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Asteroseismology and CO5BOLD

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Abstract. The field of asteroseismology has undergone a revolution in recent years largely due to the vast amounts of high-quality data coming from space missions such as *Kepler*. This has uncovered the need for a better understanding of the near-surface layers of solar-type stars, where vigorous convection gives rise to granulation features on the stellar surface. In this manuscript I briefly review a few important concepts relating to asteroseismology of solar-like stars, after which I describe some research ideas related to combining asteroseismology and CO5BOLD hydrodynamical simulations with a goal of learning more about the stellar granulation.

Key words. Asteroseismology – Stars: solar-type – Stars: atmospheres

1. Introduction

NASA's *Kepler* mission (Koch et al. 2010) has provided a wealth of high-quality data, which have allowed, for example, the detection of an asteroseismic signal in more than 500 main-sequence and sub-giant stars (see for instance Chaplin et al. 2014). Combining this outstanding dataset with 3D hydrodynamical simulations will provide us with unprecedented opportunities to learn more about stellar physics.

In this paper I will outline some of my research plans for how to use the knowledge from 3D CO5BOLD simulations to better understand solar-like stars and in particular their power spectra. The text starts with a short introduction to asteroseismology of solar-like stars and then lays out some of these ideas, while highlighting the relation to the fields of asteroseismology and exoplanet research.

2. Brief introduction to asteroseismology

Asteroseismology is the study of stellar oscillations and can be carried out for stars all over the Hertzsprung-Russell diagram, since many different types of pulsating stars are known. For a thorough introduction to asteroseismology, the reader is referred to, for instance, Aerts et al. (2010); Chaplin & Miglio (2013); here we will focus on asteroseismology of solar-like stars – and in particular those that are believed to be exoplanet hosts.

Stochastic oscillations in solar-like stars and red giants are excited by turbulent convection in the outer layers of the star. The oscillations excited in a given star will correspond to (some of) the eigenmodes of that star. These oscillation modes can be described using three numbers; n, ℓ and m (also called quantum numbers). The radial order, or the overtone of the mode, is denoted by n, and its size is related to the number of radial nodes inside the star. For the p-mode oscillations in solar-like stars, where the restoring force is pressure, n is positive (whereas often n is counted negative for gravity modes). The second number is ℓ, which is the (angular) degree of the mode. This gives the number of surface nodes on the star. Finally, the azimuthal order of the mode is denoted by m. The size of m gives the number of the surface nodes that are lines of constant longitude.

Often, to study the different pulsations in a given star, the temporal power spectrum is used. The power spectrum can be found as the norm-square of the Fourier transform of the time series, and it yields information on which pulsation frequencies are present and with what power (amplitude squared, see Fig. 1).

2.1. The power spectrum

Figure 1 shows the power spectrum of Kepler-68 (KIC 11295426) using data from *Kepler*. The different components of the power spectrum are easily identified; the solar-like oscillations are located around 2 mHz and sit atop a background. It is evident that the frequencies exhibit a very regular pattern and that their power is modulated by a Gaussian-like envelope (see for example Chaplin & Miglio 2013, for details). The frequency of maximum oscillations power, $\nu_{\max}$, is around 2100 μHz for this star.

Each of the oscillation modes in the power spectrum can be identified with a value of n (increasing for higher frequencies) and ℓ (typically 0, 1 and 2) with the $\ell = 1$ modes placed roughly midway between two modes with $\ell = 0$ and of consecutive radial order. The distance in frequency space between adjacent modes of the same degree is called the large frequency separation, $\Delta\nu_{n,\ell}$, and it is constant to a good approximation for different n and ℓ values; $\Delta\nu_{n,\ell} \approx \Delta\nu$, with a value of just over 100 μHz for the star in Fig 1.

It is very important to model the background in the power spectrum correctly, since the choice of background-model can influence the subsequent determination of the seismic parameters, for instance $\nu_{\max}$ (Kallinger et al. 2014). The background is composed of a flat contribution from photon-shot noise and the stellar background, which consists of at least one component from stellar granulation and one component from stellar activity; however some argue that additional components are needed, such as a contribution from faculae or additional granular components (see for instance Harvey 1985; Karoff 2008). Harvey (1985) suggested that the background was the sum of four Lorentzian profiles (in addition to the flat contribution from the photon noise) and updated this some years later to allow for a non-Lorentzian shape (Harvey et al. 1993):

$$B(\nu) = \sum_{i=0}^{4} \frac{A_i}{1 + (2\pi\nu\tau_i)^{b_i}} + B_0 \, . \qquad (1)$$

Here, A_i is the amplitude, τ_i is the characteristic timescale (determining where the "knee" occurs in a log-log plot of that component in the power spectrum), ν is the frequency, b_i is the exponent, and B_0 is the white-noise contribution from the photon noise.

However, the background model by Harvey is not believed to accurately account for the background seen in solar-like stars and, as mentioned above, several (mostly data-driven) modifications have been suggested. Thus, the correct description of the background remains elusive owing largely to the fact that convection and its imprint on the power spectrum is not yet understood (Kallinger et al. 2014, and references therein).

2.2. Scaling relations

In asteroseismology often scaling relations are used to determine stellar parameters based on quantities that can be determined from the power spectrum. In this way it is possible to, for instance, determine the mass of a star using the stellar effective temperature, the large separation and the frequency of maximum power. One scaling relation relates the large separation to the mean density of the star as (Ulrich 1986; Kjeldsen & Bedding 1995; Bedding &

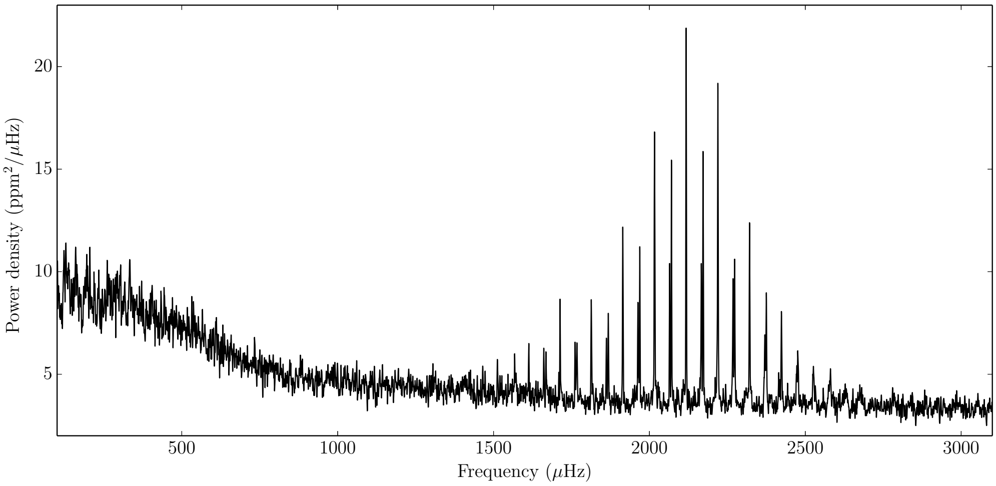

Fig. 1. Power spectrum of KIC 11295426 (Kepler-68) showing the oscillations modes (around 2100 μHz), the stellar background (at low frequencies) and a flat white-noise contribution. The power spectrum has been smoothed twice with a Gaussian filter with a width of 1 μHz.

Kjeldsen 2010):

$$\Delta\nu \propto \sqrt{\bar{\rho}}\,. \tag{2}$$

Another one links the frequency of maximum power to the surface gravity of the star and its effective temperature through (Brown et al. 1991; Kjeldsen & Bedding 1995):

$$\nu_{\rm max} \propto \frac{g}{\sqrt{T_{\rm eff}}}\,. \tag{3}$$

Thus, simply by measuring the large frequency separation and the frequency of maximum oscillations power, it is possible to obtain directly the stellar mass, radius, mean density and surface gravity by using these scaling relations.

The stellar granulation background can yield similar information. It has for example been shown by Bastien et al. (2013) that the granulation signature can yield information about the stellar surface gravity, which was also predicted by, for instance, Ludwig et al. (2009). Bastien et al. (2013) found that they could use the so-called 8-hour flicker, a measure of the light curve variations on an approximately 8-hour times scale, to estimate the surface gravity of late-type stars. However, 8-hour flicker has been shown to only work well for stars within a limited range of surface gravities (Kallinger et al. 2014). As a possible alternative, it was suggested by Kallinger et al. (2016) that the characteristic time scale of convection can be used to determine accurate surface gravities for all stars with a convective envelope. This agrees with the fact that a tight relation between the characteristic frequency of granulation, $\nu_{\rm gran}$ (the inverse of the characteristic time scale) and $\nu_{\rm max}$ was both predicted and observed by Kallinger et al. (2014).

3. Research projects

It is clear that many aspects of the granulation – also its appearance in a stellar power spectrum – are not yet understood. Therefore, this is one of the main focus areas of my research plans. In this section, I will very briefly highlight some of these plans involving combining CO5BOLD simulations and asteroseismic analyses of *Kepler* data to learn more about the stellar granulation.

As should hopefully be evident from Sect. 2.1, a very important goal is to supplement the ongoing efforts to determine the optimal background model. I intend to pursue this by identifying a formulation driven by the expectations from 3D simulations by comparing output from CO5BOLD to stellar power spectra made from *Kepler* data. This will be important for measurements of stellar structure using asteroseismology, since, as mentioned above, for instance the determination of $\nu_{\max}$ can be affected by the choice of background model.

Along a slightly different path, it would be useful to develop a method to determine stellar radii from the signature of granulation, rather than only surface gravities as the methods mentioned above. This is, for instance, highly relevant for the exoplanet host stars, where a good knowledge of the stellar radius is paramount for the precise determination of the exoplanet radius of a transiting exoplanet (see for instance Lundkvist et al. 2016). On the basis of the 3D CO5BOLD simulations by Ludwig & Steffen (2016) it can be argued that a combination of ν_{gran}, and the frequency integral of the granulation-related power, σ_{gran}, would be a good indicator of stellar radius for the unevolved stars (given a knowledge about the metallicity and effective temperature).

Thus, such a tool would, for instance, be useful for stars where an asteroseismic radius cannot be established from the oscillation signal, which could be the case for many of the stars that will be observed by TESS. TESS will be able to detect solar-like oscillations in sub-giant and red-giant stars and also main-sequence stars depending on the length of the observations and the systematic noise level of TESS (see Campante et al. 2016). However, many stars will not show a detection. It is possible that the granulation feature could be used to yield stellar radii for some of these, although the noise level may make the robust modelling of the granulation profile a challenge (Campante et al. 2016).

Furthermore, identifying where the photometric signal from granulation disappears would also be interesting, since it would, for example, yield an understanding of the limitations of using the granulation signature to give information about a star.

4. Conclusion

Although we have a good basic understanding of the physics of the stellar interior, many detailed aspects, concerning the outer layers, remain unclear. One of the important issues for asteroseismology of solar-like stars is the turbulent convective motions in their outer layers, which gives rise to granulation noise on the surface (albeit also exciting the oscillations). In this short manuscript I have highlighted a few ways to exploit this granulation signature to learn more about the stars and the granulation signal itself by combining knowledge from asteroseismology and 3D hydrodynamical simulations.

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