FIRST VIEW OF THE SOLAR CORE FROM GOLF ACOUSTIC MODES

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Abstract. After 8 months of very continuous measurements, the GOLF instrument, aboard SOHO, has detected acoustic mode frequencies of more than 100 modes, extending from 1.4 mHz to 4.9 mHz. In this paper, we compare these results with the best available predictions coming from solar models. An examination of the well known seismic parameters confirms the improvements performed in this field during the last decade and validates the present comparison. We then carefully deduce the information obtained on the solar core from the usual inversion techniques using the GOLF set of frequencies for l=0, 1, 2, 3 coupled to the LOWL second year data set for l > 3. Special attention has been devoted to the accuracy of the frequencies used and to the physical processes which may influence directly or indirectly, the solar core structure.

Key words: sun–helioseismology, sun–oscillations, solar modelling

1. Introduction

Helioseismology is emerging clearly as an impressive tool to verify the internal structure of the Sun. Due to its remarkable constraints, this discipline has exploited the Sun as a real physics laboratory, forcing substantial progress on the equation of state, the opacities and the diffusion of the elements from the surface to the core during the hydrogen burning phase (Turck-Chièze et al. 1993, Berthomieu 1996, Christensen-Dalsgaard 1996a). Nevertheless, constraints on the solar core are illusive due to the small number of modes penetrating this region and the limited time they spend there (less than 10% of the travelling time for the radial mode). We can observe important recent advances due to the present global oscillations ground networks: BiSON (Chaplin et al 1996a, 1996b) IRIS (Gelly et al 1997) and the impressive LOWL instrument which covers the range of degrees from 0 to 99 (Tomczyk et al 1995). With space observations, one can expect to reach some better constraints, by enlarging the range of modes accessible in a shorter period of observation and by improving the accuracy of the frequency determination. Effectively, the stability of the SOHO spacecraft and orbit, together with the very high counting rate of GOLF (typically 8-12 10^6cts/s) leads to a very low statistical noise at high frequencies. This can even be reduced, by exploiting the incoherent signal between the detectors located on the two sides of the sodium cell or between the signals obtained every 10s at twoclose positions the sodium lines blue wing . The final result is a gain by a factor 5 to 10 on the level of noise at high frequencies, in comparison with existing ground-based networks. At lower frequencies, the p-modes spectrum benefits from the absence of atmospheric perturbations and the practically 100% duty cycle (Gabriel et al 1997).

In this paper, we first compare, the GOLF frequencies (Lazrek et al, 1997b) with the classical helioseismic variables deduced from asymptotic approximations. In the second part we discuss the inversion of the GOLF frequencies together with complementary LOWL data, obtained during a reasonably close period of time, in order to derive the sound speed profile in the solar core. In the final part, we discuss the physical processes which may be constrained by the presently available observed frequencies.

2. Direct absolute comparisons

The space-based GOLF experiment has identified more than one hundred acoustic modes which penetrate the region of solar energy production ($r < 0.3\ R_\odot$). The list of these acoustic mode frequencies is given by Lazrek et al. (1997b). It contains results for modes of degree $l = 0$ (radial orders n = 9–35), $l = 1$ (n = 9–34), $l = 2$ (n = 9–33), $l = 3$ (n = 9–33), $l = 4$ (n = 13–21), and $l = 5$ (n = 17–20) for the period from April 11 to the end of December 1996.

We compare first the absolute values of the acoustic mode frequencies, obtained with GOLF with those deduced from different solar models for l=0 and 1. Figure 1 shows the differences in μHz for these degrees; for clarity, GOLF error bars are superimposed on one model only. Three general trends seem to clearly appear:

- (1) the agreement is exceptionally good (smaller than 1 μHz) at low orders (n<15) (low frequency below 2.2 mHz) for the models that include

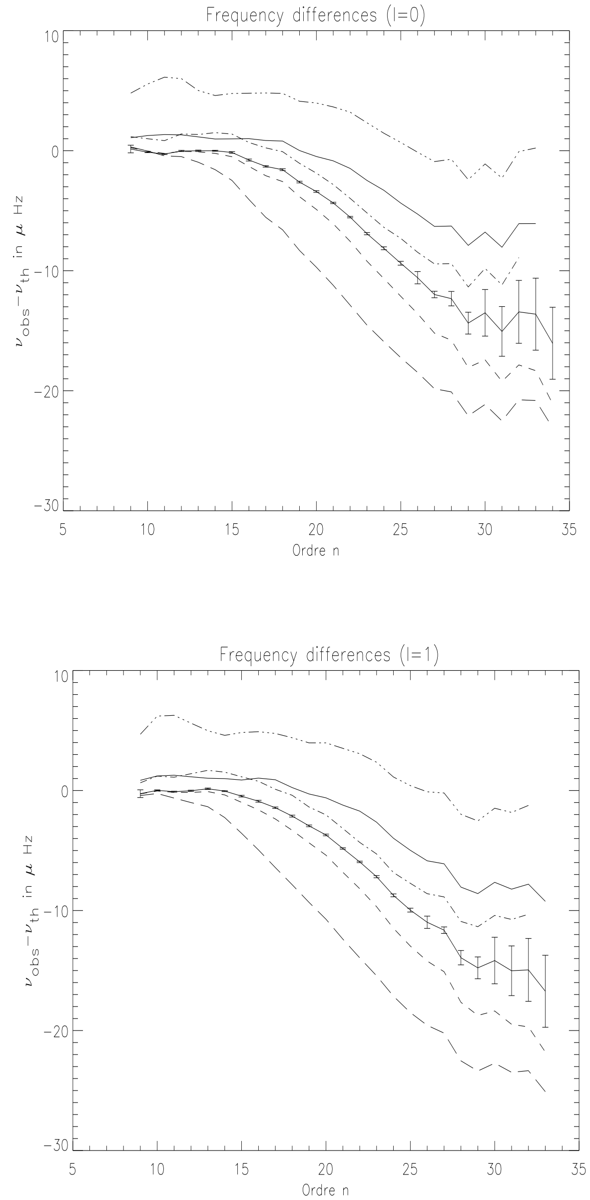


Fig. 1. Frequency differences between GOLF observations and different solar models for radial modes (a) and modes l=1 (b), in the sense (Sun) - (th): $- \cdot\cdot\cdot -$: Turck-Chièze and Lopes (1993); full line: Gabriel and Carlier (1997); $- \cdot -$: Guzik *et al* (1996); full and experimental error bars: Christensen-Dalsgaard *et al* (1996); $- - -$:Morel, Provost, Berthomieu (1997); *large* $- --$: Brun *et al* (1996).

updated physics (Livermore equation of state and opacities) and gravitational settling of elements (Christensen-Dalsgaard *et al* 1996, Guzik, Cox, Swenson 1996, Gabriel and Carlier 1997, Brun *et al* 1997, Morel, Provost, Berthomieu 1997), in comparison with models where these effects where not yet introduced (Turck-Chièze and Lopes 1993). In this last case, the difference is approximatively of 6 μHz from the present solar frequencies.

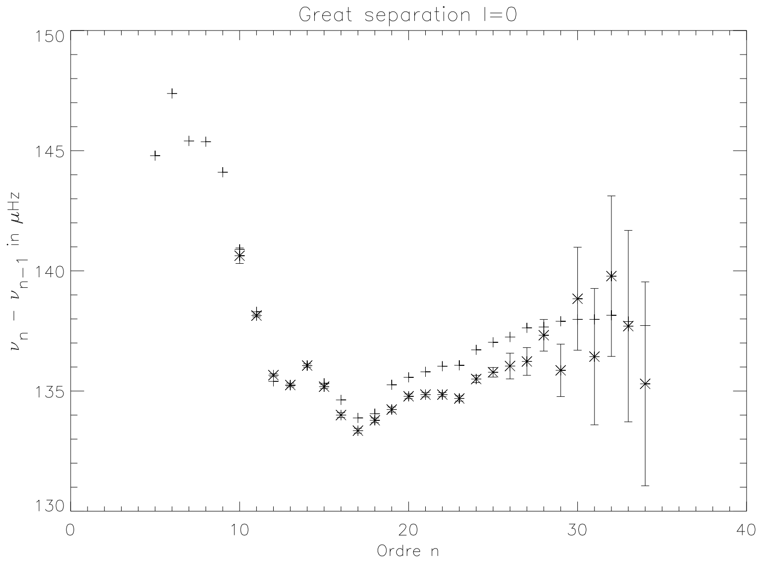
Nowadays, these modes of low order are considered as predictable, because their external reflection is located sufficiently low below the phostosphere, in a region where the physical processes are presently reasonably well understood.

- (2) at higher frequencies (the order n between 15-30 or ν between 2.2 and 4.2 mHz), the models deviate from the experimental values depending on the treatment of the external layers. Effectively, the frequency dependence of those modes is mainly correlated to the different outer turning points determined by the cut-off frequency. One may notice that the models for which the slope is reduced are those where the structure equations are solved above the solar effective radius without introducing a specific atmosphere (Gabriel and Carlier 1997, Turck-Chièze and Lopes 1993; see also Brun *et al* (1997) for a discussion on this point). Present studies show that a number of phenomena must be correctly treated in this photospheric region, about 200 km deep: the effect of opacity, the equation of state, turbulent pressure, improved treatment of convection and non-adiabatic correction (Kosovichev 1995, Henney and Ulrich 1995, Guzik Cox, Swenson 1996) in order to derive precise reflection of the modes in these outer layers.

- (3) Finally it seems that this slope flattens off for the very high order (above n=30), but this has to be confirmed, owing to the difficulty to measure such modes and the error bars inherent in their measurement. This difficulty is due to the small lifetime of these modes (several hours). Consequently one observes very wide profiles, partly mixed to neighbouring ones, with a shape complicated by the effects of the stochastic excitation, even if, the very low instrumental noise of GOLF allows us to see the modes clearly. This difficulty has been discussed in recent analysis of the IRIS data (Gelly et al. 1997).

3. Seismic indicators of the internal solar structure

The direct comparison of the absolute values of mode frequencies gives little information on the solar internal structure, and mainly encourages improvements of solar modelling for the outer layers. It is well established that the next step is to extract structural information from several useful variables which emphasize different parts of the Sun. The most simple indicators have been suggested by the first asymptotic theory (Tassoul 1980):



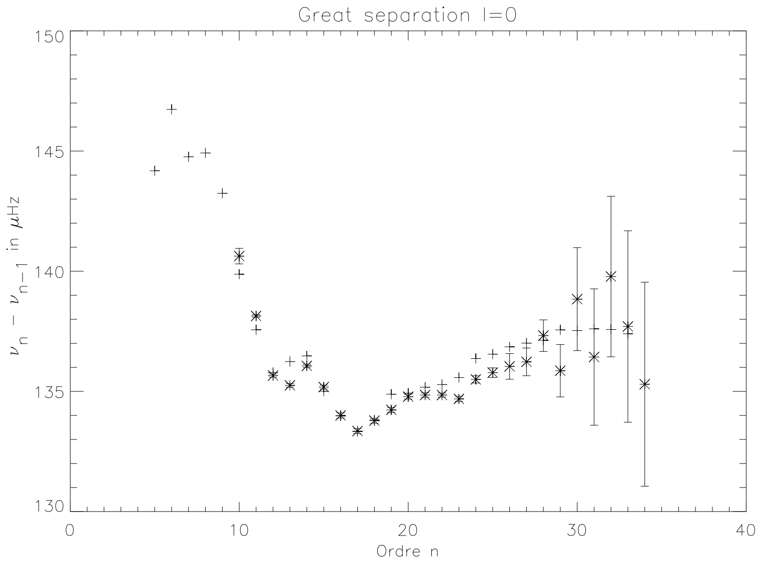


Fig. 2. Great separation for l=0. GOLF observations corresponding to stars with error bars and to solar models with crosses: a) comparison with Christensen-Dalsgaard et al (1996), b) comparison with Turck-Chièze et Lopes (1993)

$$\nu = \nu_0(n + l/2 + \alpha) - A\frac{l(l+1) + \delta}{n + l/2 + \alpha} \tag{1}$$

with

$$\nu_0 = \left(2\int_0^{R_\odot} \frac{dr}{c}\right)^{-1} \quad A = \frac{1}{4\pi^2}\left(\frac{c(R_\odot)}{R_\odot} - \int_0^{R_\odot} \frac{dc}{dr}\frac{dr}{r}\right) \tag{2}$$

α depending on the reflecting properties of the surface and δ on the internal properties.

This simple formulation has the advantage of showing correctly the role of the sound speed and is extremely useful for the identification of modes. It predicts that modes with the same degree and consecutive radial order are almost equally spaced, with a separation close to 135 μHz. This variable is called the great separation:

$$\Delta\nu = \nu(n,l) - \nu(n-1,l) \tag{3}$$

Of course, we know from the numerical frequencies deduced from a stellar pulsation code applied to the structure of a solar model (Christensen-Dalsgaard 1982) that the approximation of a constant value is rather crude and that the frequency dependence is much more complex. This is confirmed by the observations. Figure 2 shows what we get for GOLF, in comparison with two models. The general trend is the same for the models and for the real sun, and could be well understood in a second order approximation of the asymptotic behaviour (Lopes and Turck-Chièze 1994) where the effect of the outer layers of the Sun is explicitly present.

In this approximation, the expression (1) is replaced by the following:

$$\nu_{l,n} = \nu_0(n + L/2 + \alpha(\nu)) + (\gamma_t - 1)\frac{L}{\pi} - \frac{1}{4\pi^2\nu_{l,n}}[A_t L^2 + 2\Psi_t] \tag{4}$$

In this expression, $\alpha(\nu)$ is the phase shift of the waves at the surface of the Sun, which depends on the frequency, $L = l + 1/2$

$$\gamma_t = \frac{2\pi\nu_{l,n}}{L}\int_0^{r_t} \frac{dr}{c} \tag{5}$$

A_t is an extension of the variable A, including the lower turning point in the integral. Ψ_t introduces the effect of the gravitational potential, not included in the first order approximation and the physics of the most external layers which determines the acoustic potential of the waves (see Lopes and Turck-Chièze 1994 for a complete description of the variables).

In this framework, the effect of the partial ionisation of helium and hydrogen clearly appears at low orders and is the physical interpretation of the oscillating shape. In this region, one may notice the precise agreement between GOLF data and models including the Livermore equation of state. At higher orders, above n=20, one may distinguish the residual of

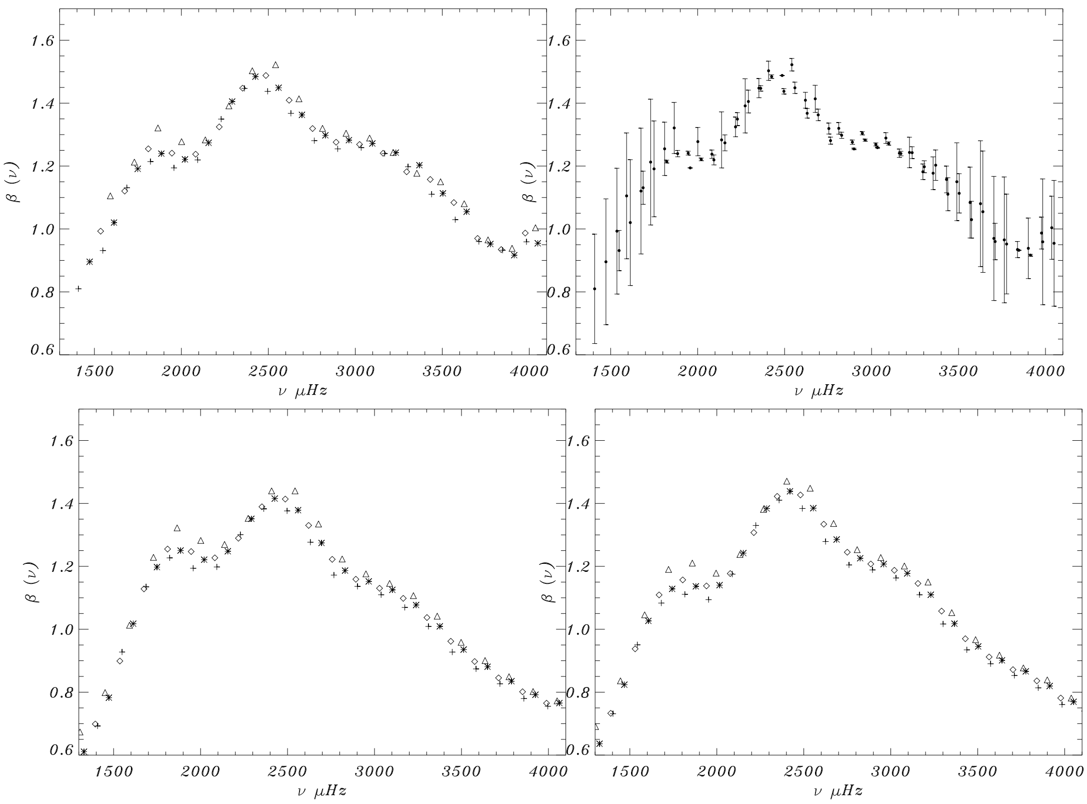


Fig. 3. Frequency variation of $\beta(\nu)$, calculated using modes with degrees smaller than 4 with the following convention: $\ell = 0$ $(+)$, $\ell = 1$ $(\star)$, $\ell = 2$ $(\triangle)$ and $\ell = 3$ $(\diamond)$. a) for GOLF data, b) the same including experimental error bars, c) for the model Christensen-Dalsgaard et al (1996), and d) for the model of Turck-Chièze and Lopes (1993).

the influence of the very external layers, which better reproduces the data when the difference in absolute value of the frequencies is smaller (model Turck-Chièze and Lopes 1993), even if the detailed physics is not handled completely.

Another way to emphasize the region of partial ionisation of the light elements has been introduced recently in considering the derivative of the phase shift of the global acoustic oscillations. This variable β is generally used to describe the outer layers from high degree modes but a generalized formalism has been developed in order to reach similar information from low degree modes (Lopes and Turck-Chièze 1994). In the second order approximation, the definition of β is the following:

$$\beta_{l,n} = -\nu^2 \frac{d}{d\nu}\left(\frac{\alpha(\nu)}{\nu}\right) + \frac{1}{\pi^2\nu}\Psi\left(\frac{L}{2\pi\nu}\right) \tag{6}$$

In practice, one can obtain a simple estimate of the first term from a list of frequencies, by using a clever determination of the derivatives. Of course the result is shifted from the usual value of this parameter by the effect of the gravitational potential (see Pamyatnykh, Vorontsov and Däppen 1991):

$$\beta(\nu, l) = \frac{\omega - n(d\omega/dn) - L(d\omega/dL)}{d\omega/dn} \tag{7}$$

with $\omega = 2\pi\nu$.

Figure 3 shows that GOLF may provide such information rather properly (except for l=3 fig. 3b, even if the errors seem overestimated) and that the results are in good agreement with solar modelling, in absolute values and shape. One sees, even more clearly than in the prevoius case, the oscillation, directly connected to the variation of the adiabatic exponent, which is nicely reproduced by the Livermore equation of state in the model of Christensen-Dalsgaard et al (1996). The two limits of this function are of course difficult to derive, owing to the poor quality of the derivatives. Once more, the region above 3 mHz, sensitive to the description of the atmospheric layers and the treatment of the superadiabatic region, needs to be improved, but is better reproduced by the second model.

This variable would be particularly useful in deriving the external properties of stars, for which only the global oscillations can be observed (Lopes, Turck-Chièze, Michel and Goupil 1997).

The most simple indicator of the inner solar structure of the Sun is the small separation:

$$\delta\nu = \nu(n, l+2) - \nu(n+1, l) \tag{8}$$

which depends on the second term of the expression (1) and consequently puts some constraint on the derivative of the sound speed near the core. This variable is drawn in figure 4. It shows that the present solar models including microscopic diffusion are in very good agreement with the general observed trend, even if one notices some small oscillation of the data for which we have no interpretation. In fact, this variable is, nowadays, not enough informative on the detailed description of the core.

In summary, we see that direct comparisons are useful in examining the quality of the measured data and serve to demonstrate the real accuracy

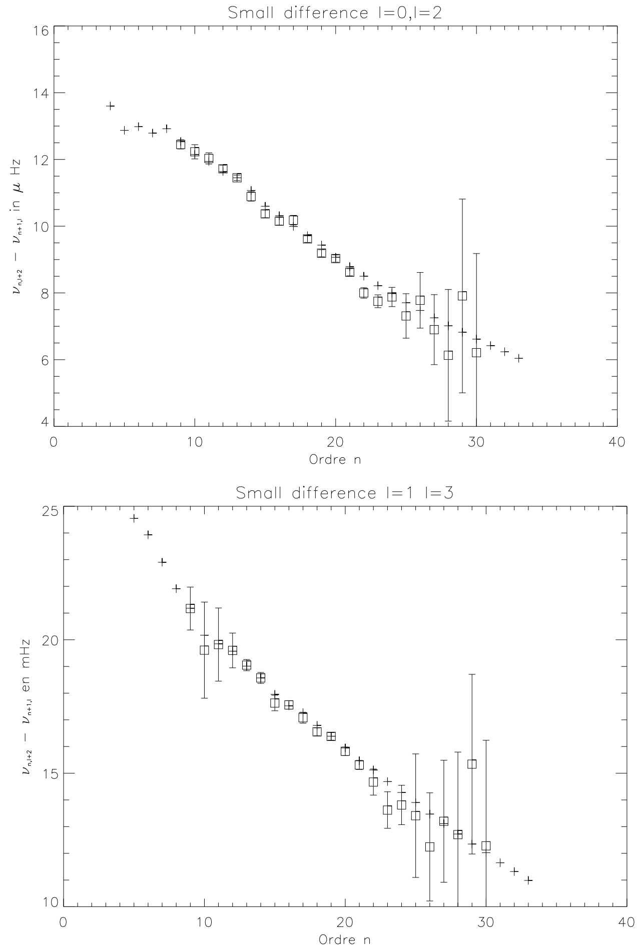


Fig. 4. Small separation for l=0,2 a) and for l=1,3 b). GOLF observations are represented by squares with error bars and the theoretical predictions from the solar model of Christensen-Dalsgaard et al (1996) by crosses.

achieved. Comparing the present data with numerical calculations of acoustic frequencies shows that the progress made in recent years on the physical processes: composition, opacities, equation of state, coulomb effect and microscopic diffusion, is successful, even if the description of the external layers is not yet totally reliable. This conclusion is important before trying to extract information coming from the solar core.

For all of these indicators we have really focused on the solar core. In fact, in order to investigate the small effects of the solar core physics on acoustic mode frequencies, inverse analyses of the frequencies are required.

4. Determination of the internal sound speed

The first inversion of the GOLF data has been carried out combining the preliminary GOLF data set corresponding to a period of about 4 months beginning on April 11th 1996 (Lazrek et al 1997a, Grec et al 1997) with the LOWL data for the period of February 1995 to February 1996 (Tomczyk *et al* 1995), which is the most precise list of acoustic mode frequencies available today. For this inversion, the GOLF dataset has been limited to the range 1.5–3.5 mHz, to match the frequency range of data available at degree greater than 3.

The results of this inversion have been published in Turck-Chièze et al (1997) and Gabriel et al (1997), and is in good agreement with the results obtained by the combination of BiSON and LOWL (Basu et al 1997c).

The accuracy reached for the internal sound speed in such an inversion is impressive and justifies trying to investigate the role of the different parts of the Sun on the solar core profile, in particular the role of the description of the outer layers which are not totally well described up to now (see above). This analysis is under study and will be discussed elsewhere.

It is the first time that such a complete list of frequencies is available in so short period of time (8 months instead about 3 years for the low frequencies). This is a very important aspect when determining the variation of the frequencies with the solar cycle (Libbrecht and Woodard 1990). Even if this is small at low frequencies, it will be important to try to measure it. So, we first focus on the quality of the determination of the frequencies and their error bars in order to see whether the data set is free from residual perturbations, such as that due to stochastic excitation or other processes. The previous study on the seismic indicators has shown small dispersion in the frequencies. We first look at the global data sets: GOLF and LOWL to see the consistency and the scatter of the data to study afterwards their impact on the inversion.

Asymptotically p-mode frequency differences between a model and the real Sun can be expressed as the sum of three functions:

$$S_{nl}\frac{\delta\omega_{nl}}{\omega_{nl}} \simeq \mathcal{H}_1(\omega/L) + \mathcal{H}_2(\omega) + \frac{\mathcal{H}_3(\omega/L)}{\omega^2} \tag{9}$$

Here the scaled term S_{nl} is related to the mode inertia, and $L = l + 1/2$. The functions $\mathcal{H}_1$, $\mathcal{H}_2$, and $\mathcal{H}_3$ can be obtained from a weighted least squares fit to the data. In Christensen-Dalsgaard, Gough & Pérez Hernández (1988) and Christensen-Dalsgaard, Gough & Thompson (1989) only $\mathcal{H}_1$ and $\mathcal{H}_2$ were considered. However the inclusion of the function $\mathcal{H}_3$ for low degree modes improves significantly the asymptotic fit and the corresponding inversion for the sound speed differences in the core (Pérez Hernández and Christensen-Dalsgaard, 1997). Here we shall use equation (9) as a preliminary analysis of the non-asymptotic sound-speed inversions showed below.

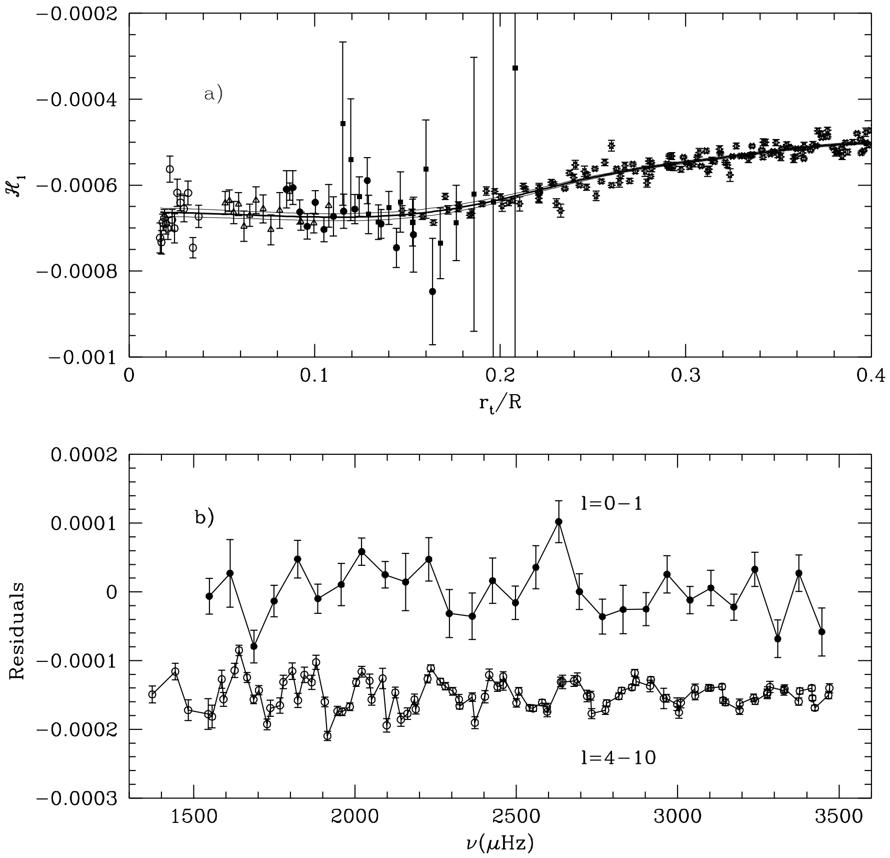


Fig. 5. a) Expression of the variable H1 with the following convention: l=0 open circles, l=1 open triangles, l=2 full circles, l=3 full squares, LOWL data: stars. b) Residuals of the asymptotic fit for the mode degrees indicated. Those with $l = 4 - 10$ have been displaced downwards for clarity.

In figure 5a), we represent the function $\mathcal{H}_1$, using the solar model of Christensen-Dalsgaard et al (1996) as a reference and the data coming from GOLF and LOWL instruments:

$$S_{nl}\delta\omega_{nl}/\omega_{nl} - \mathcal{H}_2(\omega) - \mathcal{H}_3(\omega/L)/\omega^2 \tag{10}$$

The solid line is $\mathcal{H}_1$ as function of the turning point r_t, defined by the asymptotic equation $r_t/c_t = L/\omega$. The thin lines correspond to the errors in this quantity derived from a Monte Carlo simulation. Also shown are the data points with the corresponding observational errors.

One notices firstly the good agreement between the LOWL and GOLF data even if they did not correspond to exactly the same period of time.

This justifies performing the inversion with these two combined sets of data. This favorable situation is probably due to two factors: the two instruments measure Doppler displacement velocities (see discussion of Toutain et al 1997 on the difference velocity/intensity) and the two measurements are very close in time around solar minimum, where the outer layers are reasonably stable.

Secondly, we note that the sound speed differences are related to the derivative of $\mathcal{H}_1$ with respect to L/ω. It can be seen that $\mathcal{H}_1$ decrease from $0.4R_\odot$ to $0.1R_\odot$ corresponding to negative sound speed differences; the maximum negative slope (and hence minimum sound speed differences) is around $0.2R_\odot$. From $0.1R_\odot$ to the centre, $\mathcal{H}_1$ is almost flat, corresponding to sound speed differences close to zero.

Finally, figure 5 a) shows that the scattering in the GOLF data seems sometimes larger than the formal errors derived, even if some other error bars seem overestimated. This allows an assessment of the reality of the almost flat solution from $0.1R_{\{}odot$ to the centre.

A further insight can be found by plotting the residuals of the asymptotic fits for the $l = 0, 1$ modes that penetrate in this region. These are shown in figure 5 b). It can be seen that they are not randomly distributed. At low frequencies there is an oscillatory component which seems also present for modes with $l = 4 - 10$ and hence could correspond to sun-model differences located in a layer above the turning point of the $l = 10$ modes.

After this preliminary analysis, a complete inversion has been performed. Although our main goal is to probe the structure of the core, the inversion requires that modes of higher degree be included, in order to correctly account for contributions from the outer parts of the Sun to the observed frequencies. The preceding analysis has demonstrated that there is good agreement between the GOLF and the LOWL frequencies in the region of overlap. Thus we use the GOLF frequencies for $l = 0 - 3$ and the LOWL frequencies for $l = 4 - 99$; in the latter case the data were restricted to modes with frequency $\nu \leq 3500 \mu Hz$.

The inversion was carried out by means of the Subtractive Optimally Localized Averages Technique of Pijpers & Thompson (1992). The frequency differences were expressed in terms of the differences $\delta c^2/c^2$ and $\delta\rho/\rho$ in squared sound speed and density, and the inversion was carried out to infer $\delta c^2/c^2$. Details of the implementation were provided by Basu et al (1996a and b). Any inversion for solar structure must correct for the contributions to the frequency differences from the near-surface region (see also Fig. 1). This requires access to modes in the required frequency range for a substantial range in degree. For this reason the inversion had to be restricted to modes below $3500 \mu Hz$, where LOWL frequencies were available, even though the GOLF data extend to higher frequencies. Model S of Christensen-Dalsgaard et al. (1996) was used as the reference model.

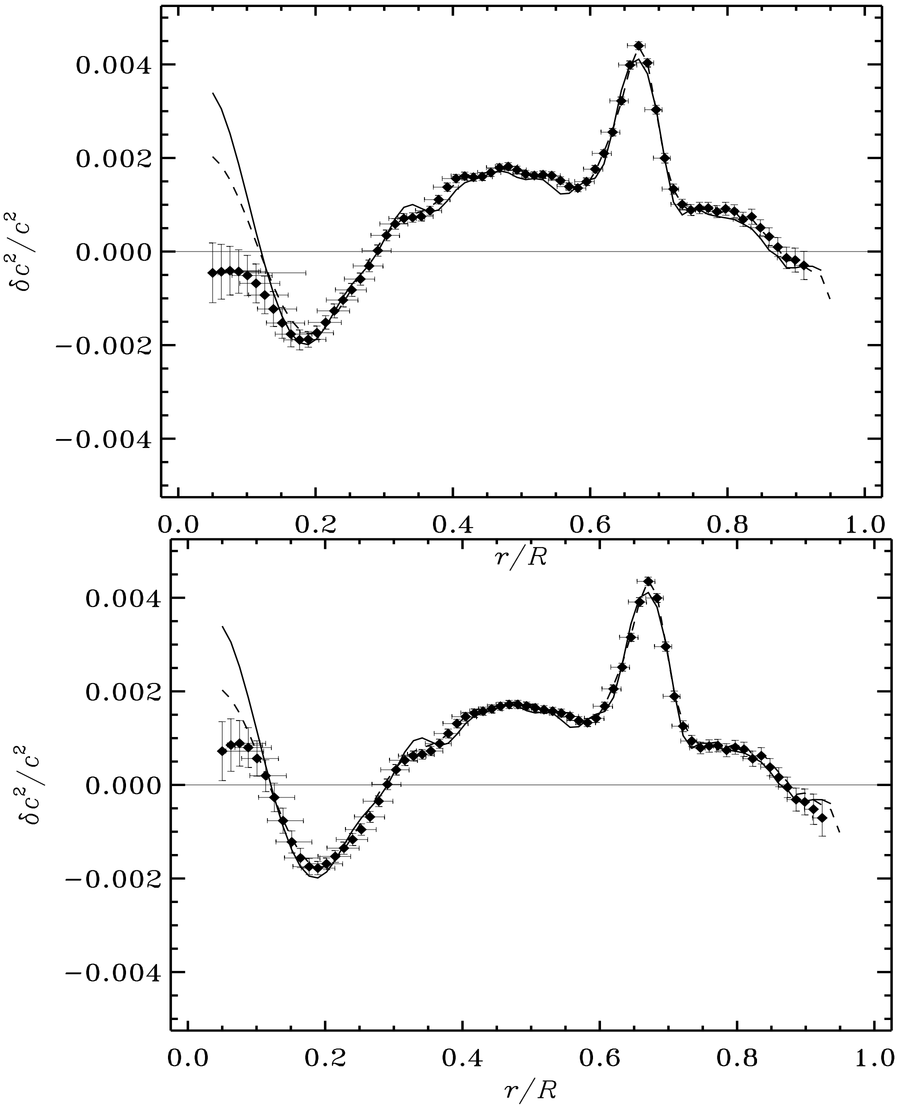


Fig. 6. Difference between the square of the sound speed in the Sun and in Model S of Christensen-Dalsgaard (1996), in the sense (Sun) - (model). The vertical bars indicate one σ errors in the inferred differences, while horizontal bars provide a measure of the resolution of the inversion. For comparison, the solid line shows the results obtained by Basu et al (1997c) from analysis of a combination of BiSON and LOWL data, while the dashed line shows the results obtained with just 4 months of GOLF data, combined with LOWL data (Turck-Chièze et al. 1997). a) for the GOLF frequencies of Lazrek et al (1997b) b) idem excluding some anomalous points

Figure 6 a) shows the result of the inversion, using the table of Lazrek et al. (1997b). In the figure are superimposed the previous determination of the sound-speed difference obtained with 4 months of data (Turck-Chièze et al 1997), as well as results obtained by using BiSON data in combination with LOWL (Basu et al 1997c). The results are very nearly the same except below 0.1 $R_\odot$ where only $l = 0$ and 1 may penetrate. In order to check the influence of the data and their errors, we have performed another inversion, using a subset of the complete set of GOLF frequencies where we have extracted about 10 points which are far from the general trend (figure 6 b). This confirms that the solution below 0.1 $R_\odot$ is extremely sensitive, even to changes involving just a few modes.

It is evident from the figure that the sound-speed difference in the inner core is still somewhat uncertain; the differences between the different solutions may well reflect the difficulty in determining properly the frequencies to the level of accuracy that we need. It is clear that with a longer series and the use of the total range of frequencies, one may improve the situation. Even so, it is remarkable that we are able to obtain measurements of conditions in the inner core of the Sun with a precision of a few parts in a thousand.

5. Discussion on the physical processes

With only 8 months of data, we are able to confirm using GOLF the profile of the sound speed obtained with the best ground-based systems, at least down to 0.1 $R\odot$. It appears clear that GOLF data contributes in determing this profile in considerable detail. Through helioseismology, we are now on the threshold of important new investigations of the physics of the solar core. This is extremely important in order to get an astrophysical answer in the problematic of the neutrino puzzle. In this section, we compare the solar sound speed with theoretical values corresponding to different solar models, calculated in different centres, in order to note the sensitivity to some ingredients of solar modelling. In all these models, the microscopic diffusion is included.

One important ingredient of the neutrino predictions is of course the description of the nuclear reaction rates which produce these neutrinos. It has been shown that the predicted neutrino fluxes has still a greater sensitivity to this part of the calculation, due to the difficulty in determining cross sections with better than 10% accuracy (Dzitko, Turck-Chièze, Delbourgo-Salvador, Lagrange 1995). We compare in figure 7 the present GOLF inferred solar sound speed (figure 6a) with the sound speed corresponding to models where we have modified the pp reaction rate by +5% or the $(^3He,^4He)$ by -30% (equivalent to +10% on $(^3He,^3He)$ astrophysical factor) in order to simulate what we have previously called “ the minimal nuclear solar model”. This means a model, compatible with the present knowledge of the nuclear reaction rates, but which minimizes the neutrino fluxes (Dzitko *et al* 1995, Turck-Chièze 1996). In the case of ($^3He,^4He$) reaction rate, we have multiply by 3 the uncertainty to simulate the complementary ($^3He,^3He$) reaction rate and also amplify a very small variation (except in the real centre).

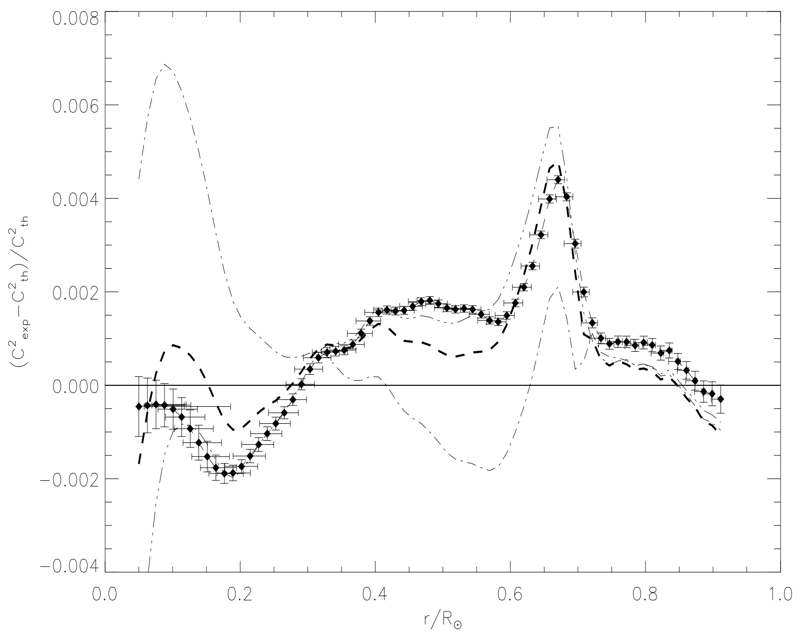


Fig. 7. Sound-speed difference between the Sun (GOLF + LOWL acoustic mode frequencies) and different solar models for the present list of GOLF frequencies (Lazrek et al 19 97b). Continuous line with error bars: reference model of Christensen-Dalsgaard (1996), − − − Saclay model using CESAM code: Brun et al 1997, -.- idem with pp reaction rate modified by + 5%, −...− idem with the reaction rate ($^3He,^4He$) reduced by 30%.

The effect on the sound speed is clearly visible for a 5% variation of the pp reaction rate, even if such modification of the nuclear core affects the value of the frequencies by no more than $0.5\mu Hz$ in absolute values (Brun *et al* 1997). However, any reasonable modification of the other reaction rates of the pp chain will be difficult to detect, due the small variation of energy induced or because they do not influence the luminosity.

A second discussion is illustrated by the figure 8. On this figure, we first compare three solar models to show that slight modifications of the physical processes influence of course the sound speed profile (Christensen-Dalgaard et al 1996, Morel, Provost, Berthomieu 1997, Brun et al 1997). Then, one examines the effect of the readjustment of the structure, or how a difference observed in the intermediate region between the nuclear and the convective

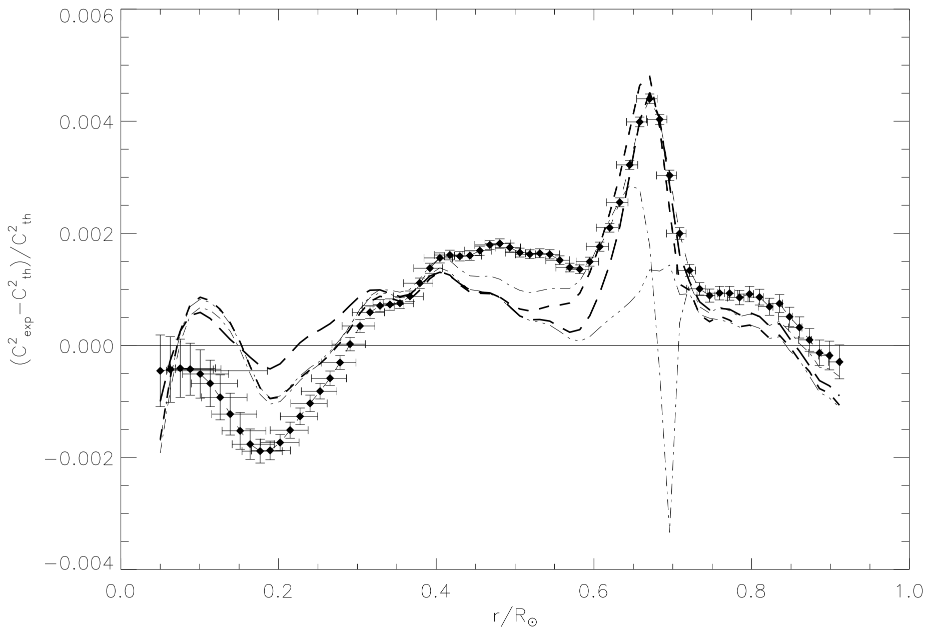


Fig. 8. Difference between the square of the solar sound speed and several solar models, continuous line for the model of Christensen-Dalsgaard et al (1996) — — — for Brun et al 1997, *large* — — for Morel, Provost, Berthomieu 1997, —...— for a model of Brun et al including a large effect of penetrative convection, —.— for a model of Brun et al including a variation of opacity of +5% for temperature between 2.4 and 2.8 10^6 K.

zones may influence the profile of the solar core. A pronounced peak at about 0.67 $R_\odot$ is observed on the different solar models. We have checked that this is not a signature of a variation of the adiabatic exponent in the region of partial ionisation of the CNO elements, since their composition is too small. We show in this figure that it cannot be only the signature of convective penetration (Zahn 1991), since it is too broad. In fact, it could be a signature that the microscopic diffusion is not correctly handled. Effectively, at the base of the convective transition, oxygen plays a crucial role by the bias of the opacity coefficients, so that the rather broad peak observed could be a signature of a not totally known composition of CNO (including effect of the diffusion) at this region of the Sun. We can argue, following fig. 32 of Turck-Chièze et al (1993) that it begins at the position where the opacity increases due to bound-bound contribution processes of this element. Of course the opacity coefficients of heavy elements (iron, neon, oxygen) play a crucial role in the whole intermediate region (Courtaud et al 1990, Tripathy, Basu and

Christensen-Dalsgaard 1997). The figure shows that an opacity modification of the order of 5% may be sufficient to remove this peak. We cannot exclude that other small inflections of the sound speed profile are the signature of some other heavy elements. So one may find in the present profile of the sound speed some constraint to better quantify or verify the best microscopic calculations. One observes in this crude correction of opacity how the solar difference in the core reacts and one needs to keep in mind that the present radial core profile is largely dependent on the profile derived between 0.2 and 0.7 $R_\odot$. Of course, one cannot exclude that some effect of the rotation (not introduced presently) may also contribute to the present observed shape.

6. Conclusion

First results of the GOLF space observations give today a detailed profile of the sound speed in the inner core of the Sun. We have tried to demonstrate in details the direct impact of the present accuracy of the acoustic frequencies measurement, on what we learn on the solar structure. It seems, that the main limitation today on this precision is no longer the instrumental noise, and not really the solar "noise", as far as the acoustic modes are concerned, but is due to the stochastic character of the excitation, which the Fourier transform analysis techniques are unable to treat completely. The sound speed profile discussed here is not in contradiction with the previous results from ground instruments. The available range of frequencies is enlarged, even if, in this first study a combination of GOLF data with ground-based LOWL data from a not full coincident epoch, has not exhibited this improvement. We can hope in the near future to examine the solar core with a far greater precision, when the two complementary instruments GOLF and MDI are ready to carry out a combined very precise inversion using the whole range of frequencies available and exactly the same period of time.

Today, at a level of several 10^{-4}, extensive studies of bias are being examined, including the role in the analysis of the precision of frequencies, the procedure of inversion, but also the interpretation of the resultant sound-speed profile in terms of physical processes. This important area of feed-back may contribute to extend the classical framework of solar modelling.

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