How asteroseismology can help to precisely constrain properties of planet-host stars

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ABSTRACT: Nowadays more than 500 exoplanets have been discovered, mainly studied by radial velocity and transit measurements. Precise knowledge on their characteristics is crucial to develop theories of planetary formation and evolution. In that aim, not only star and planet(s) masses but also the evolutionary stage of systems are needed. From radial velocity measurements one has to assume the inclination and the stellar mass of the system to disentangle the mass of the planet. When transit is observable, one can measure the ratio of planetary and stellar radii. Finally, the degree of evolution of the system is determined by the one of the star. Thus the host star must be well known to obtain a full set of system properties. However, determination of stellar parameters such as the mass, radius and its evolution from classical observables (Teff, log g, [Fe/H]) suffers of large uncertainties. This is particularly true for dwarf stars on the Main Sequence. Fortunately we can obtain better constrains with the help of asteroseismology. That latter approach probes the stellar properties through observation of oscillations present in stars. With the launches of high-precision photometry space missions, CoRoT and Kepler, we are now able to detect oscillations in a huge number of stars. In particular Kepler photometry, primarily intended to detect transits of planet, can give accurate stellar parameters of planetary systems as it also affords to make asteroseismology. We propose to review different applications of asteroseismology.

1. Setting the stage: basics on planetary systems

From radial velocity (RV) measurements:

\[ M_p \sin i \propto f(P, e, K_\star) \times (M_\star + M_p)^{3/2} \]

where \( M_p, i, P \) and \( e \) are resp. mass of the planet, inclination, period and eccentricity of the planetary orbit, and \( K_\star \) the mean velocity semi-amplitude, all but \( M_\star \) and \( i \) being obtained from RV (see e.g. Torres et al. 08, AJ 677). The mass of the star \( M_\star \) has to be inferred.

If transit is observable, one gains additional constrains:

\[ \frac{R_p}{R_\star} \approx \frac{f(\delta l, D, \varepsilon, i)}{f(P)} \times \frac{(M_\star + M_p)^{3/2}}{\pi \mu_>} \]

\( \delta l \equiv i \sin l \), \( D \equiv \rho_\star^{-1/2} \), \( \varepsilon \equiv e \cos l \) and \( \mu_> \) are resp. mass of the planet, inclination, period and eccentricity of the planetary orbit, and \( K_\star \) the mean velocity semi-amplitude, all but \( M_\star \) and \( i \) being obtained from RV (see e.g. Torres et al. 08, AJ 677). The mass of the star \( M_\star \) has to be inferred.

2. Determining the fundamental stellar parameters

Usually, mass, radius and age of planet host stars are derived from stellar models by fitting of the observed quantities: \( \log g, T_\text{eff} \) and metallicity. These atmospheric parameters are derived from spectroscopy or narrow band photometry, with typical respective errors of \( \sigma_{\log g}=\pm 0.20, \sigma_{T_\text{eff}}=\pm 100 \text{ K} \) and \( \sigma_{\text{[Fe/H]}}=\pm 0.10 \text{ dex} \).

On the other hand, the characteristics of a planet transit (see Sect.1) allow to derive the mean density \( \rho_\star \) of the host star with a precision of \( 0.10 \text{ g/cm}^3 \) which allows to significantly reduce error bars on stellar parameters (Fig. 2 and Fig. 3).

3. Unveiling host-stars from solar-like oscillations

Asteroseismology can help to access the stellar information. Stellar frequencies of oscillation are defined by three numbers: \( n \) the radial order, \( l \) the angular degree and \( \varpi_\nu \) the azimuthal order. In particular for solar-like oscillators (\( \nu<0.6 \) to \( 1.5 \text{ mHz} \)), the frequency spectra show a regular pattern (Fig. 6) mainly characterized by:

\[ \Delta \nu_n = \Delta \nu_{n+1} \approx \Delta \nu_1 \]

where \( \Delta \nu_1 \equiv \nu_2 \nu_1 \approx \nu_1 \nu_0 > \nu_1 (\text{asymptotic relation}) \)

\[ \Delta \nu_2 = \nu_3 \nu_2 \approx \nu_2 \nu_1 \approx \nu_1 \nu_0 \] and \[ \Delta \nu_3 = \nu_4 \nu_3 \approx \nu_3 \nu_2 \approx \nu_2 \nu_1 \approx \nu_1 \nu_0 \] where \( \Delta \nu_n \) is the large separation (Tassoul 80, ApJS 43), related to the mean stellar density. Combined to \( \rho_\star \), these seismic diagnosis tools help to constrain fundamental stellar parameters as shown in asteroseismic diagram in Fig. 7.

Solar-like pulsations can further constrain stellar parameters particularly from the determination of \( \nu_1 \) which gives information on the evolutionary state (or age) of Main Sequence stars, e.g. Mosser et al. 06, A&A 488. In Tab.1, relative errors on stellar masses and radii for known exoplanetary systems are obtained resp. from classical determination and from fitting to individual frequencies, being cautious to surface effects.

<table>
<thead>
<tr>
<th>Stellar type</th>
<th>( M_\star \text{[M}_\odot\text{]} )</th>
<th>( R_\star \text{[R}_\odot\text{]} )</th>
<th>( \rho_\star \text{[g/cm}^3\text{]} )</th>
<th>( T_\text{eff} \text{[K]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Sequence stars</td>
<td>0.8 to 1.5</td>
<td>0.7 to 1.3</td>
<td>0.10</td>
<td>5800</td>
</tr>
<tr>
<td>Red giants</td>
<td>1.5 to 3.0</td>
<td>1.3 to 2.0</td>
<td>0.15</td>
<td>4500</td>
</tr>
<tr>
<td>White dwarfs</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.01</td>
<td>10000</td>
</tr>
</tbody>
</table>

Tab. 1. Stellar models used as a proxy for the age of a 1 \( \text{M}_\odot \) star with a solar mixture, X=0.70 and Z=0.01. Besides, spectroscopic estimation and its errors cover a large range of the evolutionary track, uncertainties on \( \rho_\star \) span on a smaller age interval, as illustrated in Fig. 4 and Fig. 5.

4. Other types of stellar pulsations

\*HR 8799 is a system with 4 known “exoplanets” (Marcos et al. 10, Nature, in press) and exhibiting a debris disk. Determining estimate of the age of this system is of prime importance to understand how it formed and to determine its nature. As illustrated in Fig. 8 for the members of HR 8799 system, an age >300 Myrs would mean they are brown dwarves while earlier age, planets. Its host-star shows 3 freq. of pulsation identified as \( \text{Dor-like} \) (Zorzi et al. 99,MNRAS 303).

A first seismicology study shows that 2 families of models reproduce observed freq. One has ages <400 Myrs and the other >1100 Myrs (Moya et al. 10a,b; A&A 405,MNRAS 409).

Reinforced seismicology analysis based on more and more precise frequencies is essential to get a good estimation of the age of the system and hence distinguish the nature of these 4 objects.

\*V381 Peg is a sdB pulsator, that is a star on the Extreme Horizontal Branch. Silvotti et al. 07 (Nature 449) found a planet orbiting it. The new detected frequencies (Luz et al. 09, A&A 498) in this star will allow to determine the system properties and understand how can a planet survive the Red Giant evolution phase of its host-star.

For more details on the physical nature of stellar oscillations and their application in other frameworks, we invite you to refer to Arlette Noels’ lectures during this CPS school.