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The solar I-V cross-spectrum: A powerful diagnostic for helioseismology(*)

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Summary. — We discuss results and limitations of a new model for the components of the solar intensity (I) and velocity (V) photospheric fluctuations. The model is able to take into account the complex behavior of a low-frequency p-mode, as observed in all the four I and V spectra. We also demonstrate that the solar I-V cross-spectrum provides a sensitive diagnostic for the interaction between the oscillatory and non-oscillatory components of the solar velocity and intensity signals.

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1. – Introduction

The method of excitation for the 5-minute solar oscillations is still undetermined. However, the process most often quoted as being responsible is the stochastic excitation by turbulent convection. This is mainly because numerical simulations of solar convection can provide acoustic flux with the right order of magnitude and the correct energy spectrum [1]. Moreover, convective events producing acoustic noise have been observed and studied in details [2, 3]. However, other events, related to the solar magnetic field, have also be claimed to play a role in the production of acoustic noise [4, 5]. Therefore, we believe that further research is needed to clarify the exact processes responsible for the acoustic emission, and the continuous feeding of solar global oscillations.

Solar oscillations are usually studied via their velocity (V) power spectrum. Over the last few years, following the example of F.-L. Deubner in his study of solar photospheric dynamics (*e.g.* [6]), our group has largely demonstrated the advantages for helioseismology of using simultaneously the intensity (I) and V fluctuations, and also the I-V

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cross-spectra (*i.e.* phase difference and coherence), in addition to the more traditional I and V power spectra. This paper, in particular, discusses results and limitations of a new model based on the I-V cross-spectra to constrain the excitation mechanism of solar global oscillations (sects. **3** and **4**). We also sketch out the main observed characteristics of the solar photospheric cross-spectra, as inferred from our analysis of GONG and MDI data (sect. **2**), and, finally, we present some conclusions.

2. – The I-V phase and coherence spectra

The overall I-V phase background has a step-like behavior with negative values at low frequency [7, 8], and positive values at high frequency; the coherence has two local maxima in the centers of negative and positive phase regimes [9].

Crossing a single p-mode line profile, the I-V phase peak has a typical shark-fin shape, and the coherence peak is surrounded by two side dips, with the high-frequency dip being deeper than the low-frequency one [9].

Oliviero *et al.* [10] and Severino *et al.* [11] pointed out that observations strongly suggest that the asymmetry of the coherence is related to the asymmetry of the intensity and velocity power spectra. That the p-mode profiles are asymmetric, and the asymmetry sense is opposite in I and V power spectra was discovered by Duvall *et al.* [12].

The p-mode power asymmetry is related to the details of the acoustic source. In fact

i) depth and multipole nature of the source can make line profiles asymmetric, but with the same sense for both I and V (natural asymmetry, *e.g.* [13, 14]);

ii) a background component correlated with the mode and, hence, related to the acoustic source, can reverse the asymmetries in I and V power spectra [15, 16].

The complex behavior of a low-frequency p-mode as observed in all the four I and V spectra can be accounted for in the frame of a new model for the components of the solar photospheric fluctuations.

3. – The model of the photospheric fluctuations

The new model is based on the assumption that the I and V fluctuations are the superposition of 1) an uncoherent component, or noise (n), with a coherent (c) component (*i.e.* having fixed I-V phase), which includes: 2) the p-modes (p), 3) a background correlated (cc) with the modes, and 4) a background uncorrelated (cu) with the modes.

Moreover, i) the background components are assumed to be constant close to the resonance, and ii) the mode I and V profiles, $I_{\mathrm{p}}(\nu)$ and $V_{\mathrm{p}}(\nu)$, and the mode V phase relative to the coherent correlated background, $\phi_{V_{\mathrm{p}}\text{-}V_{\mathrm{cc}}}(\nu)$, are the solutions of the forced damped harmonic-oscillator equation for the displacement, plus a constant phase offset, $\Delta\phi_{V_{\mathrm{p}}\text{-}V_{\mathrm{cc}}}$.

The model has in total 14 free parameters, *i.e.* the resonance frequency ν_{res} and the mode lifetime γ, 8 amplitudes (the intensity and velocity amplitudes for the mode as well as for the 3 background components), and 4 phases (the harmonic-oscillator velocity phase offset, and the I-V phase differences in the mode and in the 2 coherent background components).

This model is used to simultaneously fit the four different observed spectra of various isolated low-frequency modes using the genetic algorithm PIKAIA [17].

The mathematics, on which the model is based, is developed in Severino *et al.* [11].

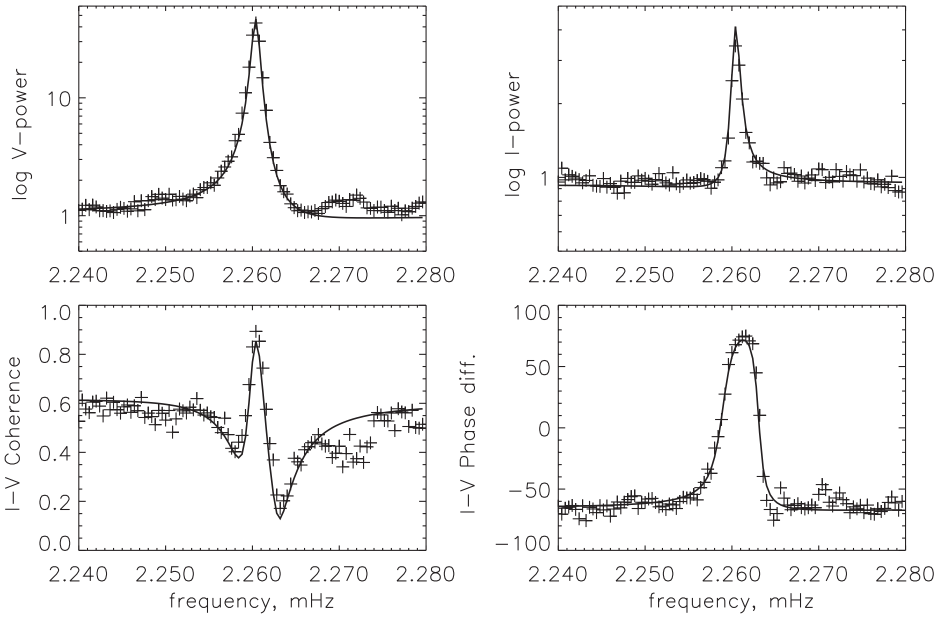

Fig. 1. – Modelled (solid line) *vs.* observed (crosses) helioseismic spectra for the p-mode of radial order $n = 10$ and degree $\ell = 17$. The upper panels refer to V (left) and I (right) power (in arbitrary, logarithmic scales), and the lower panels to coherence (left) and phase difference (right). The parameter values of the model spectra are: $\nu_{\mathrm{res}} = 2.2604$ mHz, $\gamma = 160000$ s, $|V_{\mathrm{p}}| = 6.8$, $|I_{\mathrm{p}}| = 1.6$, $|V_{\mathrm{cc}}| = 0.26$, $|I_{\mathrm{cc}}| = 0.26$, $|V_{\mathrm{cu}}| = 0.78$, $|I_{\mathrm{cu}}| = 0.68$, $|V_{\mathrm{n}}| = 0.59$, $|I_{\mathrm{n}}| = 0.64$, $\phi_{I_{\mathrm{p}}\text{-}V_{\mathrm{p}}} = 75°$, $\Delta\phi_{V_{\mathrm{p}}\text{-}V_{\mathrm{cc}}} = -10°$, $\phi_{I_{\mathrm{cc}}\text{-}V_{\mathrm{cc}}} = -66°$, $\phi_{I_{\mathrm{cu}}\text{-}V_{\mathrm{cu}}} = -66°$. The observed mode profiles are smoothed spectra from the analysis of 9-month GONG data performed by Oliviero *et al.* [10]. Notice that the spectral interval [2.268, 2.276] was excluded from the fit because it is contaminated by leakage.

4. – Model results

There are many results. Here, we summarise only the main results, the reader is referred to Severino *et al.* [11] for the other aspects.

The new model, including both coherent correlated and uncorrelated backgrounds, greatly improves the fit of all the helioseismic spectra. An example of the fit quality is given in fig. 1 (for fits with the coherent correlated background component only, see also [18, 19]).

Without the *I*-*V* phase difference and coherence, *i.e.* the cross-spectrum, as constraints in addition to the power spectra constraints, it is highly unlikely one will get the best fit possible. The coherent uncorrelated background is mainly responsible for the symmetric component of line profiles, and the coherent correlated component for the fine tuning of line asymmetries. Asymmetries are produced by the coherent correlated background which interferes with the mode *with opposite phase* on the two sides of the resonance; the effect of interference is reversed in intensity with respect to velocity [20,18].

Our experiments have demonstrated that simultaneous determination of all the 14 free parameters involved in the model is difficult, even using the I and V power and cross-spectra as constrains. This limitation depends also upon the intrinsic scatter of the data. A strategy to reduce the number of parameters to be determined in the fit consists of fixing those parameters that show the smallest variance within sets of good-quality fits. Such parameters are the resonance frequency and the mode lifetime. Another, more delicate, procedure is to establish relations between two or more parameters according to i) their variability in good fits, and ii) to plausible physical interpretations of the background signal components.

A suitable average of many good fits shows that the following values of the model parameters are preferred: $\nu_{\mathrm{res}} = 2.2606\ \ \mathrm{mHz}$, $\gamma \sim 160000$ s, $V_{\mathrm{p}} \sim 6.8$, $I_{\mathrm{p}} \sim 1.6$, $\phi_{I_{\mathrm{p}}\text{-}V_{\mathrm{p}}}(\nu) \sim 75°$, $V_{\mathrm{cc}} \sim I_{\mathrm{cc}} \sim 0.3$, $V_{\mathrm{cu}} \sim I_{\mathrm{cu}} \sim 0.7$, $V_{\mathrm{n}} \sim I_{\mathrm{n}} \sim 0.6$, $\Delta\phi_{V_{\mathrm{p}}\text{-}V_{\mathrm{cc}}} \sim -10°$, $\phi_{I_{\mathrm{cc}}\text{-}V_{\mathrm{cc}}} \sim \phi_{I_{\mathrm{cu}}\text{-}V_{\mathrm{cu}}} \sim -65°$.

The I-V phase differences in the coherent correlated and uncorrelated backgrounds are close: this result strongly suggests that the two coherent background components are due to a unique physical phenomenon.

5. – Conclusions

Our present model of the I and V photospheric fluctuations is a significant improvement on previous models, as demonstrated by its capability to fit the four I and V power and cross-spectra. The model can fruitfully be compared with some of the explanations proposed for the excitation of the solar p-modes. Our coherent (correlated + uncorrelated) background may well correspond to the seismic events observed by Goode *et al.* [2] and Strous *et al.* [3]. The presence of a significant uncorrelated background component may represent seismic events of smaller strengths unable to excite the 5 min oscillations, or, it could also indicate that the contribution of the seismic events to the coherent background signal is only partly correlated with the mode signal.

On the other hand, the large number of free parameters involved in any fitting of helioseismic spectra strongly recommends i) to include the I and V cross-spectra in addition to power spectra as observational constraints; and, moreover, ii) to exercise as much caution as possible when using the values inferred for the relevant physical parameters. An example of an *a priori* unjustified procedure is the inference of the depth of acoustic source from fitting the observed asymmetry of the velocity power line profile *only*.

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