior. These are given according to [14] by:

$$\begin{aligned}\delta\nu_{02} &= \nu_{n+1,\ell=0} - \nu_{n,\ell=2}, \\ \delta\nu_{13} &= \nu_{n+1,\ell=1} - \nu_{n,\ell=3}, \\ \delta\nu_{01} &= 2\nu_{n,\ell=0} - (\nu_{n,\ell=1} + \nu_{n-1,\ell=1}).\end{aligned}$$

We compute both for our models and for the observations the mean of the frequency small spacings  $\overline{\delta\nu_{02}}$ ,  $\overline{\delta\nu_{13}}$  and  $\overline{\delta\nu_{01}}$  for radial orders from 16 to 24, which corresponds to a frequency range about 2500 – 3600  $\mu\text{Hz}$ . The low limit of this range insures that the behavior of the frequency is almost asymptotic, the high limit corresponds to observed modes with very high accuracy. As a result, Figure 5 shows that the increase of neon induces a decrease of the small frequency spacings. The variation of these spacings is much larger than the observational boxes. However we note that the small spacings are also sensitive to the solar age. For instance, for a model 50 Myrs older,  $\overline{\delta\nu_{02}}$  is decreased by about 0.05 $\mu\text{Hz}$ .

## 5. CONCLUSION

We have used the CESAM code and OPAL facilities in order to construct solar models with different solar mixtures. Contrary to the solar model using the old

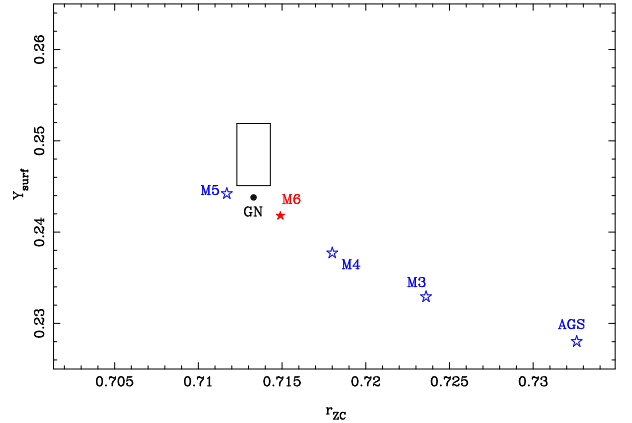


Figure 4. Characteristics of the solar envelope,  $Y_S$  and  $r_{ZC}$ , for the models. Model M-GN: full black circle. For the sequence of models computed with AGS abundance, but varying the one of neon, i.e. M-AGS and M3 to M5: open blue stars; M6: red star. The box represents the seismic values with their errors [11].

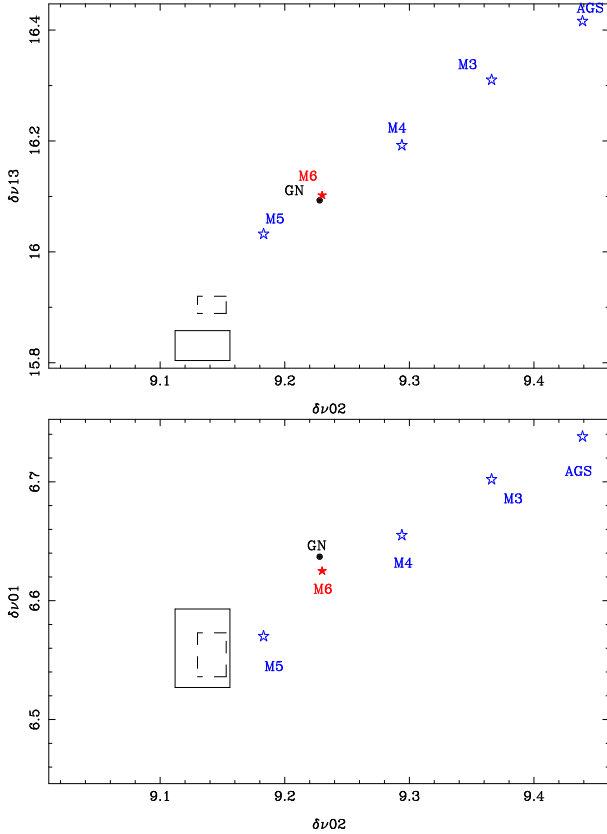


Figure 5. Upper panel: Mean frequency small spacing  $\overline{\delta\nu_{13}}$  as a function of the mean frequency small spacing  $\overline{\delta\nu_{02}}$  for the different models compared to Golf observations (full box [13], dashed box [12]). Lower panel: same for mean frequency small spacing  $\overline{\delta\nu_{01}}$  as a function of the mean frequency small spacing  $\overline{\delta\nu_{02}}$

solar abundances [10], the one with the recently revised abundances [1], reveals a significant discrepancy with helioseismological determinations of sound speed profile, convection zone depth and surface helium abundance, as it was already discussed by several authors. This discrepancy is reduced when the neon abundance is increased by about 0.4-0.5 dex, and well reduced when, in addition to the neon increase, the C, N and O are  $1\sigma$  increased, which is in accordance with the result given in [2]. We have extended the use of helioseismic constraints to the low degree small frequency spacings which are very sensitive to solar core properties. After comparing these quantities to the observed ones ([12]; [13]), we conclude that none of the models brings satisfying results, even for the model using the old abundances. As the solar core is crossed by thousands of gravity waves, we also calculated the g-modes frequencies of our several models. We concluded that the solar model using new abundances has the biggest frequency differences with the model using old abundances. We also noticed that modes with frequencies around  $250\mu Hz$  are the less sensitive modes to the change in the abundances. These last modes are mixed modes, sensitive to both the sound speed and the Brunt-Vaissala frequency variations.

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