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Helioseismology

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Abstract. Helioseismology, the study of solar oscillations, has proved to be an extremely powerful tool for the investigation of the internal structure and dynamics of the Sun. Here I will review the present status of helioseismic studies and comment on recent results and on prospects for future investigations to solve the most discussed open questions associated with solar structure modelling.

1 Introduction

The story began in the early 60's when Doppler velocity observations of the solar disk made by Leighton et al. (1962) showed clear evidence of the presence of solar surface's oscillations with periods of about 5 min. These oscillations were theoretically explained by Ulrich (1970), and independently by Leibacher and Stein (1971), as due to standing acoustic waves (i.e. p modes) – generated for some not well known reason in the convection zone and maintained by pressure forces – trapped in the solar interior. Few years later, more accurate observations carried out by Deubner (1975) were able to confirm the theoretical hypothesis about the global character and the modal nature of the solar oscillations. This unprecedented discovery opened, for the first time, human eyes to the knowledge of the solar interior and formed the basis for the development of helioseismology. Like the geoseismology, which studies the Earth's interior through the waves produced during the earthquakes, helioseismology studies the interior of the Sun through the small quakes detected at the photosphere.

Since the first observations, several thousands of modes of oscillation have been identified with great accuracy from a number of experiments, including the MDI (Scherrer et al., 1995) and GOLF (Gabriel et al., 1995) instruments on the SOHO spacecraft and the groud-based BISON (Chaplin et al., 1996), GONG (Harvey et al., 1996) and IRIS (Fossat, 1991) networks. The incredible amount of information collected over the past two decades contributed to reach a deep knowledge of the internal structure of the Sun, not imaginable forty years ago. The present paper provides a general overview of the main achievements in helioseismology. Further details can be found in the reviews written by, e.g. Christensen-Dalsgaard (2002), Kosovichev (2003) and Di Mauro (2003).

2 Helioseismic investigations

The observed solar oscillations correspond to standing acoustic waves maintained by pressure forces, which form the class of the p modes, and to standing surface gravity waves, maintained by gravity, known as f modes. In addition, we should mention the probable, although quite discussed, existence of the internal gravity waves, g modes, which are sensitive to the structure and rotation of the deeper interior of the Sun (García et al., 2007).

Oscillations have several advantages over all the other observables: frequencies of oscillations can be measured with high accuracy and depend in quite simple way on the equilibrium structure of the Sun. In addition, each mode, characterized by a specific frequency and wave number, propagates through a confined region of the Sun, probing the physical properties of the crossed medium, like temperature and composition. Thus, it is possible to deduce the internal stratification and dynamics of the Sun from a sufficiently rich spectrum of observed resonant modes.

The goal of the helioseismology is to infer the internal properties of the Sun and to understand the physical mechanisms which govern the behaviour of our star. This can be pursued by two different strategies: i)"global" helioseismology, based on the analysis of mode frequencies, which re-

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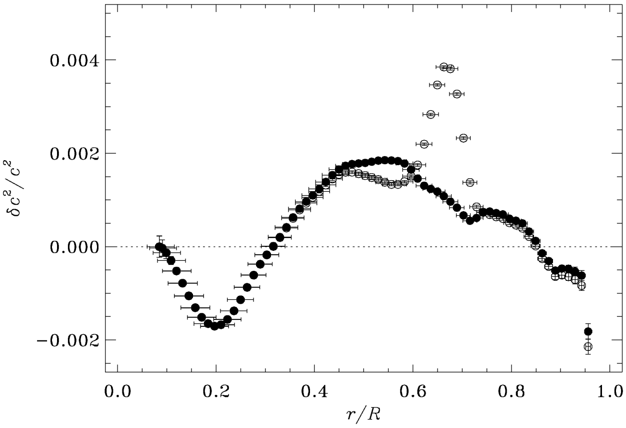

Fig. 1. The relative squared sound-speed difference between the Sun and two standard solar models (from Christensen-Dalsgaard and Di Mauro, 2007). The open symbols are obtained for Model S of Christensen-Dalsgaard (1996) while the filled symbols are for a model differing only in the inclusion of turbulent diffusion beneath the convection zone. The vertical error bars correspond to the standard deviations based on the errors in the mode sets, whereas the horizontal bars give a measure of the localization of the solution.

veals large-scale properties of the solar structure and dynamics of the Sun; ii)“local” helioseismology, based on the use of the travel times of the acoustic waves through the interior between different points on the solar surface, which provides three-dimensional maps of the sound speed and of the flows in the upper convection zone, to probe local inhomogeneities in the sub-surface and surface layers. Here I will concentrate on the results obtained by applying techniques of global helioseismology. Global helioseismology is based on the application of two different but complementary strategies. The first is the forward approach which consists in comparing the observed data with the theoretical frequencies computed for a stellar model. The second is based on the use of the observed data to deduce the internal structure and rotation of the Sun by means of data inversion.

3 The internal structure of the Sun

During the last decade, several efforts have been made in order to test the correctness of the standard models in view of the improvements accomplished in the description of the relevant physics.

The first significant result concerning the application of helioseismic analysis was obtained by Christensen-Dalsgaard et al. (1985), who reproduced the sound speed profile in the interior of the Sun. The results, so far, have shown that the solar structure is remarkably close to the predictions of the standard solar model and that the near-surface region can be probed with sufficiently high spatial resolution to allow investigation on the equation of state and to probe the He abundance in the solar envelope, as it was proved by, e.g. Kosovichev et al. (1992); Dziembowski et al. (1992); Basu and Christensen-Dalsgaard (1997).

In addition, helioseismology contributed to solve the well known 'neutrino-problem': the agreement of the solar models with helioseismic data strongly suggested that the solution of the neutrino problem had to be sought not in the physics of the solar interior but rather in the physics of the solar neutrino.

Figure 1 shows the relative squared sound-speed differences between the Sun and two recent standard models, as results of the inversion of the data set by Basu et al. (1997), which includes modes with $l < 100$ and in particular very accurate frequencies of low harmonic degree, which allow to resolve the solar core. The inversion results for Model S of Christensen-Dalsgaard et al. (1996), shown by empty symbols in Fig. 1, indicate that the differences between the Sun and the model's prediction are extremely small, except below the base of the convection zone (0.71 $R_\odot$), where the gradient of the hydrogen abundance changes abruptly as consequence of the helium settling. A significant progress can be achieved, as shown by filled symbols in Fig. 1, with the inclusion in the models of turbulent diffusion of helium and heavy elements at the base of the convective zone in order to smooth the step gradient of the hydrogen abundance (Christensen-Dalsgaard and Di Mauro, 2007).

3.1 New solar abundances

Very recently doubts about the accuracy of solar models have arisen as a result of new determinations of the solar photospheric abundances (Asplund et al., 2004). Three-dimensional NLTE analyses of the solar spectrum have shown a significant reduction in the C, N, O and Ne abundances leading to a ratio of $Z/X = 0.0165$ between the surface abundances of heavy elements and hydrogen, substantially below the previously accepted value of $Z/X = 0.0245$ (Grevesse and Noels, 1993). These elements make important contributions to the opacity in the outer parts of the radiative region and hence the reduction in their abundances strongly affects the structure of the Sun. Figure 2 shows sound-speed inversion results as obtained for two models, calculated with the CLES (Code Liégeois d'Evolution Stellaire) evolution code, which adopt respectively the old (Grevesse and Noels, 1993) and the new (Asplund, 2005) elements mixtures in the opacity tables. It appears that the difference between the Sun and the model substantially increases if the new abundances are adopted (Montalbán et al., 2004). Moreover, as noted in several investigations (e.g. Guzik, 2006), the resulting models show a too shallow depth of the convection zone and a lower surface helium abundance than the values determined by helioseismic inferences.

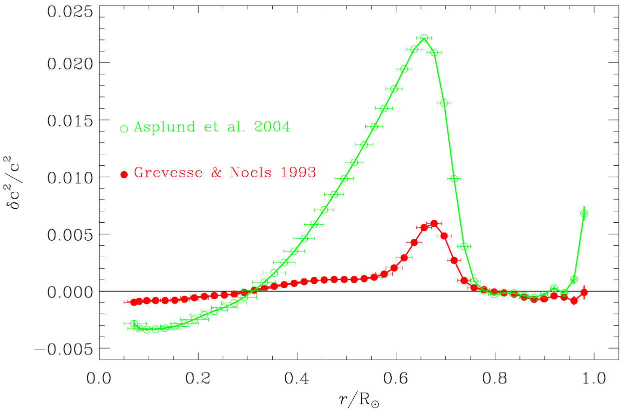

Fig. 2. The relative squared sound-speed difference between the Sun and two standard solar models (from Montalbán et al., 2004) differing in using the new solar surface abundances by Asplund (2005) and the old solar surface abundances by Grevesse and Noels (1993).

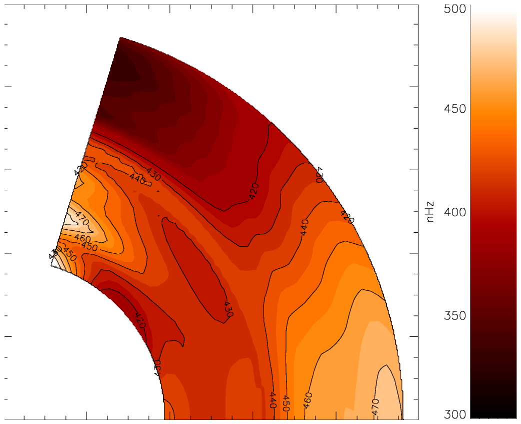

Fig. 3. Rotation rate in the Sun obtained by inversion of SOI-MDI data (Schou et al. 1998). Colours and contours indicate the isorotation surfaces. The white area indicates the region in the Sun where the data have no reliable determinations (from Di Mauro et al., 1998)

3.2 The equation of state and helium abundance

The solar plasma is almost an ideal gas, and the first adiabatic exponent Γ_1, the partial logarithmic derivative of pressure with respect to density at constant specific entropy, is therefore close to $5/3$ in most of the interior.

Helioseismic data have been used to derive the differences between the equation of state of the Sun and that of the model and to probe the helium abundance in the solar envelope. The results showed that Γ_1 deviates from $5/3$ in the zones of hydrogen and helium ionization below the surface (e.g. Di Mauro et al., 2002), and at very high temperatures as in the centre due to relativistic effects (Elliott and Kosovichev, 1998).

4 The solar dynamics

The inversion results about the internal angular velocity of the Sun are summarized in Fig. 3, which shows a cut of the interior of the Sun, where the contours and colour scale indicate the isorotation surfaces (Di Mauro et al., 1998) as determined by inversion of data set obtained by SOI-MDI in 1996 (Schou et al., 1998).

The results show that the latitudinal differential rotation observed at the surface persists throughout the convection zone, while the radiative interior rotates almost rigidly at a rate of about 430 nHz. Through the largest part of the convection zone, the angular velocity at low latitude decreases with the radius, while at high latitudes increases inwards. The near-surface behaviour is consistent with the observed surface rotation rate. The properties of the tachocline, the transition layer from latitude-dependent rotation to nearly independent rotation (e.g. Spiegel and Zahn, 1992), have been also studied. It is in fact commonly accepted that the global dynamo action, responsible for the generation of the solar 22 yr magnetic cycle, is induced by the strong toroidal magnetic fields generated by rotation shear in this thin region.

4.1 Temporal variation and the solar cycle

The rotation rate inferred by inversion of helioseismic data shows a complex variation with time, only partly correlated with the solar cycle. Regions of slightly faster and slower surface rotation, known as torsional oscillations, moving towards the equator have been studied extensively (e.g. Basu and Antia, 2003; Vorontsov et al., 2002; Howe et al., 2000a, 2005). This pattern characterized by flows which are few meters per second slower or faster than the mean solar rotation at a given latitude, extends from the surface to at least $0.92 R_\odot$ and appears closely linked to the 11-years sunspot cycle. The origin of these zonal flows is not definitely established.

Another temporal variation of the rotation rate, without a clear link to the solar cycle, was found by Howe et al. (2000b) near the base of the convective envelope. This variation with a period of the order of 1.3 yr occurs above and belove the tachocline and appears more pronounced near the equator. However, the oscillation seems to have stopped after 2001 (Howe et al., 2007). The possible physical cause of such a variation is unknown, although it could have a magnetic origin.

4.2 The rotation of the core

The problem of inferring the core physics remains one of the most important open questions. Only low-degree p modes are able to penetrate towards the centre, sampling the core for a relative short time because of the large sound speed there.

Thus, p modes, as opposed to g modes, are not very sensitive to the features of the core of the Sun. In addition, low-degree data sets obtained by different instruments are not in mutual agreement and give conflicting inversion results in the core (Di Mauro et al., 1998).

It is only very recently, after the analysis of 10 years of data collected by GOLF, that the detection of one g mode was finally announced by García et al. (2007). According to García et al. (2007) only models characterized by a core rotation faster than in the rest of the radiative zone are able to reproduce the frequency of such a g mode. This still needs to be confirmed.

5 Conclusions

Despite such overall success, helioseismology has not yet exhausted its resources, since helioseismic results clearly suggest further refinements of the solar models. To reach the required sensitivity and frequency resolution, several helioseismology experiments have been already planned to operate on-board of satellites and will soon be devoted to the measurements from space: SDO, Solar Dynamics Observatory (http://sdo.gsfc.nasa.gov/), a NASA mission to understand the variation of the solar magnetic field, the dynamical processes and their impact on Earth (launch 2008); PICARD (Thuillier et al., 2003), a CNES mission to study the Earth climate and Sun variability relationship (launch 2009); SO, Solar Orbiter (Marsden and Fleck, 2007), an ESA satellite to study the polar regions and the side of the Sun not visible from Earth (launch 2013); DinaMICS (García and Turck-Chièze, 2006), to study Dynamics and Magnetism from the Internal core to the Chromosphere of the Sun, a French project not yet planned for launch.

Finally, it is important to mention the existence of a new European initiative, the European Helio- and Asteroseismology Network HELAS, funded as a Coordination Action by the European Commission under the Sixth Framework Programme for 2006-2010. HELAS, which is led by ten major research groups from nine European countries, offers the unique opportunity to facilitate the exchange of knowledge and the coordination of research in helio- and asteroseismology through international conferences, smaller meetings, staff exchange and a strong plan for the dissemination of the latest results in the fields of helio- and asteroseismology. Further information can be obtained through the HELAS website http://www.helas-eu.org.

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