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MAIN LESSONS FROM GOLF/SOHO INSTRUMENT ON DYNAMICS OF THE RADIATIVE ZONE, FUNDAMENTAL PHYSICS AND ENERGETICS

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Abstract. The GOLF instrument aboard SoHO has reached its main objectives and reveals its power to constrain fundamental physics, energetics and dynamics of the radiative zone. The Standard Solar Model (SSM) is no more sufficient to interpret all the seismic observations of the solar radiative zone. We confront the main results of GOLF to models beyond the SSM assumptions. We discuss the missing processes and quantify some of them to build a more realistic view of our star. Present works on GOLF instrument are now turned on its capability to follow the solar activity and on a tentative to detect more gravity modes. All the results are useful for solar-like stars observed by COROT and KEPLER.

Keywords: helioseismology, sound speed, internal rotation, neutrinos, WIMPS, stellar modelling

1 Introduction

The SoHO satellite probes the Sun by acoustic modes with GOLF (Gabriel et al. 1995; García et al. 2005) and MDI (Scherrer et al. 1995) since more than 15 years. The GOLF instrument has been particular efficient to measure the low degree low order acoustic modes (Bertello et al. 2000; García et al. 2001; Gelly et al. 2002) and to detect the first gravity mode frequencies (Turck-Chièze et al. 2001, 2004; García et al. 2007, 2011). From these data, we deduce a sound speed profile and a rotation profile in the whole radiative zone.

On the other side, neutrino detections put other constraints on the solar core in total agreement with the helioseismic results, see the review of Turck-Chièze & Couvidat (2011) (TCC2011). The study of the gravitational moments shows also that the dynamical processes in the radiative zone cannot be forgotten (Duez, Turck-Chièze & Mathis 2011) and that the knowledge of the dynamics of the radiative zone depends on its history.

The Sun will stay for long the only star for which the internal radiative zone is known with such details even hopefully, thousand analogous stars begin to be studied by asteroseismology. We summarize here the main conclusions we have deduced from the analysis of the GOLF data.

1.1 Solar sound speed, density and rotation profiles in the radiative zone

The detection of the low order radial acoustic modes, that are not polluted by any surface solar cycle effect, has allowed a determination of the sound speed down to 0.06 $R_\odot$ with high accuracy (Turck-Chièze et al. 2001) in integrating 5 years of data. The inversion of these data leads to an extremely precise vertical error bar but a non negligible horizontal error bar (see Figure 1). The profile in the core has been strictly confirmed after 30 years of measurements on ground by the BiSON network for the low degree modes (Basu et al. 2009). Figure 1 (*left*) shows the absolute value of the sound speed in the core. Figure 1 (*middle*) compares the sound speed and the density profiles to two models: the Solar Seismic Model (SSeM), adjusted on the observed sound speed (Turck-Chièze et al. 2001; Couvidat et al. 2003) in slightly modifying the input physics, and the SSM that integrates the updated physics including the new photospheric CNO estimate. Both solve the classical structural equations along time.

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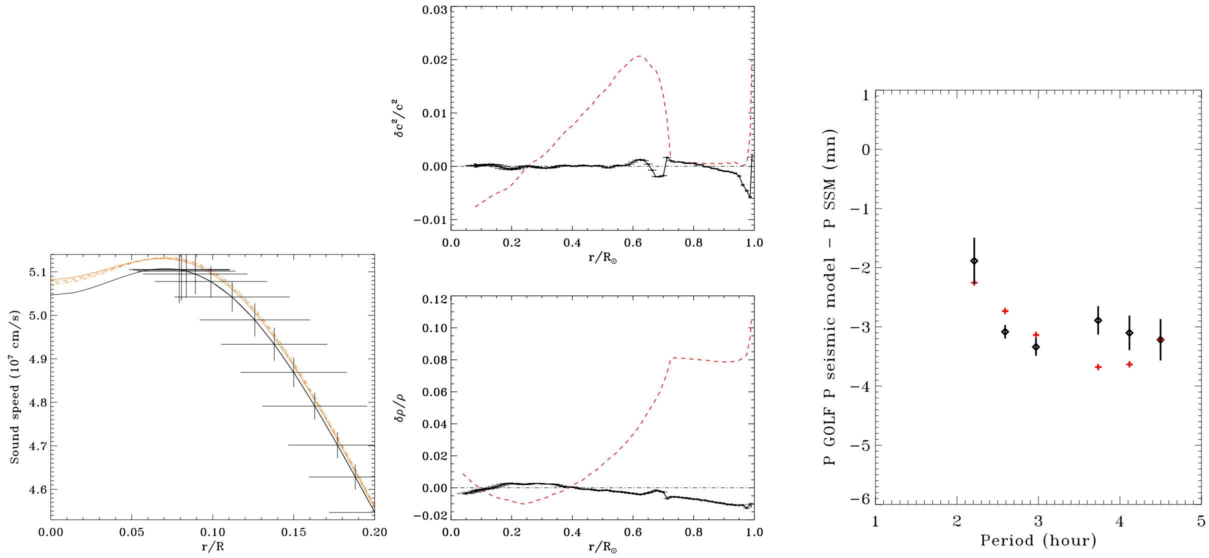

Fig. 1. Left: Zoom on the absolute value of the sound speed in the core, the vertical error bars are multiplied by 100 for their visibility. The extracted values are compared to the SSeM (in black) and to the SSM in orange + dashed lines for models with central luminosity increased by 2% and 5%. **Middle:** Differences in squared sound speed and density between GOLF+MDI/SoHO and solar model predictions. Seismic model: full line + seismic error bars, SSM model (−−). Both curves are from Turck-Chièze, Piau & Couvidat (2011). **Right:** Difference of dipole gravity mode periods between SSM and GOLF (diamonds with error bars) or SSeM (red crosses) and SSM. See also Turck-Chièze et al. (2011).

From the same seismic data plus the first detected dipole gravity modes (García et al. 2007, 2011), we can also extract the rotation profile (Figure 2, *left*) down to the same region in the core. The error bars are still large due to the small number of modes detected. The latitudinal effect must be confirmed by the detection of more splitting values which will improve such profile. Nevertheless one observes clearly an increase in the solar core that succeeds to a quasi flat rotation in the rest of the radiative zone.

1.2 A zoom on the solar core: neutrinos, gravity modes and dark matter

We have now a lot of information from this region: 5 neutrino detectors sensitive to different energy of neutrinos, more than 20 radial acoustic modes and at least 6 dipole gravity modes and the related splittings. It is important to notice that they all agree together through the predictions of the SSeM that has been built to reproduce only the sound speed of the whole radiative zone. Figure 1 illustrates this point comparing the absolute sound speed with models and the large period difference of the gravity modes between SSM and SSeM but the proximity of the observational values of GOLF (Figure 1 *right*) with SSeM. TCC2011 show also in their table 9 the excellent agreement between the prediction of the emitted neutrinos and the 5 neutrino detectors. The central temperature is strongly constrained by the boron neutrino flux and the central density by the gravity mode frequencies, so the solar values must be well reproduced by the seismic model values: $T_C = 15.75\ 10^6$ K and ρ_C $=153.6$ g cm^{-3}. This information is also useful for putting some constraints on the potential presence of dark matter (Turck-Chièze et al. 2011).

This seismic model has been extremely useful for its predictions but it is not a physical model of the Sun. It cannot predict any dynamical process that one needs to introduce in the radiative zone or at the surface. So step by step it will be replaced by more sophisticated model of the Sun.

2 The stars are rotating objects

For the first time, we get a complete solar internal rotation profile, so one needs to explore the transport of momentum due to rotation along stellar evolution. By chance, we also have some hints from other stars thanks to the splitting of their mixed modes for subgiant or red giant stars (Deheuvels et al. 2011; Beck et al. 2011).

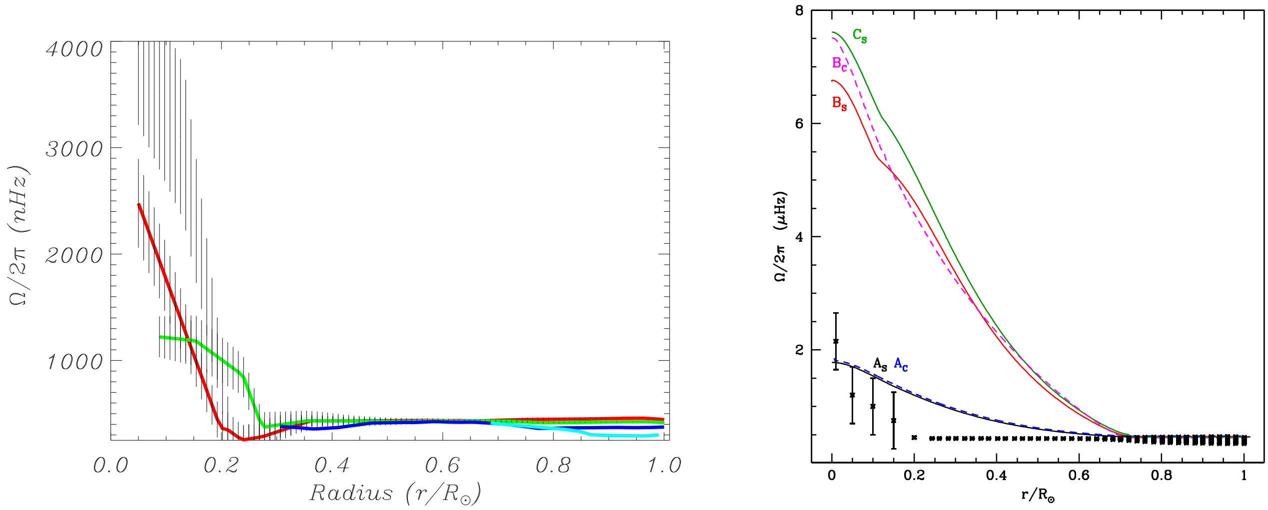

Fig. 2. Left: Radial rotation profile extracted from the first gravity dipole modes detected with the GOLF instrument and all the acoustic modes observed with GOLF+MDI. From García et al. (2011). **Right:** Comparison of the mean profile to different models (A, B and C) see text. From Turck-Chièze et al. (2010).

Let compare the obtained rotation profile to models including rotation and transport of rotation (Turck-Chièze et al. 2010). We have built several models to follow the time evolution of the rotation profile. In these computations, we have followed the internal structure of the premain sequence evolution corresponding to the decoupling of the star from the disk. We have built two classes of models. The first class (A) consists in purely academic models starting with a low rotation that evolves naturally toward the present external velocity of 2 km/s. The second class (B and C) has surface velocity of 20 to 50 km/s before the arrival on the main sequence and then are spin down by magnetic braking following the Skumanich (1972) law down to the present solar rotation. Models B and C are compatible with observations of Bouvier (2009). Our transport of momentum follows the prescription of Zahn (1992). The radial gradient of rotation is mainly established during the contraction phase, the first 45 Ma. Then the evolution of this profile is quite slow. Moreover, the meridional circulation associated to the rotation transport becomes quickly extremely slow in comparison with what one can observe in the convective zone. Figure 2 (*right*) illustrates our results. We note that the important gradient observed in the whole radiative zone, for models B (20 km/s at the arrival on the main sequence) and C (50 km/s) do not agree with the rotation profile observed by seismology. Models A agree better in the core but do not respect the observations of young stars nor the spin down observed along the main sequence. Moreover in the two kinds of modeling, one never reaches a flat rotation profile outside the nuclear core as it is well established now by MDI results (Korzennik & Eff-Darwich 2011).

So the progress done on the solar internal rotation profile by the detection of gravity modes coupled to acoustic modes is presently not understood. This year, asteroseismology adds new results: a gradient of about a factor 5 between core and surface in a subgiant star (Deheuvels et al. 2011) and a gradient of about a factor 10 in giants (Beck et al. 2011). These complementary observations are compatible with a slow transport effect along the main sequence coupled to an acceleration of the core rotation in red giants in comparison to the surface rotation. Such important results encourage certainly to go further on the dynamics of the radiative zone.

3 Young solar analogs, Missing Processes and Conclusion

The limitation of SSM appears also in its lack to model the young solar analogs. These stars are generally extremely active and their UV manifestation can be about 1000 times greater than the present solar activity.

As the internal rotation profile seems largely influenced by that stage of evolution, one needs to introduce the processes that are connected to that early activity. The energetic balance, in the SSM framework, is dominated by the nuclear production in the core and the transfer of energy by radiation. Part of the energy could be transformed through kinetic energy, magnetic one during the early stage where the Sun was mainly convective. Moreover the comparison between the central conditions of the Sun, verified by neutrinos and gravity modes, and the external luminosity let place for small difference of several per cent which cannot be understood inside the assumptions of the SSM where radiative transfer is instantaneous.

Using young stellar analogous of the Sun and their time activity evolution laws, a greater initial mass than the one of the present Sun is possible, this produces an increase of luminosity with important consequences for the formation of planets. See Turck-Chièze, Piau & Couvidat (2011).

The building of dynamical models of solar-like stars consists also to introduce the presence of a fossil magnetic field built in the first stage when the star was still connected to the disk and largely convective. More and more indicators call for such a complex view of the radiative zone. We have begun to build some key ingredient to explore such possibility in using a magnetic field topology which takes into account poloidal and toroidal mixed fields (Duez, Mathis & Turck-Chièze 2010). The difficulty is to estimate the strength of such a field and to find some indirect manifestation of this field: we have thought to quadrupole moments but they are already rather properly explained by the rotation profile (Duez, Turck-Chièze & Mathis 2011) or to some effects on the quadrupole gravity modes but their identification is still puzzling (Turck-Chièze et al. 2004). We shall begin with toy models of transport of momentum by magnetic field and diffusion as suggested by Mathis & Zahn (2005). Other stars, observed in seismology, will help in this new progress to build more realistic representation of solar-like stars and the bridge between young stellar object and main sequence stars.

Conclusion: The main results obtained by GOLF instrument: the sound speed, density and rotation gradients are not presently explained. The missing dynamical processes are well identified and only partly introduced due to the lack of young stellar seismic constraints and solar quadrupole gravity mode splitting measurements. KEPLER for stars and GOLF-NG (Turck-Chièze et al. 2008) for gravity mode detection will help. In the meantime, we continue to improve the analysis of GOLF to hopefully detect these quadrupole modes.

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