GLOBAL LOW FREQUENCY ACOUSTIC MODES AFTER HALF A SOLAR CYCLE ABOARD SOHO: AN IMPROVED VIEW OF THE NUCLEAR CORE

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ABSTRACT

Solar global oscillations have now been measured for more than 20 years. The study of these modes has contributed to improve, along time, the description of the solar core. We have now a proper access to this part of the Sun, with ground networks observing for more than 10 years and the three instruments aboard SOHO in a quasi continuous mode for now half a cycle. In this talk, we show the advantages of *the global acoustic modes measured at low frequency.* They are due to their longer lifetime and the reduced influence of the turbulent and variable surface effects. As a consequence, we have converged last year, after 30 years of unsucess, to a boron-8 emitted neutrino flux in perfect agreement with the better understood detection of these neutrinos on earth. *The splitting at low frequency is also now properly determined* but the extracted rotation information is still limited in the core. It contains nevertheless the first dynamical vision of this part of the radiative zone. We will focus on it up to the end of the SOHO mission, together with *the gravity mode region* and the *possible internal signature of the magnetic field.* Some limits are given on these observables. Further improvements of their detectability are under study and will be mentioned.

1. INTRODUCTION

Seismology is really entered in its golden age. Solar global acoustic oscillations (degrees ℓ= 0,1,2) are mainly used up to now, to probe the solar core below 0.3 R$\odot$ through the sound speed, and more recently through the density profile, using frequencies of higher degrees to explore the more external parts. In this perspective, the low frequency domain is particularly useful as the corresponding cavity is less influenced by the variable surface (see section 2). Up to now, we have explored the classical physics of the solar core through sound speed and density profile and deduced neutrino predictions (section 3). Now, our activities are turning toward dynamical effects with rotation profile (section 4) and the search of gravity modes (section 5). Of course the future is oriented to stellar asteroseismology (MOST, COROT, EDDINGTON), so it is also important to note that the solar global modes, measured on a large range of frequencies contain the whole information from the surface to the central region and represents a unique case, extremely useful, for extending our expertise on the internal structure of other stars. We are also preparing a successor of GOLF called GOLF New Generation (section 6).

2. THE QUALITY OF THE LOW ORDER ACOUSTIC MODES

Three seismic instruments are present aboard SoHO (GOLF, MDI, VIRGO). So, we are able to do a lot of comparisons of the different methods and of the level of noise of the different instruments at different frequencies (Toutain et al. 1997, Bertello et al. 2000). It appears clearly that the Doppler velocity measurement is an excellent way to measure acoustic modes, probably because the measurements are less perturbed by the very turbulent level of the photosphere and also because the very low noise stability (at a level of some 10^{-6}) is only required on a very small time scale (currently several ten seconds). The low frequency part of the acoustic spectrum, typically below 2.2 mHz are known to be less sensitive to the surface effects due to the position of the external turning points of these modes, so they are less sensitive also to the variability of the solar cycle (García

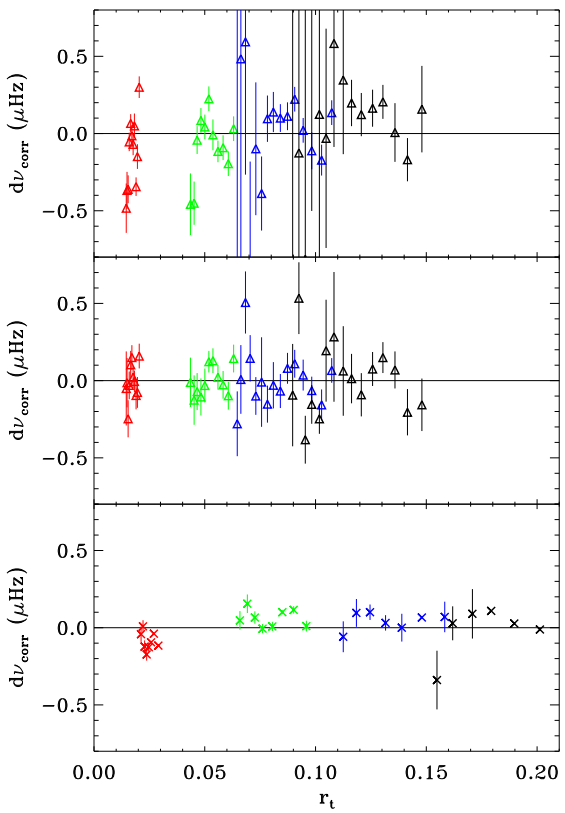

Figure 1. Difference between measured frequencies with GOLF and theoretical ones versus internal turning point, after a removal of the surface uncertainty. The upper figure corresponds to acoustic modes l=0,1,2,3 for n> 15 and 1 year of integration, the secund to the same modes but for 5 years of integration, the last one to the acoustic modes with order n < 16 and 5 years too.

et al. 2001). An other point is illustrated by Figure 1 where we compare the difference between three data sets obtained with the GOLF instrument and the theoretical values, after release of the surface effects. We notice that the first frequency determination is very uncertain and dispersed, it corresponds to one year of integration and modes $\ell = 0, 1, 2, 3$ of order n > 15. This situation is improved after 5 years of continuous integration (central figure). We notice a real improvement for the frequencies corresponding to n < 16 ($0.5mHz < \nu < 2.2$ mHz, lower figure, 5 years too). It is due to their corresponding longer lifetime. In a future spatial experiment, the time of integration can be reduced if the ratio signal/noise is improved. The amplitude of these modes are rather small (some mm/s).

So, the low order global acoustic modes (low frequencies) are extremely useful to improve the accuracy of the core: they vary less with the solar cycle and are less uncertain due to their increased lifetime. But they also penetrate less in the core, we need to measure a large number of them to do the inversion: it is the case for the Sun with SoHO. A reduction of the solar noise will permit to get them quickly.

3. THE CLASSICAL PHYSICS AND THE SOLVING NEUTRINO PUZZLE

We have gained a factor 20 on the agreement between the observed and the theoretical sound speed in 10 years. This factor comes from both sides. The observations have been improved by the extension to low frequency and their duration so the number of useful global modes has been multiplied by a factor 2. On the theoretical part, improvements along last decade have appeared step by step and touch all the ingredients: microscopic diffusion, iron abundances, bound-bound opacity calculations for a lot of elements, relativistic effects in equation of state, nuclear reactions and associated screening effects. Helioseismology has pointed problems as photospheric helium, base of the convective zone, lithium destruction, and the range of accuracy useful for each variable. At the end, we have succeed to get on both sides a satisfactory level to constrain the boron neutrino flux, largely dependent on the central condition as Tc^{24}, by seismic models. These models go slightly further than standard models, in adjusting some ingredients inside their uncertainties. We get an emitted flux in $10^6 cm^{-2}s^{-1}$ of 4.95 ± 0.72 (Turck-Chièze et al. 2001) in perfect agreement with the better understood detection of these neutrinos on earth by SNO. They succeed to measure the different types of neutrinos coming from the Sun. Their sum is 5.17 ± 0.64 from elastic scattering $\nu_x + e \rightarrow \nu_x + e$ and charge current interaction with deuterium $\nu_e + d \rightarrow p + p + e$), or 5.09 ± 0.64 from neutral current $\nu_x + d \rightarrow \nu_x + p + n + \nu_x$ (Ahmad et al. 2001, 2002).

This double convergence puts a end to the solar neutrino puzzle, giving strong evidence on a transformation of some neutrinos in a different savor. This beautiful conclusion after 30 years of efforts on astrophysical and particle physics sides does not permit yet to put constraints on the neutrino masses.

The final step may include a knowledge of the internal magnetic field. Presently, we stay at the level of a classical view of the solar core, supposing that the dynamical effects, if existing have few effects on the central structure. We have only verified that a magnetic field localised at the frontier of the nuclear core even large (several tens MG) has a few impact on the present structure and on the boron neutrino flux (4%), if we consider the effect of the magnetic pressure (Couvidat et al. 2002).

4. THE ROTATION PROFILE

Progress beyond this classical picture comes from information on rotation and magnetic field. It is well known that the splitting of the low degree modes are more difficult to extract than the centroid frequencies. This is mainly due to the role of the stochastic excitation or possible variation with the more external magnetic field, for modes of frequencies greater than 2 mHz, acting on differences of about 400 nHz which are not very large in comparison with the apparent widths of the modes. It is clearly visible if

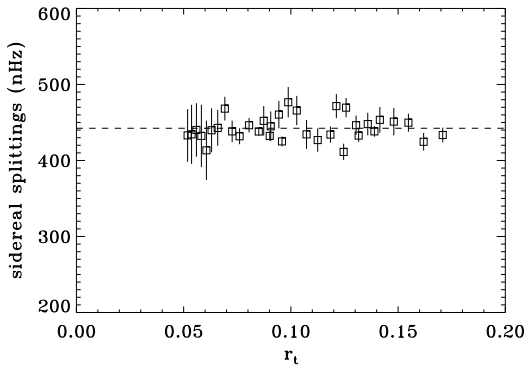

Figure 2. Sidereal splittings extracted from 5 years of observations by the GOLF instrument expressed in term of their inner turning points

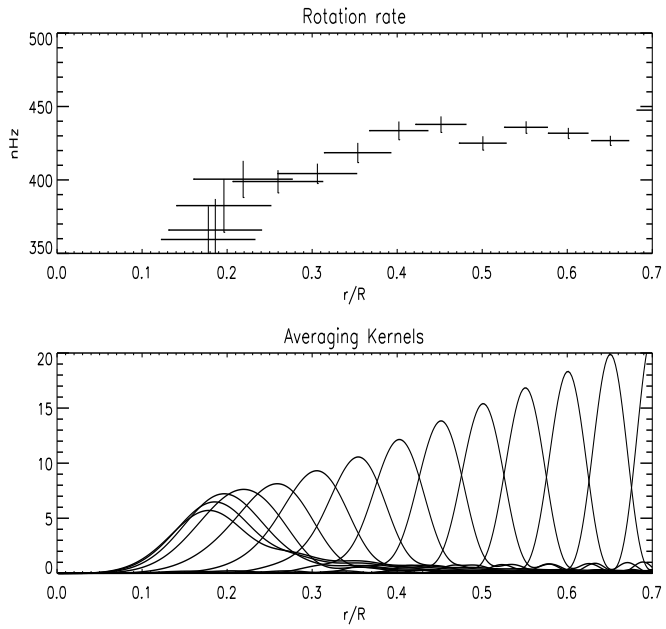

Figure 3. Extraction of the rotation in the core with the resolution kernels

we compare figure 2 corresponding to about 5 years of GOLF observation to figure 8 of Bertello et al. (2000) for two years. In the present figure we extend our database down to $\ell = 1$, n=7 with 10 splittings below 2.2 mHz. In the low frequency range, the peaks are sharp and well defined and present practically no variation along time. We can observe a relatively flat answer slightly below the external value of the equatorial splitting (about 460 nHz). Such behaviour is also observed with longer integration time for the ground observations of BiSON (Chaplin et al. 2001) and IRIS (Gelly et al. 2002). Such proper extraction allows new inversions in the solar core. Preliminary works have been performed using 1D inversion and two different methods (OLA: Corbard et al 1998; OMD: Eff-Darwich & Pérez-Hernández 1997). Figure 3 shows one of these inversions for the first method, the associated resolution kernels and the corresponding error bars. They are still large and the extraction of the two calculations does not allow to penetrate below 0.15 $R_\odot$. We note that the result and the errors bars are still sensitive to the trade-off between resolution and error bars which is fixed by the choice of a regularization parameter. A decrease in the core for the equatorial rotation is not excluded in the different calculations even it is less visible in the estimate of the second method.

This work must be pursued in 2D inversion to really see the effect of latitude coming from the surface, even we measure here only sectoral modes for global modes. It is also useful to see the influence of the intermediate degrees in the inversion (here LOWL for the shown result and MDI for the other one). The present results are consistent with previous work (Gavryusev, Gavryuseva and Di Mauro 2001) even the present splittings are slightly improved. New results will be extracted from a common study of GOLF+MDI for the low frequency global acoustic modes. The present interesting tendency may help us to put constrains on central magnetic field or on the evolution of the angular momentum due to very low frequency gravity modes.

5. THE GRAVITY MODE SEARCH IN THE HIGH FREQUENCY DOMAIN

This simultaneously study will probably extend the range of splitting accessible at low frequency but this will not allow to penetrate deeper in the core. Clearly in the case of rotation or even magnetic field, the best way to progress on the central conditions is to detect gravity modes. A lot of tentatives have been done since the launch of SOHO to detect them (see dedicated contributions in SOHO 8 and SOHO 10 proceedings). Two papers have given some limits of detections for the search of single peaks: about 1 cm/s after two years (Appourchaux et al. 1999) and about 6 mm/s after 5 years (Gabriel et al. 2002).

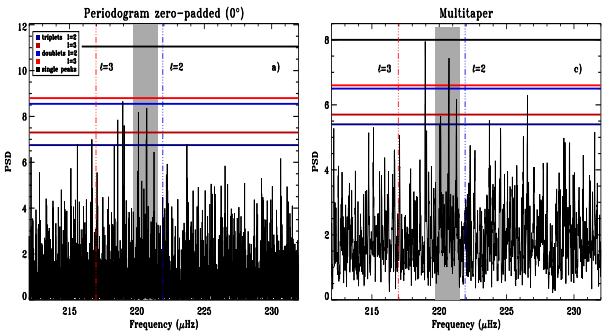

Figure 4. a) Periodograms of 1290 days with 3-times zero-padding, centered on the $\ell = 2$ n=-3. b) Multitaper estimate. The 90% confidence levels are mentioned for single peaks, doublets and triplets The grey area corresponds to the region where a structure has been identified in one or several methods.

Another strategy is under study with the GOLF data (Turck-Chièze et al. 1998, 2002; Gabriel et al. 1998) looking for multiplets to improve the confidence level to detect very low candidates. This search has been limited to the high part of the gravity modes range:

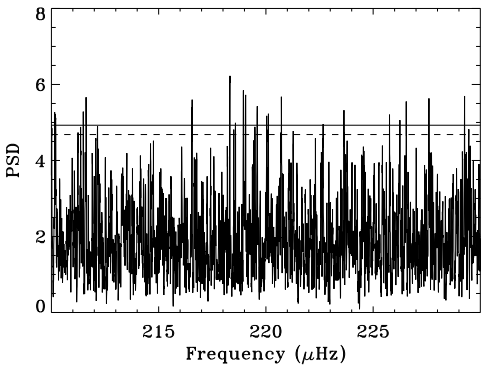

Figure 5. Detection of a quintuplet (full line) or sextuplet (dashed line) with more than 90% probability to contain signal after 2500 days of observation.

150 μ Hz -450 μ Hz which must contain the higher amplitude modes. These gravity modes are excited in the convective zone and not at the top of the radiation zone and cannot be responsable of the redistribution of the angular momentum but are already very interesting due to their sensitivity to the solar core and to the rotation of the very inner part. A complete statistical estimate has been performed in this range for different analysis as Fourier transform with 3-times zero padding and multitaper. In this strategy, we introduce some constraints on the splittings in the core compatible with the acoustic observations accepting a reduced rotation by a factor 2 or an increased of a factor 2: splittings between 200 nHz and 600 nHz (Provost et al., 1999). We detect several structures with more than 90% confidence level after 1290 days of observations (dominated by observation of the blue line). A more recent analysis with 2500 days of observations, dominated by the red line observations, that means higher in the atmosphere) continues to show structures but with less confidence level. We present them in figures 4 and 5 for the most interesting case around 220 μ Hz. In figure 4 we have detected a triplet with an adding large peak on the left. With a longer series, even the amplitudes are reduced it seems that we observe a quintuplet with more than 90% confidence level and an amplitude of about 2 ± 1 mm/s. A very interesting possibility is that we are seeing an $\ell = 2$ $n = -3$ gravity mode with 5 components and a splitting of about 600 nHz, supposing a decrease of the rotation followed by an increase in the very central core as suggested by Gavryusev et al., 2001) and a different orientation of the rotation axis. An other explanation is the detection of an $\ell = 5$ but we need to explain why GOLF could observed it better than MDI. Of course it could be also pure noise. So such detection must be confirmed by other instruments and (or) longer duration of observations. It is also astonished to observe the fine structure of this pattern which could show some interesting effect of the magnetic field as suggested by Thompson and Goode (1992). More details are given in Turck-Chièze et al. (2002).

6. FUTURE PROJECTS

The prolongation of the SoHO mission will allow to continue such observations with all the instruments together. We hope also to continue the GOLF observation on the blue line, which must increase the velocity of the signal. We are also preparing the next generation of instruments which could better attack the problem of the solar noise. In Europe, we will try to extract the Doppler velocity at different altitudes of the same line (Turck-Chièze et al. 2000), sensitive to different appearances of the granulation noise (d'Espagnat et al. 1995). We will also measure simultaneously the variation of the continuum. The hard points of this instrument is under study with the collaboration of the CNES, the french agency. The variable magnet allowing the exploration of the line in 8 points is already performed.

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