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The Dynamics of the Quiet Solar Photosphere: Simple Hydrodynamics? – History of a Fundamental Misunderstanding.

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Abstract. Most phenomena known in solar physics can be (or are exclusively) observed in the solar photosphere. Despite this involvement in most problems of modern Solar Physics, the photosphere is usually treated as an outsider of the problem and reduced to a simple hydrodynamical system. E.g. the photosphere is often reduced to the boundary condition of the problem, whereas most solar oscillation studies consider even less the role of the photosphere, just as a simple medium, which we observe the oscillations through.
Our review of the status of studies of the photosphere's dynamics shows that the hydrodynamics of the solar photosphere is not so simple, and must be considered part of the problem, even if phenomena far away from the photosphere are treated. We present the main tools for studying the dynamics of the solar photosphere.

Key words. Sun: Photosphere, Dynamics

1. Introduction

The solar photosphere acts as a boundary between the inner, convectively driven, layers, and the thinner upper atmosphere, where (gradually with increasing height) the structure is fixed by the magnetic field. Moreover, the magnetic structures expanding in the chromosphere and corona take root in the photosphere. Contrary to common believing, the dynamic behavior is quite complex, even when we concentrate on the quiet photosphere only, i.e. precluding from our interest the most striking structures that are of magnetic origin.

As the most evident consequence of its particular position at the top of the convection zone, the quiet photosphere is dominated by the convective structures of granulation. From the observational point of view, the dynamics of the braking of convective overshoot in the photosphere has been extensively studied in the past (e.g. Leighton et al. 1962; Evans 1964; Krat 1973; Canfield & Mehltretter 1973; Keil & Canfield 1978; Kneer et al. 1980; Durrant & Nesis 1981; Nesis et al. 1988; Balthasar et al. 1990; Hanslmeier et al. 1990; Komm et al. 1990, 1991b,a; Straus et al. 1992; Hanslmeier et al. 1994; Salucci et al. 1994;

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Espagnet et al. 1995; Kucera et al. 1995; Straus & Bonaccini 1997; Krieg et al. 1999; Straus et al. 1999a; Hanslmeier et al. 2000).

Due to the braking at the bottom of the photosphere, the convective overshoot can excite acoustic waves, internal gravity waves and other types of magnetohydrodynamic waves.

Beginning with low-frequencies, the clearest demonstration of the presence of internal gravity waves in the middle photosphere was given by Straus & Bonaccini (1997) (c.f. their figure 7). Other signatures were previously noted in various works (e.g. Frazier 1968; Schmieder 1976; Cram 1978; Brown & Harrison 1980; Durrant & Nesis 1981; Deubner et al. 1984; Staiger 1987; Deubner & Fleck 1989; Bonet et al. 1991; Komm et al. 1991a; Deubner et al. 1992; Straus et al. 1992; Kneer & von Uexkull 1993). Further support to the identification of internal gravity waves in the photosphere is given by Severino et al. (this proceeding, see their figure 1) and Krijger et al. (2001) (see their figure 24). The excitation of this type of waves has not yet been investigated observationally.

At higher frequencies, an investigation of acoustic waves must necessarily consider the dichotomy of chromospheric network–internetwork (e.g. Lites et al. 1982, as a fundamental example of observational work), not only in the chromosphere, but also in the photosphere, as MHD waves are supposed to be concentrated in the magnetic flux tubes on the border of the supergranular cells. Refer to Krijger et al. (2001) for a summary of the different analytic tools to this aim. Whereas, at current state, the evidence for MHD waves in the photosphere is weak (Norton et al. 1999, 2001), or might only be induced from observations in the higher atmosphere (De Moortel et al. 2002), there is no doubt about the excitation of acoustic–gravity waves, which can easily be proven with the help of power spectra at different heights in the solar atmosphere (c.f. figure 1 of Noyes 1967). Nevertheless, the contribution of these waves to the heating of the solar chromosphere inside the network cells is still in debate, as high–frequency ($\nu > 10\,\mathrm{mHz}$), propagating sound waves have not been identified without controversy (e.g. Krijger et al. 2001; Wunnenberg et al. 2002), and the contribution of shocking 3 min–oscillations (c.f. Carlsson & Stein 1995, 1997) to chromospheric heating is unclear (e.g. Theurer et al. 1997a,b; Kalkofen et al. 1999).

Contrarily to the discussion on their effects, the debate on the excitation of acoustic waves at high frequency and their evanescent counterparts at lower frequencies, which include resonant p–modes, converges towards the identification of "acoustic events" (Goode et al. 1992) in intergranular lanes as the sources of acoustic flux (Bogdan et al. 1993; Restaino et al. 1993; Rimmele et al. 1995; Espagnet et al. 1996; Goode et al. 1998; Rast 1999; Skartlien & Rast 2000; Skartlien et al. 2000; Strous et al. 2000; Hoekzema et al. 2002), even if some evidence has been reported for supplementary driving by magnetic sources(Kosovichev & Zharkova 1998; Moretti et al. 2001). We consider the latter driving of acoustic flux from above the photosphere alone as not compatible with the upward propagation observed in phase difference spectra everywhere in the photosphere (e.g. Lites & Chipman 1979; Krijger et al. 2001, and references therein).

To this point, this introduction to the dynamical behavior of the photosphere as an answer to convective overshoot has already demonstrated the variety of phenomena which makes the quiet photosphere so interesting. In the following, we concentrate on the discussion of the case of solar resonant p–modes and their interaction with non–resonant phenomena (solar background), as an example of how important a clean distinction between different dynamical phenomena is for the investigation of their excitation, and how difficult the complex hydrodynamics of the photosphere makes this distinction.

2. On the distinction of dynamical phenomena in the photosphere

The basic idea of a distinction of hydrodynamical phenomena consists in the comparison of the results of a Fourier analysis of observed signals, the so-called $k-\omega$ diagram, with the diagnostic diagram of wave propagation in a stratified plane atmosphere (refer e.g. to the review of Straus & Severino 2001, for a picture of what is described in the following). The latter shows essentially two regions of vertical propagation of waves, (a) acoustic waves and (b) internal-gravity waves, separated by a gap where waves become evanescent. As we will see further on, in this picture, the Lamb-mode of horizontal propagating sound waves plays a fundamental role: it is the lower boundary for atmospheric, acoustic waves (evanescent and propagating) in the case of no radiative damping.

The basic idea is that the horizontal wavenumber (k_h or spherical degree ℓ) and temporal frequency (ν) of a given signal, i.e. its position in the diagnostic diagram, identifies the hydrodynamical phenomenon related to that signal. From a historical point of view, such a believing originates in an important observational fact: power spectra of photospheric velocities, which have been studied first and most in details, do show two rather distinct regions, separated by a power gap which approximately coincides with the Lamb-mode. This indeed seems to indicate that the Lamb mode is the division line between the two main photospheric signals, convection on one side, 5 min oscillations on the other. *This believing is fundamentally wrong, mainly for two reasons:* (1) the diagnostic diagram is the result of a linearized treatment of the hydrodynamical equations, the wave equations, i.e. there is no reason for convection to be limited to the region below the Lamb mode; (2) the position of solar p-modes in the diagnostic diagram is determined by the hydrodynamics of the solar interior, i.e. their position determines the dynamical behavior of the part of the p-mode signal that leaks into the atmosphere, *not vice versa*. The observed distinction in the velocity power is therefore *not a result of the hydrodynamical properties of the photosphere*. Moreover, the following observational facts clearly demonstrate, that it *is not possible to identify any phenomenon just by its position in the $k-\omega$ diagram*: (a) the above mentioned gap between the two main velocity signals disappears in intensity (c.f. the contour plots in figure 2 of Straus et al. 1999a); (b) we have already seen in the introduction that a signature of internal gravity waves appears in the low-frequency part in the middle photosphere (e.g. Straus & Bonaccini 1997); (c) the base functions of the Fourier decomposition are not proper eigenfunctions of the convective signal, which is known to extent to higher frequencies above the Lamb mode (i.e. underneath the p-modes) (c.f. figure 1 of Straus et al. 1999a); (d) in the interridge-plateau regime (Deubner et al. 1990) above the Lamb mode and in between the p-mode ridges (and therefore also underneath the p-modes!) a solar background is observed which does not show the $I-V$ phase behavior of evanescent acoustic waves (e.g. Deubner et al. 1992; Straus et al. 1999a, and references therein).

As we see, the observed signal is a mixture of different dynamical phenomena almost everywhere in the $k-\omega$ diagram. As a revenge of the puzzle about the devision line described before, the Lamb mode turns out to be again a border line for the last mentioned solar background in the $I-V$ phase difference (c.f. figure 3 of Straus et al. 1999a). This interesting finding is still unexplained.

3. Excitation of solar p–modes and the role of solar background

It has been found already by terms of power spectra, that the above mentioned separation of convective and oscillatory power is not perfect. Precise helioseismic measurements have soon detected a background of solar origin beneath the p–mode signal (Harvey 1985). Two observational facts have attracted the interest to the solar p-mode background spectrum in the recent past: the opposite asymmetry of the p-mode profiles in intensity and velocity (Duvall et al. 1993), and the particular behavior of the $I - V$ phase difference in the transition from the background to the p-mode across the line profiles (Oliviero et al. 1999).

It has been pointed out early, that the only solution for the puzzle of the p-mode asymmetry inversion between intensity and velocity power spectra can be found in the effects of the solar background (e.g. Gabriel 1995; Abrams & Kumar 1996; Roxburgh & Vorontsov 1997; Nigam et al. 1998; Nigam & Kosovichev 1999; Kumar & Basu 1999b,a, 2000). This background must necessarily be *correlated* to the p-mode signal itself, i.e. it has to have a fixed phase relation to the latter. As a logical consequence of this property, the correlated background has soon been put in relation to the sources of the solar p-modes (e.g Abrams & Kumar 1996; Roxburgh & Vorontsov 1997; Nigam et al. 1998). Abrams & Kumar (1996) for example determine the depth of the sources by the phase properties of this background (c.f. Kumar & Basu 2000, and references therein for other references). Considering the small-scale "acoustic events" as a δ-function, both in time and space, compared to low-ℓ p-modes, Skartlien & Rast (2000) have demonstrated that this excitation mechanism is compatible with the observations.

In the context of studies of the p-mode excitation mechanism, the supposed chance that part of the source signal may act as a background to the p-mode signal itself makes the problem of distinction between cause (source) and reaction (p-mode) a key task, but at the same time also very difficult. In this scenario, it was the group in Napoli to stress the great importance of the supplementary informations carried by phase and coherence spectra (Straus et al. 1999a; Oliviero et al. 1999; Severino et al. 1998; Magri et al. 2001; Severino et al. 2001; Straus et al. 2001). With the help of our model of complex superposition of different signals we have shown that the *coherent* background, which is visible by its fixed $I - V$ phase difference, is partially *correlated* (Severino et al. 2001). Further developments of this model seem to call the possibility to determine the source properties (e.g. the depth) into doubt, unless further constraints can be found (Jefferies et al. 2003).

Finally, numerical simulations of solar convection (e.g. Steffen 1991; Stein & Nordlund 1998, and references therein) have been exploited as an additional resource for the study of solar p-mode excitation (Straus et al. 1999b; Georgobiani et al. 2000; Nordlund & Stein 2001; Stein & Nordlund 2001). This opens new possibilities in the future for investigations of the p-mode sources which are not available to observers. So far, they have contributed little to the solution of the problem, as they successfully reproduce most observed properties of solar convection, but (unfortunately) in all its complexity.

4. Conclusions

We stress that due to both the complex hydrodynamical behavior of the solar photosphere and the inadequacy of the harmonic [1] of the base functions commonly used Fourier analysis to most realistic solar phenomena, the photospheric signal is a mixture of different dynamical phenomena at nearly any wavenumber and frequency, i.e. at any position in the $k - \omega$ diagram. *The key task of a clean distinction of the different phenomena is therefore not yet resolved.* In any case, the identification of the dynamics of a given signal is *not possible* with the only mean of its position in the $k - \omega$ spectrum of a single parameter (e.g. power of velocity fluctuations).

[1] A promising new decomposition method – the "proper orthogonal decomposition" (Carbone et al. 2002) – might be useful in future to avoid this problem.

With the help of further informations, at first place the $I - V$ phase difference, the dominant process at a given position can be identified. However, a full distinction of all present processes with a high precision, as necessary for investigations of the excitation mechanisms, is not possible without taking all observational constraints into account. In the case of the region of solar p-modes, great progress has been done in the recent past, but the complicate profiles of intensity and velocity power spectra, *and complex cross-spectra* are not yet sufficiently understood to identify the precise excitation mechanism of these p-modes.

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