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EXCITATION OF SOLAR P MODES. EFFECT OF THE ASYMMETRY OF THE CONVECTION ZONE

K. Belkacem[1], R. Samadi[1], M. J. Goupil[1], F. Kupka[2] and F. Baudin[3]

Abstract. Excitation of stellar p modes by turbulent convection is investigated. The aim is to take into account the asymmetry of up- and downflows created by turbulent plumes through an adapted closure model. We built a generalized two scale mass flux model (GTFM) that includes both the skew introduced by the presence of two flows and the effect of turbulence within each flow. The plume dynamics modelled according to Rieutord & Zahn (1995) is used to construct a closure model with plumes (CMP). We apply it to the formalism of excitation of stellar p modes developed by Samadi & Goupil (2001). The new excitation model leads to a frequency dependence, of the power supplied to solar p modes, which is in agreement with GOLF observations. Despite an increase of the Reynolds stress contribution due to our improved description, an additional source of excitation -identified as the entropy source term- is still necessary to reproduce the maximum of excitation rate. Our modelling including the entropy contribution reproduces the maximum but over-estimates, at low frequencies, the power and calls for further theoretical improvements.

1 Introduction

In the uppermost part of the solar convective zone, turbulent entropy fluctuations and eddy motions drive acoustic oscillations. 3D numerical simulations of the stellar turbulent outer layers have been used to compute the excitation rates of solar-like oscillation modes (Stein & Nordlund 2001). As an alternative approach, semi-analytical modelling can provide an understanding of the physical processes involved in the excitation of p modes: in that case it is indeed rather easy to isolate the different physical mechanisms at work in the excitation process and to assess their effects. Among the different theoretical approaches, that of Samadi & Goupil (2001) includes a detailed treatment of turbulent convection, which enables the investigation of different assumptions about turbulent convection in the outer layers of stars (Samadi et al. 2005). In this approach, the analytical expression for the acoustic power supplied into p modes involves fourth-order correlation functions of the turbulent Reynolds stress and the entropy source term, which for sake of simplicity are expressed in terms of second-order moments by means of a closure model.

We develop a new approach and build an improved closure model. It consists in considering the convection zone as composed of two flows (the updrafts and downdrafts). Starting from the Gryanik & Hartmann (2002) approach, we develop a generalized two-scale mass-flux model (GTFM) that takes the physical properties of each flow into account. Then a theoretical description of the plumes developed by Rieutord & Zahn (1995) (hereafter RZ95) is used to construct the closure model with plumes (CMP).

The paper is organized as follows: Sect. 2 introduces the quasi-normal approximation (QNA) as well as mass-flux models. In Sect. 3, we extend the two-scale mass-flux model and we construct the CMP with the help of the RZ95 plume model. In Sect. 4, the CMP is used to compute the Reynolds stress contribution to the excitation of p modes and the results on excitation rates are discussed.

[1] Observatoire de Paris, LESIA, CNRS UMR 8109, 92195 Meudon, France
[2] Max-Planck-Institute for Astrophysics, Karl-Schwarzschild Str. 1, 85741 Garching, Germany
[3] Institut d'Astrophysique Spatiale, CNRS/Université Paris XI UMR 8617,91405 Orsay Cedex, France

2 Closure models for turbulent convective layers

The most commonly used closure model at the level of fourth-order moments is the QNA that is valid for a Gaussian probability distribution function and was first introduced by Millionshchikov (1941). The QNA assumption permits the fourth-order turbulent vertical velocity correlations to be decomposed in terms of a product of second-order ones, that is one uses

$$\langle w'^4 \rangle_{QNA} = 3\,\langle w'^2 \rangle^2 \ , \tag{2.1}$$

where w' is the turbulent vertical velocity.

This approximation (Eq. (2.1)) remains strictly valid for normally distributed fluctuating quantities with zero mean. As shown by Kraichnan (1957) in the context of turbulent flows and Stein (1967) in the solar context, the cumulant (which is the deviation from the QNA) can be large and therefore not negligible. Hence, one has to go further than this first order assumption.

Turbulent plumes are created at the upper boundary of the convection zone and fall down through the convection zone. This can be represented by two flows which introduce an additional contribution when averaging the fluctuating quantities, since averages of fluctuating quantities over each individual flows differ from averages over the total flow. This causes a non-zero skewness (asymmetry of the probability distribution function, see Eq. 2.3) for the moments of turbulent quantities when averages are computed globally over the whole system. The mass-flux models (MFM) were developed in order to take this non-zero skewness into account, as an alternative to the QNA. For vertical velocity fluctuations w', one then writes:

$$< w' > \ = \ a \ < w' >_u + (1-a) \ < w' >_d \ , \tag{2.2}$$

where a and $1-a$ are the mean fractional area occupied by the updrafts and downdrafts, respectively (Gryanik & Hartmann 2002; Canuto & Dubovikov 1998). $<>_{u,d}$ denotes the horizontal average over up- and downflows, respectively.

Such a decomposition is also proposed for higher-order moments under the assumption that $\langle w'^n \rangle \approx \langle w' \rangle^n$. Hence we have (Gryanik & Hartmann 2002; Belkacem et al. 2006).

$$< w'^4 >= (1+S_w^2) \ < w'^2 >^2 \quad \text{where} \quad \mathrm{S_w} = \frac{< \mathrm{w}'^3 >}{< \mathrm{w}'^2 >^{3/2}} = \frac{1-2\mathrm{a}}{\sqrt{\mathrm{a}(1-\mathrm{a})}} \ . \tag{2.3}$$

The asymmetry between up and downflow in the horizontal plane is taken into account through the skewness (S_w). However, such models underestimate the fourth-order moments by as much as 70% and can be worse than the QNA. Therefore, they clearly miss some important physical effects present in convective flows.

Gryanik & Hartmann (2002), hereafter GH2002, propose an interpolation between the QNA and the limit of large skewness provided by the MFM. Their aim has been to account for the fact that horizontal scales of temperature and velocity fluctuations are different (hence their improvements lead to a "two-scale mass -flux model"(TFM)) as well as to understand and measure the effects of the skewness.

$$< w'^4 >= 3 \ (1 + \frac{1}{3} S_w^2) \ < w'^2 >^2 \ . \tag{2.4}$$

This new parametrization permits a much better description of the fourth-order moments for convection in the atmosphere of the Earth (GH2002). However, it fails when using the analytical expression for the skewness (Eq. (2.3) (see Kupka & Robinson 2006)). Indeed, we have shown in Fig. 1 (see also Belkacem et al. 2006) that the interpolated expression given by GH2002 gives rises to a very good modelling of the fourth-order moment (in the adiabatic part of the solar convection region, $z > 0.5$ Mm in Fig. 1) provided the skewness is taken directly from the numerical simulation. Then, to obtain a semi-analytical closure model, a more realistic estimate for the skewnesses of velocity and temperature fluctuations is required than that provided by Eq. (2.3).

3 The closure model with plumes (CMP)

In this section, we use expression 2.4 where S_w is computed from an exact decomposition of the third-order moment. We use results from the 3D simulation to neglect some terms (see details in Belkacem et al. 2006) and we model the remaining terms by means of a plume model.

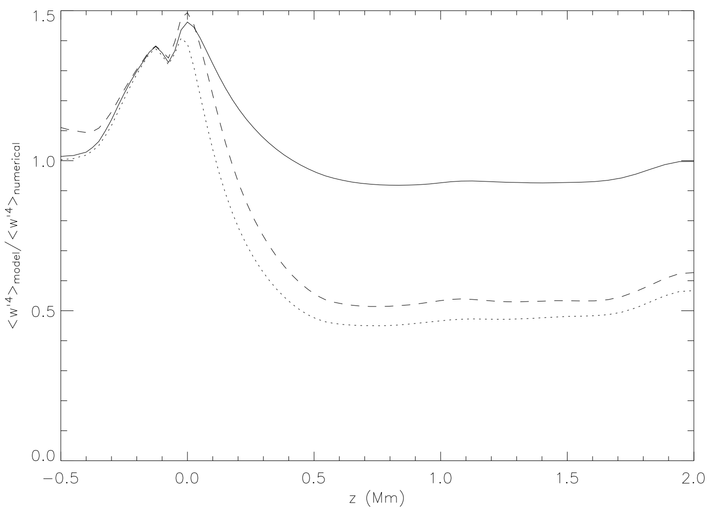

Fig. 1 Fourth-order moment ($< w'^4 >$) versus depth (z) normalized to the fourth-order moment calculated directly from the simulation. The solid line denotes the moment calculated using Eq. (2.4) with S_w taken directly from the simulation; the dashed line shows the result if S_w is instead taken from Eq. (2.3); and the dotted line is the QNA (Eq. (2.1)). Second-order moments are computed using the numerical simulation.

3.1 Turbulent two-scale mass-flux model

Our main idea is to separate the effect of the skewness introduced by the presence of two flows from the effect of the turbulence which occurs in each individual flow. By introducing zero-mean fluctuations onto each flow, we perform the decomposition of the third-order moment (see Belkacem et al. 2006, for details) and one obtain for the skewness

$$< w'^3 >= a(1-a)(1-2a)\,\delta w^3 + a < \tilde{w}'^3 >_u + \,(1-a) < \tilde{w}'^3 >_d + 3a(1-a)\Big[< \tilde{w}'^2 >_u - < \tilde{w}'^2 >_d \Big]\delta w \;. \quad (3.1)$$

The first term is the expression derived by GH2002. It is a measure of the skewness introduced by the presence of two flows. The second and third terms represent the asymmetry of the PDF within each flow induced by turbulence and the fourth term measures the difference of the turbulent velocity dispersion. This exact decomposition takes both the asymmetry due to the presence ($a = 0.5$) of two flows and turbulence into account.

3.2 The plume model

Eq. (3.1) shows that the skewness depends on six quantities and we have shown in Belkacem et al. (2006) that moments related to the upflow as well as the third-order moment of downflow turn out to be negligible in the quasi-adiabatic region of the sun because plumes are more turbulent in the downflow than in the upflow. The remaining dominant terms are modelled by the plume model developed by Rieutord & Zahn (1995) in the quasi-adiabatic convective region.

4 Application to stellar p modes; Results and Conclusions

The theoretical model of stochastic excitation considered here is basically that of Samadi & Goupil (2001) (see also Samadi et al., 2005). It takes two sources into account, which drive the resonant modes of the stellar cavity: the first one is related to the Reynolds stress tensor and as such represents a mechanical source of excitation. The second one is caused by the advection of the turbulent fluctuations of entropy by the turbulent motions (the so-called “entropy source term”) and as such represents a thermal source of excitation. We use the CMP which is more realistic than the usual QNA approximation to model the Reynolds stress contribution for which fourth-order correlation products appear.

The present excitation model gives a theoretical slope of the power, at low and intermediate frequencies, which is in agreement with the observed data (see Fig. 2). We also find that including the CMP causes a global increase of the injected power. This brings the power computed with the Reynolds stress contribution alone closer to (although, at intermediate frequency, still below) the observations (Fig. 2). Various sources

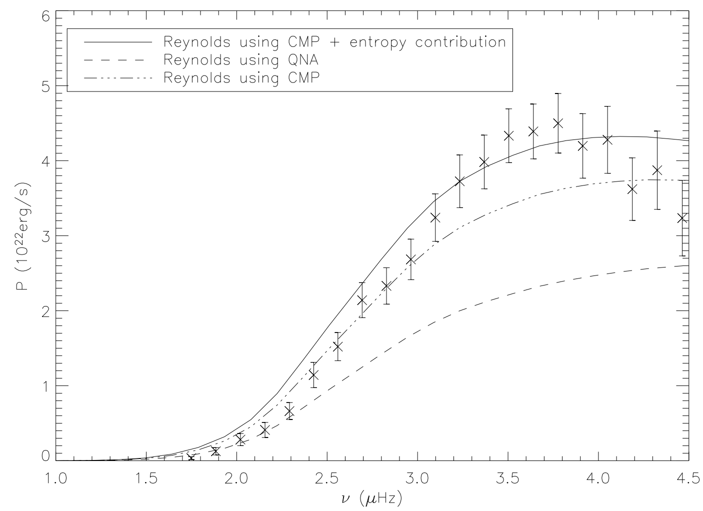

Fig. 2 Rate P at which acoustic energy is injected into the solar radial modes. Cross dots represent P computed from Baudin et al. (2005) solar seismic data from the GOLF instrument. The curves represent theoretical values of P: the dashed line corresponds to a calculation of P using the QNA closure model and only the Reynolds stress as an excitation source term, the dashed-dots line is the same except using the CMP as closure, and the solid line is P using the CMP with both the Reynolds and entropy contribution.

of uncertainties are likely to exist to explain the discrepancies. Concerning the CMP itself, the main point is the super-adiabatic region which needs further theoretical developments to obtain a closure model in this zone. Some improvements in the modelling of entropy contribution are necessary, namely one has to apply the CMP for this term and the passive scalar assumption for entropy fluctuations must be removed.

The CMP closure model, indeed, strongly depends on the structure of the upper convection zone, and this emphasizes that the structure of this region is of great importance in the theoretical prediction of the power supplied into the p modes. Comparisons of amplitudes with observational data make it possible (in the future) to obtain physical constraints on the asymmetry of the convection zone flows as well as on the nature of turbulence in solar-like stars.

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