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Kepler Detected Gravity-Mode Period Spacings in a Red Giant Star

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Red giants are evolved stars, representing the future Sun, and were recently discovered to oscillate in acoustic modes similar to those found in the Sun (*1*, *2*). These modes are stochastically excited by convective motions in the star's outer layers and obey frequency spacing laws understood in terms of the theory of stellar oscillations (*3*, *4*). These frequency patterns are used to derive the basic physical stellar parameters, such as the mass and radius, with unprecedented accuracy.

Unlike pure acoustic modes, mixed modes probe deeply into the interiors of stars, allowing the derivation of stellar core properties, such as the local density structure, the chemical composition gradient, and the near-core angular momentum, that would otherwise remain inaccessible.

We detected mixed modes in the red-giant star KIC 6928997 (Kepler Input Catalog) on the basis of 320 days of observations with the Kepler satellite (*5*). The oscillation spectrum of KIC 6928997 (Fig. 1) (*6*) deviates from the pattern expected for pure, short-lived acoustic modes (fig. S1). This indicates the presence of mixed modes that 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 most of their 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 substantial amplitudes at the surface (*3*, *4*). The observed power spectrum of KIC 6928997 is in agreement with predicted spectra of such densely populated core-probing mixed modes. The lifetimes of these mixed modes must be longer than those of pure acoustic modes (*1*), because their mode broadening from damping is not yet fully resolved in the power spectrum (*6*). This is consistent with the predictions (*3*, *4*).

The observed period spacings of the mixed modes of KIC 6928997, that is, the distance in period between modes of consecutive radial order, are shown in Fig. 1B. The spacings of dipole modes lead to a characteristic shape, which is understood from theory as a consequence of the interaction between the acoustic and gravity mode cavities for such modes (fig. S2) and is a key indicator of the core properties. There is a good qualitative agreement between our observations (Fig. 1B) and the pattern of theoretically predicted spacings for an appropriate stellar model (Fig. 1C). The observed period spacing, along with its detected characteristic structure, provide a lower bound for the constant period spacing, which is directly dependent on the density contrast between the core region and the convective envelope.

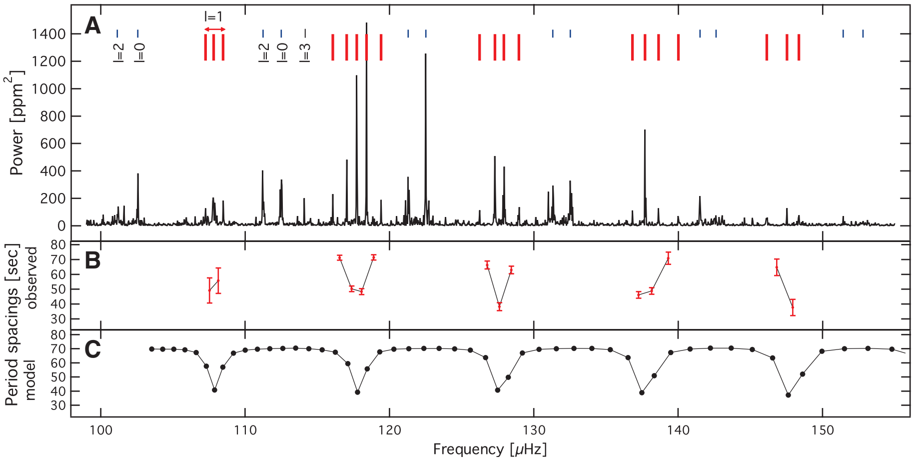

Fig. 1. (**A**) Oscillation spectrum and (**B**) corresponding period spacings of mixed $\ell = 1$ modes for the red-giant star KIC 6928997 as observed by the Kepler satellite. The position of the radial and quadrupole acoustic modes ($\ell = 0$ and 2) is indicated in blue, $\ell = 3$ in black, and the fine structure of the mixed modes in red ticks. ppm, parts per million; error bars in (B) indicate the uncertainty of the observed period spacings. (**C**) Adiabatic period separations for $\ell = 1$ modes derived from a stellar model similar to KIC 6928997 (*6*).

References and Notes

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Supporting Online Material

www.sciencemag.org/cgi/content/full/science.1201939/DC1
Materials and Methods
Figs. S1 and S2
References

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