nature Vol 459|21 May 2009|doi:10.1038/nature08022

LETTERS

Non-radial oscillation modes with long lifetimes in giant stars

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Towards the end of their lives, stars like the Sun greatly expand to become red giant stars. Such evolved stars could provide stringent tests of stellar theory, as many uncertainties of the internal stellar structure accumulate with age. Important examples are convective overshooting and rotational mixing during the central hydrogen-burning phase, which determine the mass of the helium core, but which are not well understood[1]. In principle, analysis of radial and non-radial stellar oscillations can be used to constrain the mass of the helium core. Although all giants are expected to oscillate[2], it has hitherto been unclear whether non-radial modes are observable at all in red giants, or whether the oscillation modes have a short or a long mode lifetime[3–7], which determines the observational precision of the frequencies. Here we report the presence of radial and non-radial oscillations in more than 300 giant stars. For at least some of the giants, the mode lifetimes are of the order of a month. We observe giant stars with equally spaced frequency peaks in the Fourier spectrum of the time series, as well as giants for which the spectrum seems to be more complex. No satisfactory theoretical explanation currently exists for our observations.

Stochastic oscillations with small amplitudes have been firmly detected in a few bright red giants of spectral types G and K, with both spectroscopic and photometric data[3–16]. However, the exact information contained in the power spectra of red giants is still much debated. This is well illustrated by the star ε Oph, the only red giant up to now for which ground-based radial velocity data[3] as well as 28 days of contiguous space-based photometric data[4] have been gathered.

Two completely different ways of interpreting the power spectrum of this star have been presented. One interpretation[3,4] advocates the presence of a single comb of broad equidistant peaks of radial modes only. A direct fit with Lorentz profiles of these peaks leads to a mode lifetime of approximately 2.7 days. The second interpretation[5], however, advocates the presence of at least 21 independent narrow-lined modes, both radial and non-radial, with a lifetime between 10 and 20 days. Many of the peaks that in the former interpretation are considered to be part of the wings of a stochastic realization of a broad Lorentz profile, are thus considered independent oscillation modes in the second interpretation. Up to now, no consensus has been reached in the literature whether the mode lifetimes in ε Oph, or any other G or K giant, are short or long. We refer to the Supplementary Discussion for an outline of arguments in favour of either interpretation. From this overview it is clear that there is neither consensus nor a proper understanding of stochastic oscillations in red giants. Moreover, all present studies deal with a small number of (often the same) giants. This is because gathering time series of red giants of sufficiently high quality is challenging. A larger sample of high-quality time series of red giants is the only way to gain a better understanding.

Here we present such a sample of high-precision photometric time series measured by the satellite CoRoT[17]. The Supplementary Methods supplies details on this mission, and an outline of the data reduction steps that we performed. To identify the red giants among the observed targets, we devised a semi-automated classification algorithm that relies on the power spectrum of the targets. We first selected the targets brighter than Johnson V magnitude $m_V = 15$, because simulations showed that for fainter giants the signal-to-noise ratio would not allow us easily to detect a power excess. For a target to be an acceptable red giant candidate, we required first that its power spectrum should show a background noise with increasing amplitude at low frequencies, which is what we expect because of granulation, similar to that of the Sun[18]. In addition, we required that a single power excess due to oscillations must be present, with a position between 10 and 120 μHz (ref. 19) and a width of at least 5 μHz. An increasing noise level at low frequencies due to granulation is a necessary but not a sufficient condition, because instrumental noise may show the same signature. Finally, we always verified by eye that possible frequency peaks linked to the satellite's orbit (owing to stray-light, for example, or the satellite's passage through the South Atlantic Anomaly) did not affect the classification. Following the procedure outlined above, we retained more than 300 candidate red giant pulsators. The colour-magnitude diagram shown in Supplementary Fig. 1 confirms that these pulsators are indeed located on the red giant branch.

The selected red giants show a large variety of power spectra. This is demonstrated in Fig. 1 where a stack of Fourier power spectra of nine pulsating red giants is presented. The power spectra show the unprecedented low noise level at the higher frequencies where red giant oscillations can be easily detected and analysed. A particularly interesting power density spectrum is the one of the red giant CoRoT-101034881, presented in Fig. 2, which shows a regular pattern of oscillation peaks. Folding the power spectrum leads to the echelle diagram shown in Fig. 3 in which the 12 modes form three 'ridges' corresponding to the radial, dipole and quadrupole modes. The power spectrum of this giant therefore provides clear evidence for the existence of non-radial modes. Three more examples of such giants are presented in Supplementary Figs 2–4.

It should be noted, however, that the theoretical spectrum of non-radial modes in red giants is much denser than what we observe here[2,20]. Presumably only the non-radial modes that are standing waves in the outer oscillation cavity of the giant are visible, while

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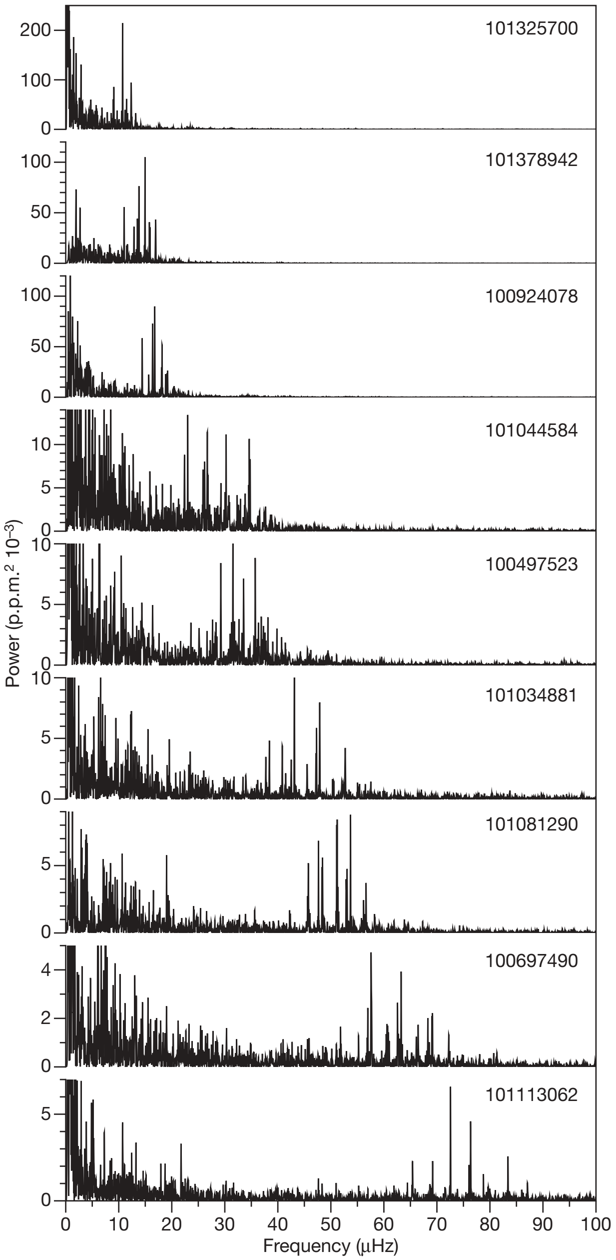

Figure 1 | A stack of power spectra of nine red giant pulsators. The power is expressed in parts per million (p.p.m.) squared divided by 1,000. The oscillation frequency peaks are clearly visible, around 75 μHz for the bottom panel, down to 10 μHz for the top panel. The values for the corresponding frequency $\nu_{\max}$ of maximum oscillation power are consistent with what is expected from scaling laws[19]. At low frequencies (<10 μHz) our detection is limited by the granulation noise, and at high frequencies (>80 μHz) the amplitudes of the oscillations drop eventually under the threshold of the detection algorithm. The nine-digit numbers given are the CoRoT identifiers of the targets. We refer to Supplementary Table 1 for their USNO-A2 identifiers.

the non-radial modes oscillating in the inner cavity, which would make up a 'forest' of frequency peaks, are not visible. Another peculiarity of the power density spectrum shown in Fig. 2 is the narrowness of the frequency peak profiles. In fact, fitting the modes with Lorentz profiles yields widths that are close to the widths expected for a finite time series of about 150 days, indicating a mode lifetime of at least 50 days. This result contrasts sharply with some of the interpretations of observational results found for the giant ξ Hya (ref. 7) and, to some extent, for ε Oph (refs 3, 4).

Not all red giants observed by CoRoT show a power density spectrum as clear as that of CoRoT-101034881. As a contrasting example

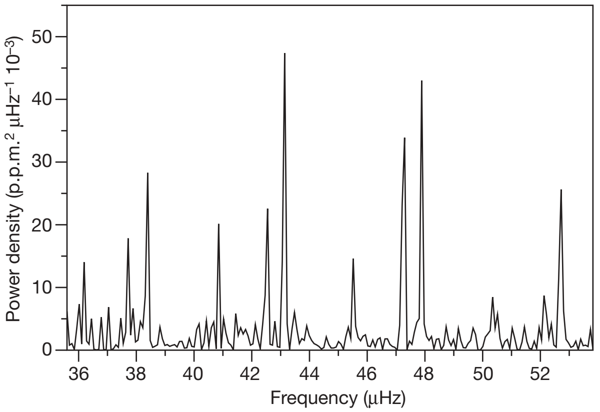

Figure 2 | Power density spectrum of the red giant candidate CoRoT-101034881 showing a frequency pattern with a regular spacing. This spacing is predicted by the theoretical asymptotic relation for high-order and low-degree oscillations[21]. Using the auto-correlation function of the power spectrum, we derive the large separation to be 4.8 μHz. This value is consistent with what is expected for red giants from scaling laws[19].

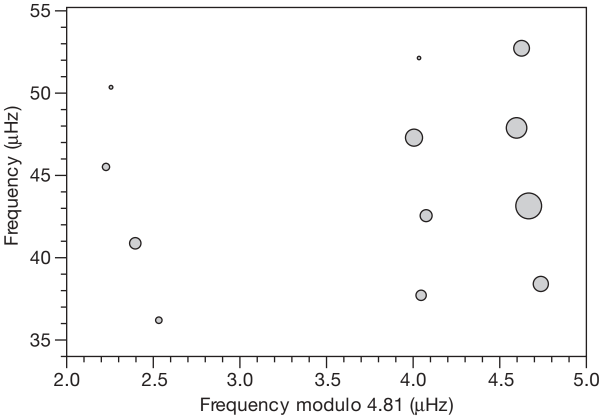

Figure 3 | Echelle diagram of the modes shown in Fig. 2, showing 'ridges' related to radial and non-radial modes. The folding frequency is 4.81 μHz. The size of the symbols is proportional to the height of the peak in the spectrum shown in Fig. 2. From the theoretical asymptotic relation for high-order and low-degree oscillations[21], we conclude that the three vertical ridges correspond to dipole modes (left), quadrupole modes (middle) and radial modes (right).

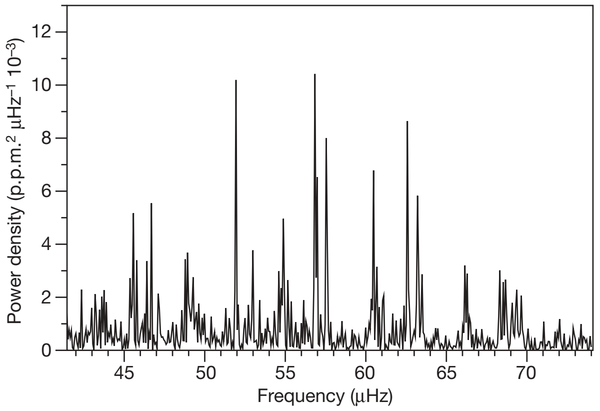

Figure 4 | Power density spectrum of the red giant CoRoT-101600807 showing broad profiles. This spectrum contrasts with that of CoRoT-101034881, highlighting the variety of red giant power spectra observed with CoRoT.

we show the power spectrum of the candidate red giant CoRoT-101600807 in Fig. 4, which also contains broad features. If these features correspond to single modes, this would imply mode lifetimes that are considerably shorter than those of CoRoT-101034881. However, if they correspond to many modes with narrow profiles, then this may imply that at least some of the non-radial modes trapped in the core of the giant are excited to detectable surface amplitudes.

Received 25 November 2008; accepted 26 March 2009.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements J.D.R., F.C. and S.H. acknowledge support from the Fund for Scientific Research, Flanders, from the research council of K. U. Leuven, and from the Belgian Federal Science Policy. A.P.H. acknowledges the support of the Deutsches Zentrum für Luft- und Raumfahrt. T.K. and W.W.W. acknowledge support by the Austrian Research Promotion Agency (FFG-ARL). J.D.R. thanks A. Miglio, M.-A. Dupret and C. Aerts for discussions.

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