Stellar turbulence and mode physics

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Abstract An overview of selected topical problems on modelling oscillation properties in solar-like stars is presented. High-quality oscillation data from both space-borne intensity observations and ground-based spectroscopic measurements provide first tests of the still-ill-understood superficial layers in distant stars. Emphasis will be given to modelling the pulsation dynamics of the stellar surface layers, the stochastic excitation processes and the associated dynamics of the turbulent fluxes of heat and momentum.

Keywords Asteroseismology · Convection · Pulsation mode physics · Stellar structure

1 Introduction

With the high-quality photometric data from the Kepler satellite (e.g. Christensen-Dalsgaard et al. 2007) and spectroscopic data from ground-based observation campaigns, and later also from the Danish SONG network (Grundahl et al. 2007), we shall be able to address more carefully many of the current problems in modelling pulsation properties in solar-like stars. In solar-like stars the acoustic-mode lifetimes and amplitudes are crucially affected by the processes that take place in the outer convectively unstable stellar layers. A proper modelling of the dynamics of the convective heat and momentum transfer is therefore essential. Recent 3D numerical simulations of the largest scales of the convection (e.g. Stein and Nordlund 2001; Samadi et al. 2003; Georgobiani and Stein 2004; Stein et al. 2004; Jacoutot et al. 2008; Miesch et al. 2008) have been proven to be extremely useful for calibrating and testing semi-analytical models for convection and stochastic excitation. However, the high-Reynolds-number (and low-Prandtl-number) turbulent convection in stars still prohibits today’s simulations from resolving all the required scales of stellar turbulence. Consequently such simulations have to use sub-grid-scale models, which may lead to different results (e.g. Jacoutot et al. 2008). Because this situation will not change in the near future, we still need analytical models for describing the convection and pulsation dynamics in stars.

Sections 2 and 3 will discuss selected problems of our current understanding of nonadiabatic pulsation dynamics in the Sun and in the hotter F5 star Procyon. Although we can reasonably well reproduce the observed pulsation properties in the Sun, the recent Procyon observations (e.g. Arentoft et al. 2008 and references therein) have revealed serious problems in our models for estimating the oscillation amplitudes in stars hotter than the Sun. In Sect. 4, therefore, we shall address the problem of selecting a proper temporal turbulence spectrum for modelling the stochastic energy-supply rate for acoustic modes.

2 Mode parameters

In solar-like stars all possible modes of oscillation are stable; thus, if a given oscillation mode is somehow excited, its amplitude will decay over a finite time, typically of the order of days to months, the inverse of which is the damping rate $\eta$. The oscillation power spectrum can be described in terms of an ensemble of intrinsically damped, stochastically driven, simple-harmonic oscillators, provided that the background equilibrium state of the star were independent of time. In that case the mode profile is essentially
Lorentzian, and the intrinsic damping rates of the modes could then be determined observationally from measurements of the pulsation linewidths. The other fundamental property of the observed oscillation power spectrum is the height, $H$, of a single peak in the Fourier spectrum. The observed velocity signal $v(t) = d\xi/dt$ (where $\xi(t)$ is the surface displacement of the damped, stochastically driven, harmonic oscillator, and $t$ is time) can then be related to the mode height $H$ by taking the Fourier transformation of the harmonic oscillator followed by an integration over frequency to obtain the total mean energy $E$ in a particular pulsation mode with inertia $I$ (e.g. Chaplin et al. 2005; Houdek 2006). For $T\eta \gg 1$, where $T$ is observing time, the squared surface rms velocity is then given by

$$V^2 := \frac{E}{T} = \frac{P}{2\eta I} = \frac{1}{2} \eta H,$$

(1)

where $P$ is the energy-supply rate in erg s$^{-1}$, and $H$ is given in units of cm$^2$ s$^{-2}$ Hz$^{-1}$. The height $H$ is the maximum of the discrete power, and it is obtained from integrating the power spectral density over a frequency bin:

$$H = \int_{v-\hat{\delta}/2}^{v+\hat{\delta}/2} |\hat{V}(\nu)|^2 \, d\nu,$$

(2)

where $\hat{V}(\nu)$ is the Fourier transform of $v(t)$, $\nu$ is cyclic frequency, and $\hat{\delta} = 1/2T$, is the frequency bin determined by the observation time $T$. It is therefore not the total integrated power, $V^2$, which is observed directly, but rather the power spectral density (Chaplin et al. 2005).