Detection of gravity-mode period spacings in red giant stars by the *Kepler* Mission

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Stellar interiors are inaccessible through direct observations. For this reason, helioseismologists made use of the Sun's acoustic oscillation modes to probe the solar structure with seismic methods (1). The quest to detect and exploit modes, which, unlike acoustic modes, carry information about the deep core of the Sun has been ongoing for several decades (2). We report the detection of modes which penetrate all the way to the stellar core inside red giants from 320 days of observations with the *Kepler* satellite (3). Moreover, we deduce the period spacings of these modes, offering a new tool to investigate the details of red giant core regions.

Red giants are evolved stars, like the future Sun will be, and were recently discovered to oscillate in acoustic modes similar to those found in the Sun (4). These modes are stochastically excited by convective motions in the outer layers and obey frequency spacing laws understood in terms of the theory of stellar oscillations (5,6). With the ongoing space missions CoRoT and *Kepler*, acoustic modes have been detected in several thousand red giants in various evolutionary stages (7), opening the door to asteroseismic inferences. The frequency patterns are also used to derive the basic physical stellar parameters, such as the mass and radius, with unprecedented accuracy.

One example of a red giant in which gravity-dominated mixed modes are detected is KIC 6928997. Its oscillation spectrum is shown in Fig.1 and is discussed in more detail in the online material. The spectrum deviates from the case where only patterns from pure, short-lived acoustic modes occur. We interpret the observed structure in Fig.1 as due to the presence of gravity-dominated mixed modes (8). In the case of red giants, such oscillations are mixed modes, as they have the character of a gravity mode in the core region and of an acoustic mode in the envelope of the star. From a theoretical perspective, modes with too large energy in the core will not be observed because they get trapped there. However, in the case of dipole ($\ell=1$) modes, the trapping is less efficient and some of these mixed modes probing the core could reach significant amplitudes at the surface (5,6). The observed power spectrum of KIC 6928997 is in agreement with predicted spectra of such densely populated core-dominated mixed modes. Although observed for nearly a year now, the lifetimes must be much longer than those of pure acoustic modes (4), because the mode broadening from damping is not yet fully resolved in the power spectrum. This is consistent with the predictions (5,6).

The exploitation of the detected gravity-dominated modes will allow the derivation of the core properties deep inside the red giant, such as the local density structure, the chemical composition gradient or the near-core angular momentum, which would otherwise remain inaccessible. The observed period spacings of the mixed modes of KIC 6928997, i.e., the distance in period between modes of consecutive radial order, are shown in panel B of Fig.1. The spacings of dipole modes lead to a characteristic shape (panel B), which is understood from theory as a consequence of the interaction between the acoustic and gravity mode cavities for such modes and is a key indicator of the core properties. We find a good qualitative agreement with the pattern of theoretically predicted spacings for an appropriate stellar model shown in Panel C of figure 1. The mean period spacing, along with the detected variability around it, are directly dependent on the density contrast between the core region and the convective envelope. These results demonstrate a new and unforeseen power of the *Kepler* data to yield unique probes of the deep interiors of such evolved stars.

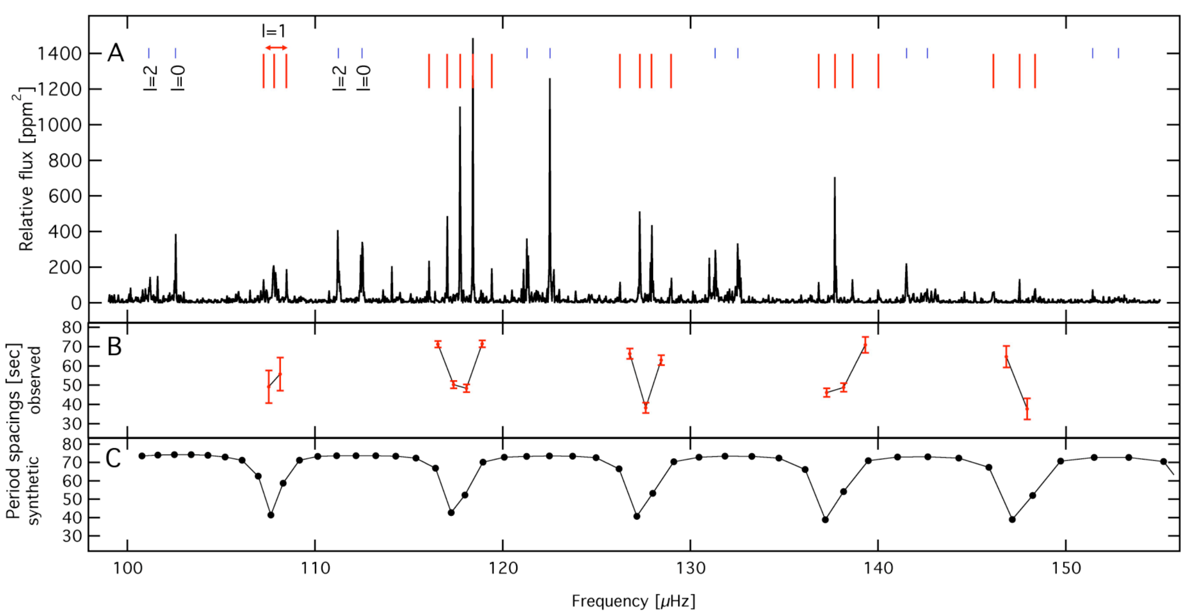

Fig 1: Frequency spectrum (A) and corresponding period spacings of mixed $\ell=1$ modes (B) for the red-giant star KIC 6928997 as observed by the *Kepler* satellite. The position of the acoustic modes ($\ell=2$ and 0) is indicated with blue ticks and the fine structure of the mixed modes with red ticks. (C) Synthetic adiabatic period separations derived from a stellar model similar to KIC 6928997 (8).

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8 Materials and methods are available as supporting material on Science Online.
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Online Abstract

Stellar interiors are inaccessible through direct observations. For this reason, helioseismologists made use of the Sun's acoustic oscillation modes to tune models of its structure. The quest to detect modes, which probe the solar core has been ongoing for decades. We report the detection of gravity-dominated mixed modes penetrating all the way to the stellar core in red giant stars from 320 days of observations with the *Kepler* satellite. The period spacings of these mixed modes are directly dependent on the density gradient between the core region and the convective envelope.

Supporting online material

Material and Methods
- Data treatment
For this analysis, 320 days of consecutive measurements in the long-cadence mode (one measurement every 30 minutes) with the *Kepler* satellite have been used (S1). The photometric band-pass is roughly compatible with a very broad combination of the V- and R-bands of the Johnson system. We computed the Fourier-transform of these photometric time series and extracted the mode information from fitting Lorentzian-profiles to the power spectrum as described in the next section.

- Extraction of mode parameters and mode identification
Solar-like oscillations are stochastically driven by convective motions and therefore get constantly damped and re-excited. This leads to a finite lifetime of the modes, and a broadening of the mode in the power spectrum. To extract the modes' parameters, we fit a series of Lorentzian profiles

$$P_{(\nu)} = \sum_{n=1}^{M} \left(\frac{H_n}{1 + \left(\frac{2(\nu-\nu_n)}{\Gamma_n}\right)^2} \right) + B$$

to the modes in a given frequency range, whereby H_n is the height in power of the Lorentzian profile, ν_n is the oscillation frequency of the mode, and Γ_n is the mode line-width. The granulation background B has been treated as constant white noise in this analysis, as its variation over the inspected frequency range is negligible. The line-width Γ_n is inversely proportional to the modes lifetime. This procedure as described was followed in the current analysis for individual and multiple peaks.

For a seismic analysis to be successful, knowledge of the spherical degree ℓ of a mode is mandatory. In the case of solar-like oscillations, this can be derived from a so-called échelle diagram. For pure short-lived acoustic modes, the frequency spectrum is very regular and well understood in terms of the so-called large separation Δν, which represents the approximate scale of the comb-like structure (S3,S4).
The center frequency of the power excess was determined to be a to be When plotting the power spectrum like structure, the modes degree is derived from the frequency separations of the ridges.

For KIC 6928997, the comb-like structure scales with Δν=10.05±0.09μHz centered on the frequency ν_{max}=120±1μHz. In the échelle diagram, the modes of degree ℓ=1 do not follow the comb-like pattern of acoustic modes, but we clearly show the fine structure of these modes ℓ=1 (fig.S1).

- Comparison with synthetic spacings
We computed the spacings for an appropriate stellar model, representing a giant with a mass of 1.5 solar masses and an age of 2.44 giga-year old star, in the adiabatic approximation, with the RADIUS-pipeline (S5). Only the spacings significantly deviating from the maximum value of 75 seconds correspond to frequencies with detectable amplitudes.

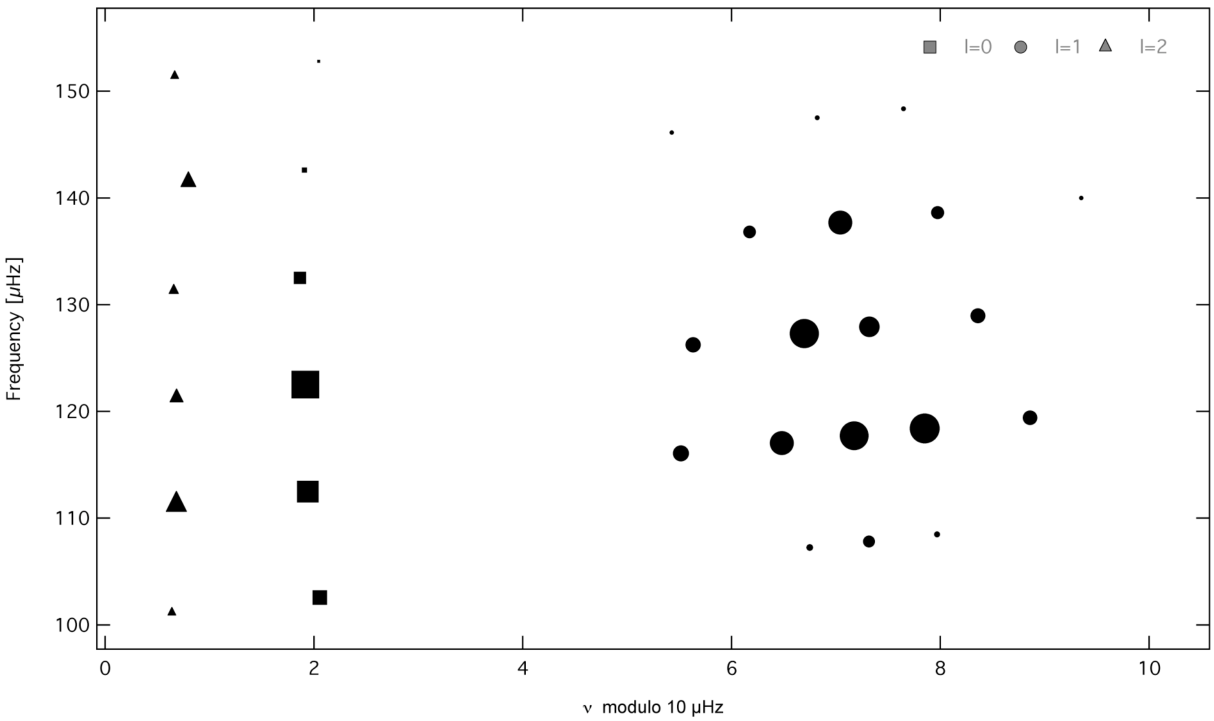

Fig.S1. The échelle diagram for KIC 6928997. The size of the symbols corresponds to the height of the individual modes in the power spectrum.

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