Pulsating Hot Subdwarfs in Omega Centauri

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We recently discovered the first globular cluster hot subdwarf pulsators in Omega Centauri (ω Cen). These stars were initially thought to belong to the class of rapidly pulsating subdwarf B stars, which are well established among the field star population and have become showcases for asteroseismology. However, our spectroscopic analysis revealed the ω Cen variables to be significantly hotter than expected, indicating that they form a new class of subdwarf O pulsators clustered around 50 000 K, not known among the field star population. Non-adiabatic pulsation modelling suggests that the driver for the pulsations occurs via the same iron opacity mechanism that is at work in the rapidly pulsating subdwarf B stars.

The formation and evolution of hot subdwarf B- and O-type stars (sdB and sdO) stars is one of the remaining mysteries in stellar evolution theory. While it is commonly accepted that the cooler sdB stars (T_{eff} ~ 20 000–40 000 K) are compact and evolved extreme horizontal branch (EHB) stars that have lost too much of their hydrogen envelope near the tip of the red giant branch (RGB) to sustain hydrogen-shell burning on the asymptotic giant branch (AGB) after core helium ignition, the details of their evolution, in particular the dramatic mass loss, remain unclear. The hotter sdO stars (T_{eff} ~ 40 000–80 000 K) are even more challenging to understand, likely comprising a mixed bag of post-EHB, post-RGB and post-AGB stars.

One of the most promising ways of testing different evolutionary scenarios is by inferring fundamental properties, such as the total stellar mass or the thickness of the remaining hydrogen envelope, from asteroseismological analysis of pulsating hot subdwarfs. This has been done with particular success for the rapidly pulsating subdwarf B ($sdBV_r$) stars (Fontaine et al., 2012). These are a well-established class of pulsator found in a narrow instability strip between ~ 29 000 and 36 000 K, characterised by multiperiodic luminosity variations on a short timescale of 100–200 s. The observed variations can be explained very nicely in terms of non-radial pressure mode instabilities driven by an opacity mechanism associated with a local overabundance of iron in the driving region.

Although hot subdwarfs are known in large numbers both among the Galactic field population and in globular clusters (where they are identified as EHB or blue hook stars), the exploitation of their pulsations has traditionally been limited to the field star population for the simple reason that, until recently, no hot subdwarf pulsators had been found in a globular cluster.

A search for hot subdwarf pulsators in ω Cen

Like so many observational astronomy discoveries, the identification of the first hot subdwarf pulsator candidate in a globular cluster was serendipitous. We

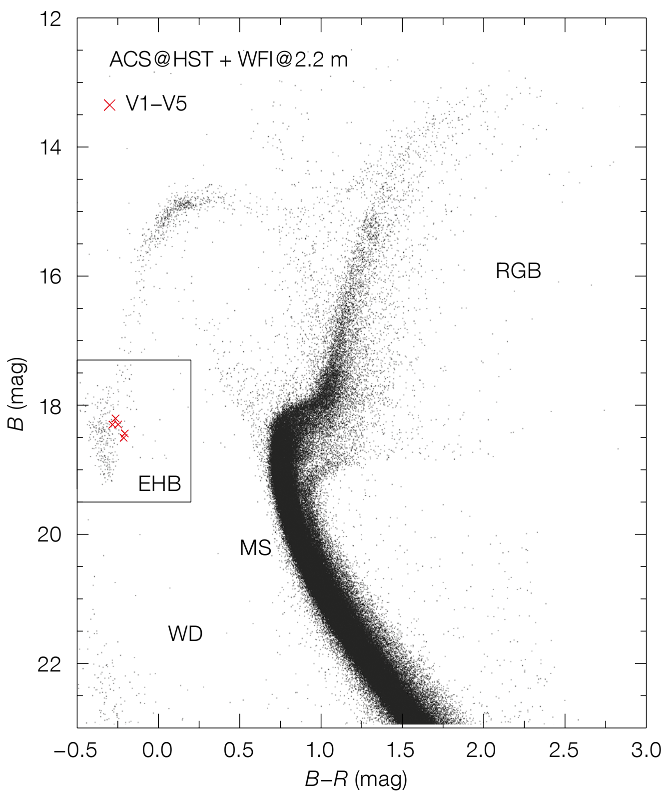


Figure 1. Colour–magnitude diagram of ω Cen based on the merged HST ACS/WFI catalogue. The box shows the colour–magnitude cuts applied for our selection of EHB star candidates, and the five rapid sdO pulsators are indicated by red crosses.

were obtaining time-series photometry with the Superb Seeing Imager 2 (SUSI2) on the New Technology Telescope (NTT) for an unrelated observing programme and chose a more or less random field in ω Cen as a backup target at the end of the night. Since at that point the hunt for sdBVr stars in bright nearby globular clusters had been going on for some time without success, we could hardly believe it when our analysis of this short two-hour dataset revealed a 115-second periodicity in a star for which the colour magnitudes were consistent with a hot subdwarf.

This initial discovery paved the way for an extensive follow-up survey with two main observational components: time-series photometry obtained with EFOSC2 and ULTRACAM at the NTT, and multi-object spectroscopy gathered using FOcal Reducer/low dispersion Spectrograph (FORS2) at the Very Large Telescope (VLT). More details can be found in Randall et al. (2016).

The time-series photometry amounts to nearly 100 hours of fast-cadence (~ 10 s) monitoring of some 300 stars scattered across off-centre fields in ω Cen and identified as EHB candidates based on a colour–magnitude cut in a merged Hubble Space Telescope Advanced Camera for Surveys (ACS) Wide Field Imager (WFI) catalogue (Castellani et al., 2007). The corresponding colour–magnitude diagram of ω Cen as well as the colour–magnitude ranges used for our EHB target selection are shown in Figure 1. It appears that this simple selection method is quite reliable, since from our spectroscopic sample of 60 stars only two turned out to not be hot subdwarfs.

From the photometry we were able to not only confirm the variability of the pulsator candidate identified with SUSI2, but also discovered an additional four pulsating EHB candidates, bringing the total number to five (denoted V1–V5 in the order that they were discovered). The pulsational properties of the variables are quite similar, each star showing two to three well-separated oscillations in the 85–125 s range with amplitudes up to ~ 2.5 % of their mean brightness. Figure 2 shows examples of the Fourier amplitude spectra obtained, the pulsations being clearly visible above the 3.7σ detection threshold imposed. It is worth noting that the highest amplitude peaks show fine frequency structure corresponding roughly to the resolution of the dataset, which are attributed to significant amplitude variations of the pulsations. Such amplitude variations are well documented for the field $sdBV_r$ stars and are therefore not unexpected.

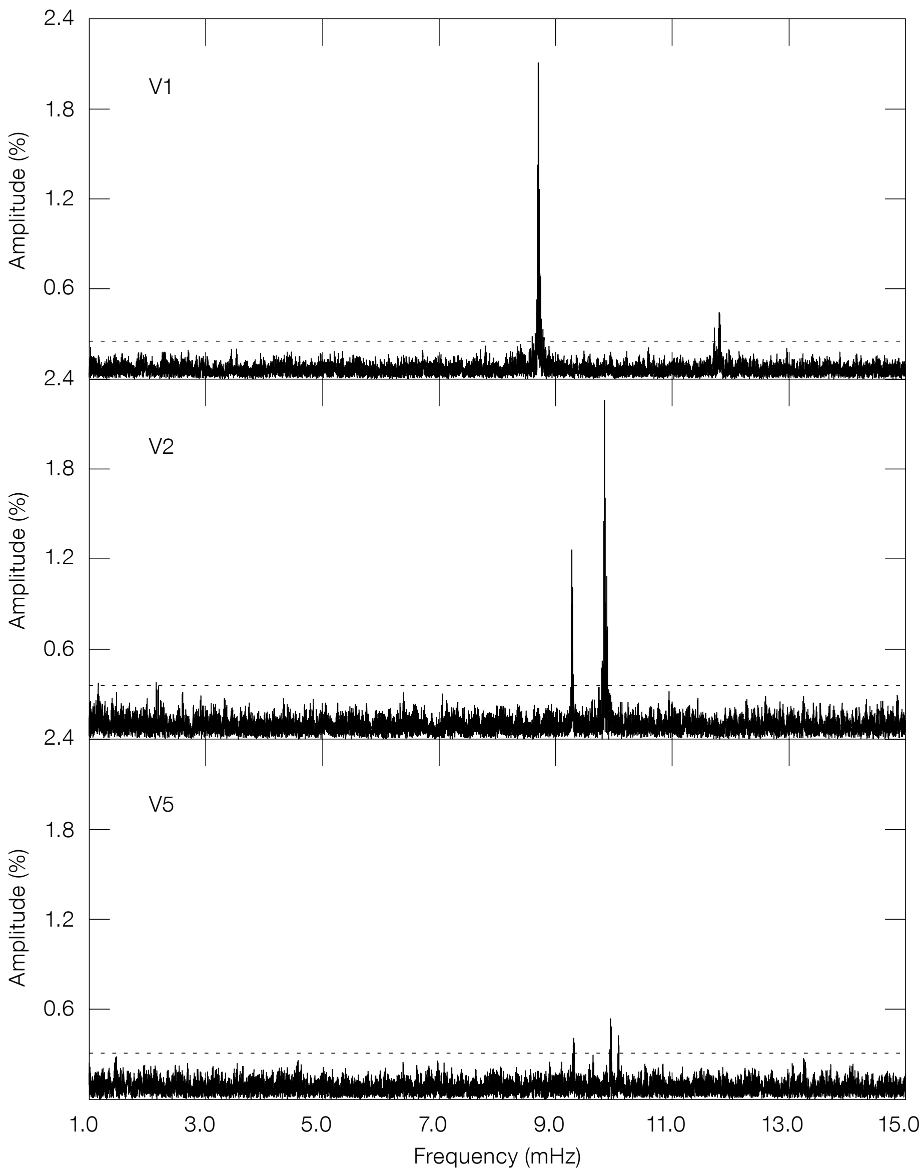
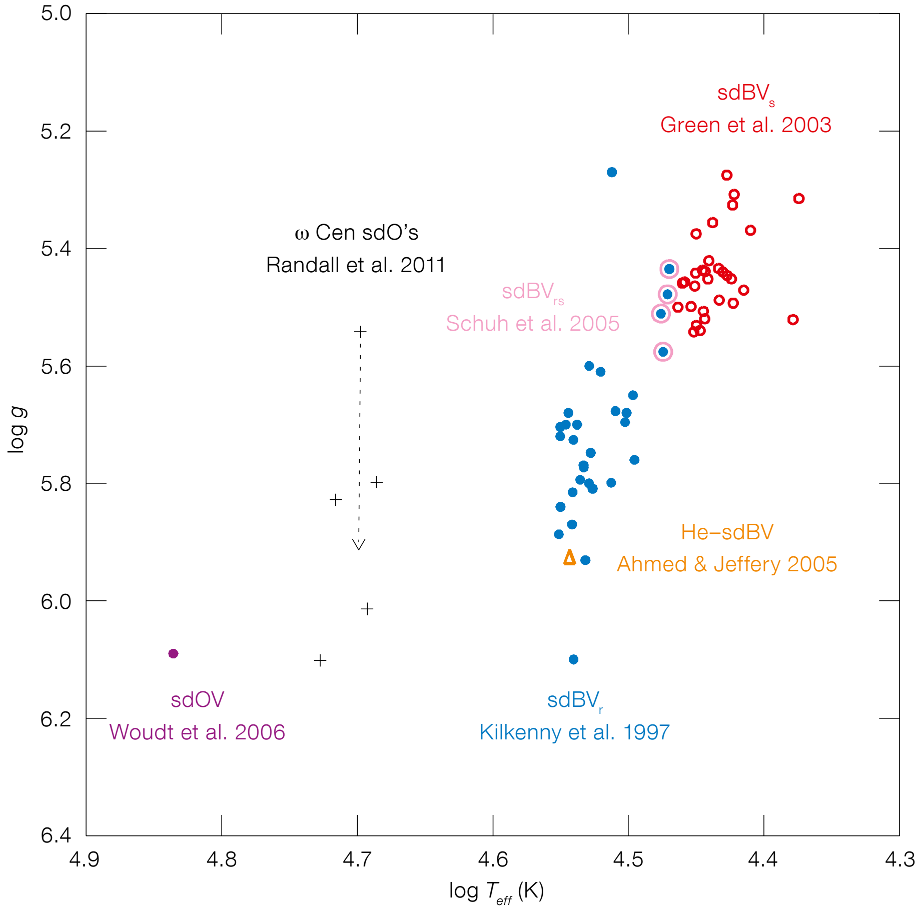


Figure 2. Fourier amplitude spectra for three of the ω Cen variables based on the combined ULTRACAM *u′* light curves. The horizontal dashed line indicates the 3.7σ detection threshold imposed.

Surprising results from spectroscopy

Given our knowledge of hot subdwarf pulsators in the field and the pulsational properties observed for the ω Cen variables, we quite naturally assumed we had found the long-sought-after globular cluster counterparts to the $sdBV_r$ stars. However, the spectroscopic data of the new variables painted a different, even more intriguing picture: rather than the expected temperatures around 30 000 K, our atmospheric analysis yielded significantly higher values around 50 000 K, implying that these stars are in fact a new type of sdO pulsator never observed among the field star population!

Figure 3. Location in T_{eff}–log g space of the ω Cen variables compared to the different types of field hot subdwarf pulsators known. The reference to the discovery paper is indicated for each.



This can be fully appreciated from Figure 3, where we show the location of the ω Cen pulsators compared to the known field hot subdwarf pulsators. Only the previously mentioned sdBV$_r$ pulsators and the one lone field sdOV star show periods on short timescales comparable to the ω Cen variables, while the other types of pulsator oscillate on longer timescales of one to several hours. None of the field star variables falls in the ~ 48 000–52 000 K range where the ω Cen pulsators are found. Conversely, we did not identify any counterparts to the field star variables in ω Cen, although this is quite possibly due to the limitations of our dataset both in terms of quality and sample size.

The empirical ω Cen instability strip derived from our survey is shown in Figure 4. Here we have included only the 26 targets for which we have both high quality light curves from photometry as well as reliable atmospheric parameters from spectroscopy. Apart from a clear bias towards the pulsators, which were specifically included in the spectroscopic sample, there should be no additional selection effects beyond the colour–magnitude cuts described earlier. From the plot it is not entirely clear whether all stars falling within the instability strip pulsate, or whether non-variable stars co-exist in the same region of T_{eff} – log g space, as is the case for the sdBV$_r$ pulsators in the field.

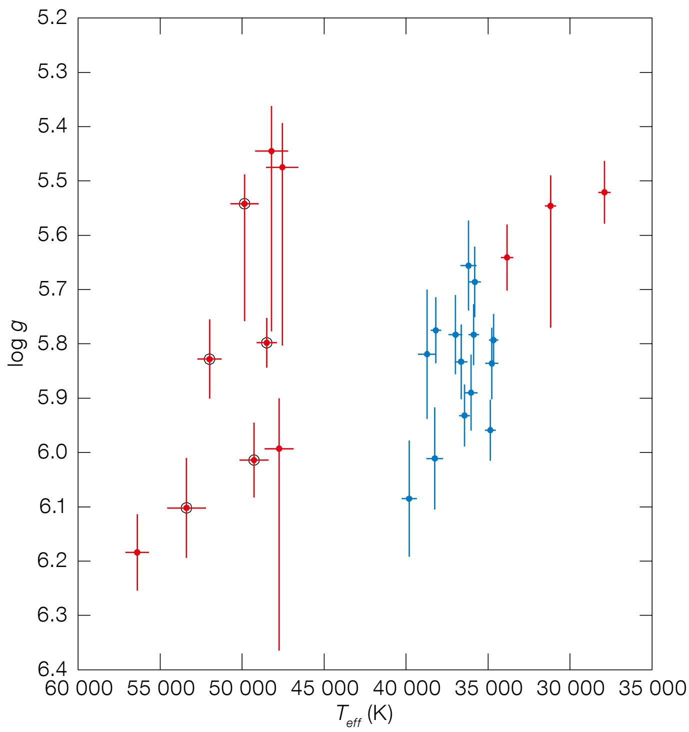


Figure 4. Observed hot subdwarf instability strip in ω Cen. The five pulsators are marked by large open circles. Red symbols indicate H-rich stars, blue ones refer to He-rich targets.

Pulsation calculations

Keeping in mind their very similar pulsation properties and relative proximity in atmospheric parameter space, it seemed likely that the pulsation driving mechanism active in the ω Cen variables is the same opacity mechanism that explains the sdBV$_r$ instability strip so well. Therefore, we extended our existing stellar envelope models to higher temperatures, encompassing the entire range where hot subdwarfs are found. These so-called Montréal second-generation models incorporate traces of iron that are levitating

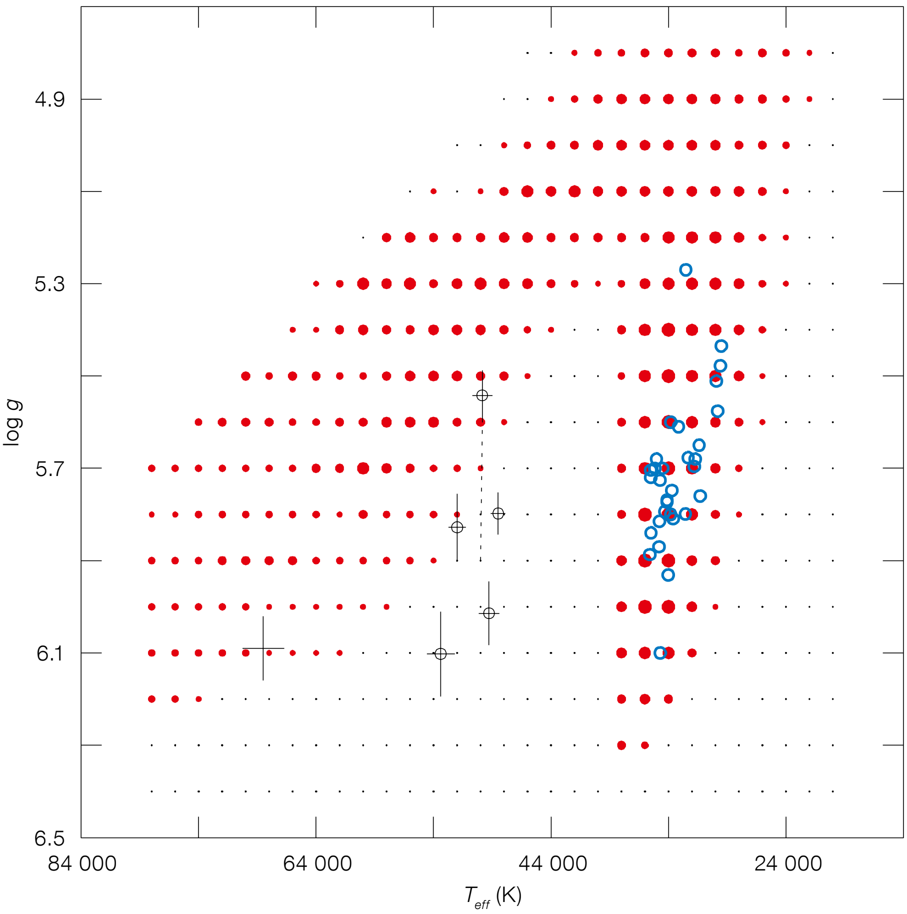


Figure 5. Theoretical instability strip for rapid pressure-mode pulsations in hot subdwarfs. Each red point indicates a model where pulsations are driven. The blue circles show the location of observed $sdBV_r$ stars in the field, while the black cross represents the one sdO field pulsator known. The ω Cen pulsators are depicted as black open circles with error bars; the dotted extension to higher log *g* values for one of them indicates that the spectroscopic log *g* is likely underestimated due to contamination from nearby stars.

in a pure hydrogen envelope under the assumption that an equilibrium has been reached between radiative levitation and gravitational settling (Charpinet et al., 1996; 1997). The iron abundance profile as a function of stellar depth is then necessarily a function of log *g* and T_{eff}. Since the presence of an opacity bump associated with an overabundance of iron in the driving region allows pulsations to be excited, it follows that this will happen only for models with certain log g/T_{eff} combinations.

From our non-adiabatic oscillation calculations, we find that pressure-mode pulsations (corresponding to short periods up to a few hundred seconds) are indeed driven not only for sdB star models around 30 000 K, but also at higher temperatures above ~ 50 000 K. This can be seen nicely in Figure 5, where we show the theoretical instability regions for the entire log g – T_{eff} space where hot subdwarfs are found.

Unfortunately, while the cooler instability strip matches the location of the $sdBV_r$ stars perfectly, the hotter instability region does not quite reach the ω Cen pulsators, which lie beyond the predicted red edge. This mismatch may be partially due to the effective temperatures from our optical spectra being underestimated for these very hot stars, however the periods of the oscillations predicted are also significantly shorter than those observed. It is clear that the models need to be improved, particularly with regards to other metals besides iron being included in the diffusion calculations. Nevertheless, we are confident that we have identified the basic driving mechanism in the ω Cen pulsators to be the same opacity mechanism that is at work in the $sdBV_r$ stars.

The plot thickens

Far from giving definite answers, the results of our survey have instead raised more questions. But that is the beauty of observational astronomy: you rarely find what you expect, and the deeper you look the more complicated the picture becomes, opening up new avenues of research. In this case, the unexpected discovery of a hitherto unknown type of pulsator in ω Cen triggered an intense search for direct counterparts among the field population, which however came back negative (Johnson et al., 2014). On the other hand, a space-based search for rapid hot subdwarf pulsators in the globular cluster NGC 2808 (Brown et al., 2013) revealed six rapid pulsators with periods on timescales similar to the sdOV and $sdBV_r$ stars discussed here. Given the low quality of the available spectroscopy, it is completely unclear whether any of these pulsators correspond to the ω Cen variables, or indeed any of the known field hot subdwarf pulsators. Further investigations and more detailed observations are clearly warranted.

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