*Precision Asteroseismology*
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# Seismic studies of planet-harbouring stars

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**Abstract.** During the past decades, stellar oscillations and exoplanet searches were developed in parallel, and the observations were done with the same instruments: radial velocity method, essentially with ground-based instruments, and photometric methods (light curves) from space. The same observational data on one star could lead to planet discoveries at large time scales (days to years) and to the detection of stellar oscillations at small time scales (minutes), such as for the star $\mu$ Arae. Since the beginning, it seemed interesting to investigate the differences between stars with and without observed planets. Also, a precise determination of the stellar parameters is important to characterize the detected exoplanets. With the thousands of exoplanet candidates discovered by *Kepler*, automatic procedures and pipelines are needed with large data bases to characterize the central stars. However, precise asteroseismic studies of well-chosen stars are still important for a deeper insight.

**Keywords.** asteroseismology, exoplanets

## 1. Introduction

A review concerning the seismic studies of planet-harbouring stars should begin with the most well known of all these stars: our own Sun. This is the occasion for me to acknowledge all the work done by W.A. Dziembowski in that respect, and quote more specifically the only paper we cosigned, in which we studied the importance for helioseismology of the helium settling coupled with turbulence below the solar convection zone (Richard *et al.* 1996). However, in the following I will focus on exoplanet-harbouring stars.

There are many reasons why astrophysicists interested in exoplanets should bother about the asteroseismology of the central stars of planetary systems:

- The observations for stellar oscillations and exoplanet searches are done with the same instruments. In some cases, the same observations, analysed on different time scales, can lead to both planet detection and seismic studies. This was the case for the star $\mu$ Arae, observed with HARPS during eight nights in June 2004. These observations, aimed for asteroseismology, led to the discovery of the exoplanet $\mu$ Arae d (Santos *et al.* 2004b).
- "Some people's noise is other people's signal." Indeed, when searching for exoplanets, the signal-to-noise ratio is limited by the stellar oscillations, which appear as noise for the radial velocity variations induced by the planetary motions, whereas they represent in fact the stellar oscillation signal. Other limitations are related to granulation and stellar activity.
- Asteroseismology is important to obtain precise values of the parameters of exoplanet-hosting stars. Seismic studies, combined with spectroscopic observations, can lead to values of the stellar parameters which are much more precise than from spectroscopy alone.
- Asteroseismology can lead to the discovery of new planets. One case, already mentioned, is that of $\mu$ Arae. Studies of seismic period variations (the so-called "time delay

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method") can also lead to the discovery of planets like that detected around the extreme horizontal branch star V391 Peg (Silvotti *et al.* 2007). Note also the spectacular discovery of a compact planetary system which remained after the giant stage, around the hot B subdwarf KIC 05807616, by Charpinet *et al.* (2011).

- Finally, precise asteroseismology can lead to constraints on the internal structure of planet-hosting stars, and may help to understand star-planet interactions, such as angular momentum exchange, consequences of planetary matter accretion onto the star, tidal effects in the case of hot Jupiters, etc.

At the present time, the main goal of asteroseismology of exoplanet-hosting stars is to precisely derive their masses, radius, effective temperatures and ages, in order to obtain more precise results on the parameters of the detected planets themselves. Another objective consists in obtaining hints about the theories of planetary formation and migration. This can be obtained both from statistics of a large number of stars and from deep precise studies of some of these stars.

## 2. The "old times"

### 2.1. *The saga of $\mu$ Arae*

The exoplanet-hosting star $\mu$ Arae (HD 160691, HR 6585, GJ 691) is a G5 V star with a visual magnitude $V = 5.1$ mag, and an Hipparcos parallax $\pi = 65.5 \pm 0.8$ mas, which gives a distance to the Sun of 15.3 pc and a luminosity of $\log L/L_\odot = 0.28 \pm 0.012$. This star was observed for seismology in August 2004 with HARPS. At that time, two planets were known. The observations aimed for seismology lead to the discovery of a third planet, $\mu$ Ara d, with period 9.5 days (Santos *et al.* 2004b). Finally, evidence for a fourth planet was discovered by Pepe *et al.* (2007).

The HARPS seismic observations allowed identifying 43 oscillation modes of degrees $l = 0$ to $l = 3$ (Bouchy *et al.* 2005). The modelling was done with the TGEC (Toulouse-Geneva stellar evolution code). Atomic diffusion was included in all the models using the formalism derived by Paquette *et al.* (1986), as explained by Richard *et al.* (2004). The treatment of convection was done in the framework of the mixing-length theory, and the mixing-length parameter was adjusted as in the Sun. Adiabatic oscillation frequencies were computed using the adiabatic PULSE code (Brassard 1992).

From the analysis of the frequencies and comparison with models, the following values $T_{\rm eff} = 5770 \pm 50$ K and [Fe/H] $= 0.32 \pm 0.05$ dex were derived. Spectroscopic observations by various authors gave five different effective temperatures and metallicities (see references in Bazot *et al.* (2005)). The values obtained from seismology are much more precise than those obtained from spectroscopy alone.

### 2.2. *The special case of $\iota$ Hor*

Among exoplanet-hosting stars, $\iota$ Hor is a special case for several reasons (see Laymand & Vauclair (2007) and Vauclair *et al.* (2008)). Three different groups have given different stellar parameters for this star: Gonzalez *et al.* (2001), Santos *et al.* (2004b) and Fischer & Valenti (2005). Meanwhile, Santos *et al.* (2004b) suggested a mass of $1.32\,M_\odot$ while Fischer & Valenti (2005) gave $1.17\,M_\odot$.

Some authors (Chereul *et al.* 1999, Grenon 2000, Montez *et al.* 2001) pointed out that this star has the same kinematical characteristics as the Hyades: its proper motion points towards the cluster convergence point. Two different reasons were possible for this behaviour: either the star formed together with the Hyades, in a region between the Sun and the centre of the Galaxy, which would explain its overmetallicity compared to that of the Sun, or it was dynamically cannabilized by chance (see Famaey *et al.* 2007).

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Solar-type oscillations of $\iota$ Hor were detected with HARPS in November 2006. Up to 25 oscillation modes could be identified and compared with stellar models. The results led to the following conclusions for $\iota$ Hor (Vauclair *et al.* 2008): [Fe/H] is between 0.14 and 0.18; the helium abundance $Y$ is small, $0.255 \pm 0.015$; the age of the star is $625 \pm 5$ Myr; the logarithm of the gravity is $4.40 \pm 0.01$ and its mass $1.25 \pm 0.01\, M_\odot$. The values obtained for the metallicity, helium abundance and age of this star are those characteristic of the Hyades cluster (Lebreton *et al.* 2001).

This star was particularly interesting to study for various reasons, and the results lead to important conclusions. Among these, the importance of the helium value has to be stressed. It is important to realize in all asteroseismic studies that the helium abundance does not always follow the metallicity. A high metallicity may very well be associated with a low helium, even if this seems in contradiction with normal chemical evolution. In this case, the results for the stellar parameters are very different from those obtained with a high helium abundance.

## 3. New ages

Asteroseismology was given a new boost with the launch of space telescopes partially devoted to the observations of solar-like oscillations in stars. The two recent most important space projects in this respect, *CoRoT* and *Kepler*, were conceived to detect both exoplanets and solar oscillations. Studying the oscillations of exoplanet-hosting stars is a logical by-product of the observations done with these two telescopes.

*CoRoT* (see Deheuvels, these proceedings) was launched on December 27, 2006. With a 27-cm mirror, it has two focal planes, one for the exoplanet field, one for the seismic field, and four CCD cameras. Its orbit is a polar one, at 900 kilometers. *Kepler* was launched on March 7, 2009. Its mirror diameter is 1.4 meters and its orbit is heliocentric. Both space missions have unfortunately finished their duties, but the amount of results is very large in both cases, although somewhat different in the way it is treated. They both led to a huge amount of data, which have to be treated in a statistical way, but *CoRoT* also led to deeper studies, at least for one very well observed exoplanet-hosting star HD 52265.

### 3.1. *Statistical studies with large data bases*

Thousands of exoplanet candidates were detected by *Kepler*, and about 700 planetary systems are now confirmed. This huge amount of data have to be treated with good and rapid methods to find the parameters of the central star with good enough precision, and derive the characteristics of the planets.

Large teams began to work several years ago on this subject, doing “hares and hounds” tests and comparing the modelling results obtained with various codes and methods. This is the case for the “asteroFLAG” team sponsored by the International Space Science Institute (ISSI) in Bern, Switzerland (Chaplin *et al.* 2008, Stello *et al.* 2009, Mathur *et al.* 2010, Benomar *et al.* 2012). They showed, for example, that the radius of the star may be derived with an accuracy of a few percent with knowledge of the large separation only. However, these studies generally assume a fixed stellar original abundance of helium, which remains a problem as discussed below.

Rapid derivations of the stellar parameters often use the scaling relations first proposed by Kjeldsen & Bedding (1995), which give the stellar mass and radius as a function of the large separation and the frequency at the maximum of the power spectrum. Improvements in the use of these relations are obtained by introducing the stellar gravity, which is known with much better precision from seismology than from spectroscopy.

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Such a method has been used in a recent paper by Huber *et al.* (2013), in which the parameters of the central stars of planetary systems detected by *Kepler* are derived and compared with previous catalogs (Batalha *et al.* 2013). They find that the seismic parameters are similar to the spectroscopic ones for main-sequence stars, but not for evolved stars, for which the seismic values are systematically lower that the spectroscopic one, which leads to a larger stellar radius. They also can confirm previous statistics about planetary formation:

- Jupiter-like planets are more frequent around hotter stars.
- Sub-Neptune planets are found throughout the sample.
- There are more multiple systems around cool stars and more single planets around hot stars.
- No clear trend has been found for the orbital characteristics.

A crucial unknown parameter, very important for the determination of the stellar characteristics, is the helium abundance. Unfortunately, helium is not directly observable in the spectra of solar-type stars. Most studies assume that the helium abundance follows the metallicity in the same way as the general laws for the chemical evolution of galaxies. This is important for exoplanet-hosting stars, which are statistically overmetallic compared to stars without detected planets. However, as we have shown for the star $\iota$ Horologii, this may be wrong. It may happen that the star is overmetallic with a small helium abundance, as for the Hyades. In this case, the results obtained by using a high helium abundance may be wrong (Vauclair *et al.* 2008, Escobar 2013).

### 3.2. *Deep studies of one exoplanet-hosting star HD 52265*

Among all the main targets of the space telescope *CoRoT*, which were observed continuously during several months, one was specially chosen because it was known to harbour at least one planet. HD 52265 is a metal-rich main sequence star. Initially misclassified as a G0 III-IV star in the Bright Star Catalog, it has later been recognized as a G0 V dwarf.

It has a magnitude of $V = 6.301$ and a parallax of $\pi = 34.54 \pm 0.40$ mas, which leads to a distance of $d = 28.95 \pm 0.34$ pc and a luminosity of $\log L/L_\odot = 0.29 \pm 0.05$ (see references in Ballot *et al.* (2011) and in Escobar *et al.* (2012)).

The *CoRoT* observations were carried out during 117 consecutive days from 13 November 2008 to 3 March 2009, during the second long run in the galactic anti-center direction. The beautiful data which were obtained could lead to thirty one p-mode identifications, as well as precise determination of the atmospheric parameters and detailed element abundances. A large separation of $\Delta\nu = 98.4 \pm 0.1$ $\mu$Hz and a small separation of $\delta\nu_{02} = 8.1 \pm 0.2$ $\mu$Hz were derived.

A spectroscopic follow-up was done during the *CoRoT* observations with the NARVAL spectropolarimeter on TBL at the Pic du Midi Observatory (France). An upper limit of $\sim 1-2$ G was obtained for the magnetic field of this star (see Ballot *et al.* 2011).

Grids of stellar models were computed using the Toulouse-Geneva-stellar-Evolution Code (TGEC). Details about this code may be found in Hui-Bon-Hoa (2008), Théado *et al.* (2009, 2012). The unique capability of this code compared to other ones is that it can now include the effect of radiative accelerations in the computations of atomic diffusion. The radiative accelerations are computed with the SVP method (Single Value Parameter approximation, see Alecian & LeBlanc (2002), LeBlanc & Alecian (2004)). For each model, the oscillation frequencies were computed and compared with the observations using the various usual tests, including comparisons of frequency differences and detailed comparisons of echelle diagrams. Surface effects were included with the Kjeldsen *et al.* (2008) recipe.

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**Table 1.** Results for the parameters of the exoplanet-hosting star HD 52265, observed with *CoRoT*, after Escobar *et al.* (2012).

| | |
|---|---|
| $M/M_\odot = 1.24 \pm 0.02$ | $[\mathrm{Fe/H}]_i = 0.27 \pm 0.04$ |
| $R/R_\odot = 1.33 \pm 0.02$ | $\mathrm{Y}_i = 0.28 \pm 0.02$ |
| $L/L_\odot = 2.23 \pm 0.03$ | $[\mathrm{Fe/H}]_\mathrm{s} = 0.20 \pm 0.04$ |
| $\log g = 4.284 \pm 0.002$ | $\mathrm{Y}_\mathrm{s} = 0.25 \pm 0.02$ |
| Age (Gyr) $= 2.6 \pm 0.2$ | $T_\mathrm{eff}$ (K) $= 6120 \pm 20$ |

**Table 2.** Results obtained for HD 52265 from AMP automatic analysis, using all observed frequencies (a) or only the most reliable frequencies (b), after Escobar *et al.* (2012).

| | AMP(a) | AMP(b) | | AMP(a) | AMP(b) |
|---|---|---|---|---|---|
| $M/M_\odot$ | 1.22 | 1.20 | [Fe/H] | 0.23 | 0.215 |
| $R/R_\odot$ | 1.321 | 1.310 | $\mathrm{Y}_i$ | 0.280 | 0.298 |
| $L/L_\odot$ | 2.058 | 2.128 | Age (Gyr) | 3.00 | 2.38 |
| $\log g$ | 4.282 | 4.282 | $T_\mathrm{eff}$ (K) | 6019 | 6097 |

The final results for this star, as given in Escobar *et al.* (2012), are quite precise (Table 1). They have been compared with the results obtained using two different automatic fits, the Asteroseismic Modeling Portal (AMP, Metcalfe *et al.* 2009) and the SEEK code (Quirion *et al.* 2010). The results are very good with AMP (Table 2). They are slightly different with SEEK, which gives a larger mass and radius and a smaller age: $M = 1.27 \pm 0.03 M_\odot$, $R = 1.34 \pm 0.02 R_\odot$ and age $= 2.37 \pm 0.29$ Gyr. These differences may be related to their convergence to a different helium value, as discussed in Escobar *et al.* (2012).

## 4. Conclusion

Asteroseismology on the one hand, and exoplanet detection on the other hand, are parts of a new era for astrophysics, especially for stellar physics. The instruments which are devoted to exoplanet searches also look for stellar oscillations. Coupling both studies is interesting and important to lead to precise values of the parameters of the central stars of planetary systems, for a better characterization of the planets.

At the present time, space projects lead to large amount of data, so that the large data bases have to be treated in a statistical way. Automatic procedures are important in that respect. However deep studies of individual stars are still necessary to test the physics and check the values obtained with statistical studies.

For solar type stars, the original helium abundance, which is not derived by spectroscopy, may lead to erroneous results if not evaluated correctly. This may be the largest difficulty at the present time for these kind of studies.

In the near future, we may expect that precise stellar studies will lead to a better understanding of star-planet interactions, abundance variations, angular momentum transfer, tidal effects, etc.

This is an open field in which many new results may be expected, with new projects such as the PLAnetary Transits and Oscillations of stars spacecraft (*PLATO*) coming soon.

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