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The dynamics of the solar radiative zone

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Abstract

The picture of the solar radiative zone is evolving quickly. This review is separated in two parts. We first recall how the two powerful probes of the solar interior, namely the neutrinos and helioseismology have scrutinized the microscopic properties of the solar radiative plasma. Recent observations stimulate today complementary activities beyond the standard stellar model through theoretical modeling of angular momentum transport by rotation, internal waves or (and) by magnetic fields to get access to the dynamical motions of this important region of the Sun. So in the second part, we summarize the first impact of such processes on the radiative zone.

Keywords: Solar interior; Helioseismology; Neutrino; Gravity waves

1. The microscopic properties of the dense solar plasma

The Sun is a reference for the whole of Astrophysics and is, up to now, the only star for which we can test many of the theoretical hypotheses made in describing stellar interiors. Such a dense plasma is not yet accessible to laboratory investigations. The detailed knowledge of solar neutrinos permits to verify the complex nuclear and atomic processes taking place in the solar core due to their great sensitivity to the central temperature, while helioseismology uses pulsation eigenmodes to probe plasma properties throughout the Sun.

The radiative zone is extremely important to study because the equilibrium between gravitational energy, nuclear energy production and the energy escaping by photon interaction is governed mainly by this region which contains 98% of the solar mass. We consider first microscopic motions in this radiative region. The conditions of temperature and density ensure that the plasma is totally ionized for its main constituents, hydrogen and helium, but heavier species such as iron and silicon down to oxygen are only partially ionized.

The bound–bound interaction of photons and matter is very efficient to evacuate the energy produced in the first radial quarter (practically half the solar mass). This contribution is highly sensitive to the metal content ($\propto Z^4$), so it is necessary to calculate the interaction for *all* constituents of the Sun (from hydrogen to iron). The small amount of iron (some 10^{-4} of hydrogen in fraction number) contributes to about one fifth of this cross-section in central conditions (Fig. 1) (Turck-Chièze et al., 1993).

In Sections 2 and 3, we summarize the assumptions which have been verified along the last decades on the microscopic properties of the solar radiative plasma. Section 4 discusses current directions of improvements to describe the dynamical properties of this dense solar plasma.

2. The helioseismic investigation of the radiative zone

Helioseismology was already a mature discipline when SoHO has been launched in December 1995. The theoretical framework was already developed and after single site observations, ground networks (GONG, IRIS, BiSON) became operational. Two very important results have

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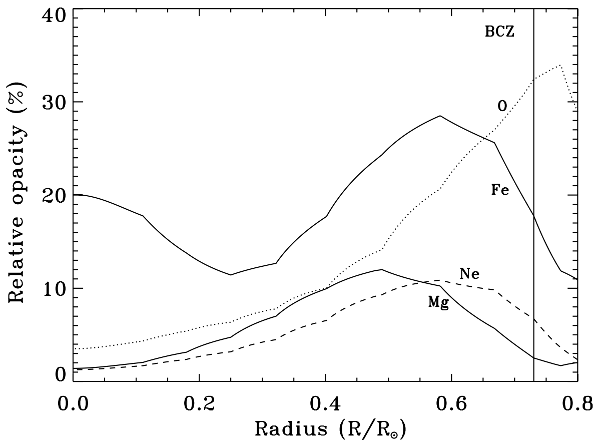

Fig. 1. Relative contribution of the heavy elements to the total opacity for the Asplund composition [for a detailed analysis of the composition sensitivity see Turck-Chièze et al. (2005a)].

appeared just before the launch: the determination of the photospheric helium content (Vorontsov et al., 1991; Basu and Antia, 1995) and the determination of the depth of the convective zone (Christensen-Dalsgaard, 1991). These demonstrated the power of seismic measurements to answer crucial questions. In fact, before helioseismology, the solar *helium content* (the second element in mass fraction) was only deduced from theoretical solar models. Its practically cosmological helioseismic estimate (0.25 in mass fraction) showed the limit of the basic hypotheses of stellar models and confirmed the need to introduce extra phenomena such as the slow atomic diffusion already introduced by Cox et al. (1989). This process leads today to a reduction of practically 10–15% of the He mass fraction at the solar surface (Christensen-Dalsgaard et al., 1993; Thoul et al., 1994; Brun et al., 1998).

SoHO has played a dominant role during the last decade for the investigation of the radiative zone. Effectively acoustic modes explore remarkably well the dynamics of the convective zone of the Sun, but it is not so easy to extract information coming from the deeper radiative zone. The very long and stable mission of SoHO has been crucial to progress on the properties of these layers down to the core. Effectively, the number of modes that reach this zone is reduced (modes of degrees $\ell \leqslant 20$) and the corresponding acoustic modes are still mainly sensitive to external layers. One needs very precise determined frequencies to scrutinize the whole radiative zone including the solar core. Unfortunately, global acoustic modes of high frequencies (easier to observe) have a resonant cavity that includes the outer layers, largely perturbed by the turbulence and the varying superficial magnetic field. Furthermore, these modes have a reduced lifetime leading to broad peaks dominated by the stochastic excitation of the modes. One success of SoHO, obtained by measuring the Doppler velocity shifts through two instruments (GOLF: Global Oscillations at Low Frequency specially designed for this purpose and MDI: Michelson Doppler Imager), has been the capability to reach the low frequency range of the acoustic spectrum. The corresponding modes have higher lifetime so narrower peaks but smaller intensities (Bertello et al., 2000; García et al., 2001, see their Fig. 1). From these modes, it has been possible to extract a very clean sound speed profile down to $0.06R_\odot$ (Turck-Chièze et al., 2001a) and a reasonable density profile (Fig. 2).

Helioseismology was the key for validating the various ingredients used in the construction of the solar model. It is in fact interesting to notice that each phenomenon (specific nuclear rate, specific opacity coefficient, screening or Maxwellian tail distribution) has a specific influence on the sound speed profile (Turck-Chièze et al., 1997). We have indeed shown that the present sound speed does not favour any tiny variation of the Maxwellian distribution nor strong screening or large mixing in the core (Turck-Chièze et al., 2001b). This is of particular importance to check the validity of the involved nuclear processes. It has also been possible from the sound speed profile in the core and due to the signature of each specific reaction rate (Turck-Chièze et al., 1997) to put an observational constraint on the value of the p–p reaction rate which was

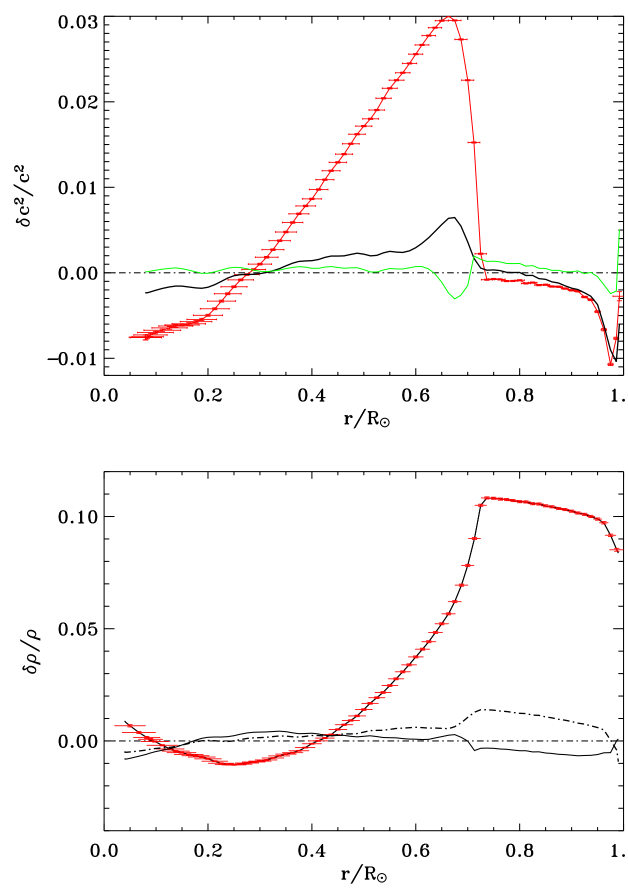

Fig. 2. Squared sound speed and density differences between the seismic measurements obtained with GOLF+MDI/SOHO and the standard model with the Grevesse and Noels (1993) (solid line), the seismic model (gray or dashed lines) and the standard model with the Asplund composition (2004, 2005) (solid line + seismic uncertainties). From Turck-Chièze et al. (2004a).