

## A survey of hot subdwarf pulsators in $\omega$ Cen

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**Abstract.** We recently discovered an apparently new class of pulsating Extreme Horizontal Branch (EHB) star in  $\omega$  Cen. Tightly clustered around  $\sim 50,000$  K, these H-rich sdO stars exhibit rapid, multi-periodic oscillations on a timescale of 100 s. While four such objects have been detected in  $\omega$  Cen, no counterparts have yet been found among the field population. Conversely, the rapid sdB pulsators around 31,000 K that are well-studied in the Galactic field have yet to be found in a globular cluster. We discuss the implications of this and also report the discovery of a fifth EHB pulsator in  $\omega$  Cen.

### 1. INTRODUCTION

The formation of hot subdwarf (sdO and sdB) stars constitutes one of the last remaining mysteries in stellar evolution theory. Found among the Galactic field population as well as in globular clusters, it is generally accepted that these evolved, compact Extreme Horizontal Branch (EHB) stars are the progeny of Red Giant Branch (RGB) stars that underwent significant mass loss on the RGB phase, leaving them with envelopes too thin to ascend the Asymptotic Giant Branch (AGB). A number of different evolutionary scenarios have been proposed, including binary formation channels with a common envelope phase, stable and unstable Roche lobe overflow [1, 2]. It has also been suggested that some globular cluster EHB stars may be the progeny of the helium-enhanced sub-populations found

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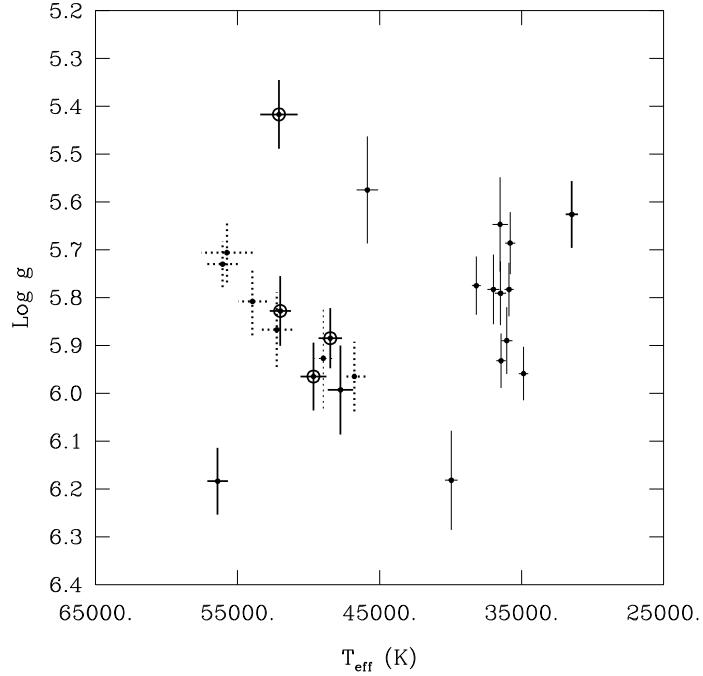
in a few globular clusters [3] or the aftermath of hot helium flashers [4]. Systematic differences in the observed binary properties of field and globular cluster EHB stars point towards different evolutionary scenarios dominating the EHB formation in the two stellar environments [5]. It was suggested [6] that this may be explained by a He-white dwarf merger channel becoming more important for older stellar populations, but this remains to be confirmed.

One very promising way of testing the different evolutionary scenarios proposed is through asteroseismology, where the fundamental parameters of a star are determined to a high accuracy by modelling its oscillation spectrum. This has been done with great success in particular for the rapid sdB ( $\text{sdBV}_r$ ) pulsators. These objects are found within a well-constrained instability strip around  $T_{\text{eff}} \sim 31,000$  K among the Galactic field population, and typically exhibit periods between 100–200 s. First comparisons of the derived asteroseismic mass distribution with those predicted from different evolutionary scenarios are highly promising [7], and as statistics build up we will likely be able to place firm constraints on the relative importance of different evolutionary channels for EHB stars among the field population. Unfortunately, asteroseismic exploitation lags far behind for EHB stars that are part of a cluster population. We ultimately hope to use asteroseismology to compare the evolution of EHB stars in clusters and among the field population and determine if and how they differ.

## 2. EHB PULSATORS IN $\omega$ CEN

Until a couple of years ago, no EHB pulsators were known in globular clusters. However, a rapid time-series photometry survey monitoring several hundreds of EHB stars in the globular cluster  $\omega$  Cen recently uncovered four rapid, non-radial pulsators with periods in the 85–115 s range and amplitudes up to 3% of the mean stellar brightness [8, 9]. Initially assumed to constitute the globular cluster counterparts to the extensively studied  $\text{sdBV}_r$  stars in the Galactic field, subsequent spectroscopy instead revealed them to be hydrogen-rich sdO stars with temperatures tightly clustered around  $T_{\text{eff}} \sim 50,000$  K [10]. This was a highly intriguing discovery, since such EHB pulsators are not known to exist outside of  $\omega$  Cen. Despite extensive searches for sdO pulsators among the Galactic field population [11], the only currently known field sdO pulsator [12] is significantly hotter with  $T_{\text{eff}} \sim 70,000$  K [13], and is helium-rather than hydrogen-rich. In terms of pulsation properties however, the two types of sdO pulsator are extremely similar, showing shorter periods and higher amplitudes than typical cooler  $\text{sdBV}_r$  stars.

First non-adiabatic pulsation computations indicate a link between the different types of EHB pulsators. Indeed, the rapid oscillations observed in both the sdB and sdO domains can be qualitatively explained by a  $\kappa$ -mechanism associated with a local overabundance of heavy elements in the driving region. The so-called “second-generation” models incorporating the diffusion of iron in an otherwise pure hydrogen-envelope were first used more than a decade ago to successfully model the  $\text{sdBV}_r$  instability strip [14, 15]. More recently, it was shown that individual models with  $T_{\text{eff}} \sim 70,000$  K are able to excite modes with periodicities in a similar range to those observed in the known field sdO pulsator [16]. In light of the  $\omega$  Cen pulsator discovery we finally computed a grid of models sampling the entire sdO/sdB domain in the  $\log g - T_{\text{eff}}$  plane, and found the sdB and sdO instability strips to be connected at low surface gravities. While our current temperature estimates place the hydrogen-sdO pulsators just to the red edge of the theoretical sdO instability strip [17], we nevertheless believe the basic driving mechanism to have been identified. It is quite probable that the effective temperatures derived from optical spectroscopy were underestimated, and that the real temperatures of the  $\omega$  Cen pulsators (as could be determined more accurately from UV spectroscopy) are up to  $\sim 5000$  K higher. On the modelling side the red edge of the instability strip will likely be pushed to lower temperatures with the incorporation of other heavy elements (such as nickel) besides iron. We hope to address these issues in the near future, enabling a better characterisation of the observed and theoretical EHB instability regions.

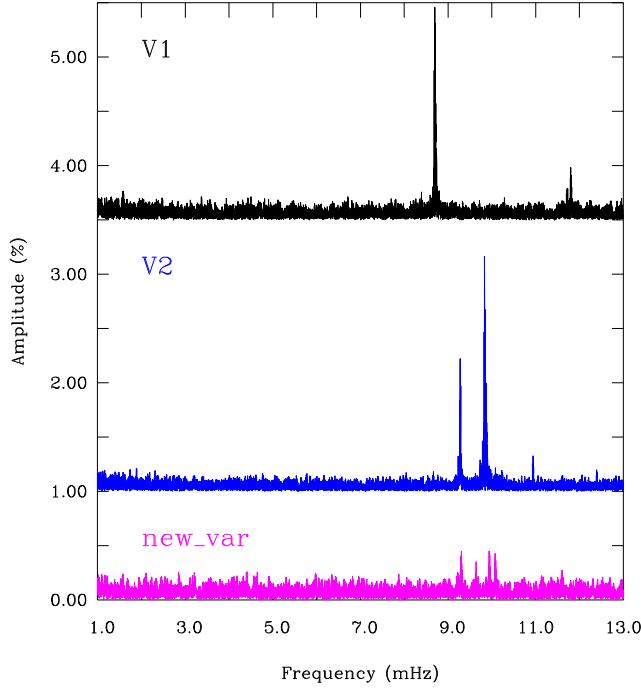


**Figure 1.** Current EHB star instability strip for  $\omega$  Cen, as obtained on the basis of our EFOSC2 and ULTRACAM photometry surveys combined with FORS spectroscopic measurements. The large open circles with error bars show the four variables, while small points with error bars indicate stars that appear to be constant. Blue symbols refer to He-rich EHB stars, while red symbols denote H-rich objects. The points with dotted error bars show the location of 6 sdO stars in the Galactic field that were monitored for pulsations and found to be constant.

### 3. DIFFERENCES BETWEEN THE EHB INSTABILITY STRIP IN $\omega$ CEN AND THE GALACTIC FIELD?

The currently observed EHB instability strips in  $\omega$  Cen and in the Galactic field are completely anti-correlated. While the first sdBV<sub>r</sub> star still remains to be identified in any globular cluster, the H-sdO pulsators in  $\omega$  Cen appear to have no counterpart amongst the field star population. Does this constitute a real discrepancy, or are we simply facing an observational bias due to small-number statistics?

Figure 1 shows the  $\omega$  Cen instability strip based on 18 targets for which we derived self-consistent atmospheric parameters on the basis of FORS spectroscopy, and for which we have EFOSC and/or ULTRACAM time-series photometry. In this view the H-sdO instability strip appears well-defined and pure, however this is most likely due to the strong selection effect applied when specifically choosing the four variables on top of an otherwise random sample of EHB stars. Keeping in mind the common driving mechanism, it seems more probable that, like the sdBV<sub>r</sub> pulsators, the H-sdO variables co-exist with constant stars in the same region of the  $\log g - T_{\text{eff}}$  diagram. This could naturally explain why none of the field sdO stars around 50,000 K that have so far been searched for pulsations were found to oscillate. Unfortunately, sdO stars are few and far compared to sdB stars, and we were so far able to monitor only 6 field star pulsator candidates for which we have accurate atmospheric parameters consistent with those of the  $\omega$  Cen pulsators. These targets are plotted alongside the  $\omega$  Cen EHB stars in Fig. 1 (dotted error bars). Assuming that, like for the sdBV<sub>r</sub> variables [18] just one out of 10 sdOs within the instability region pulsates, our null results are not yet indicative of systematic differences between the field and globular cluster sdO populations. In  $\omega$  Cen we monitored several hundred EHB



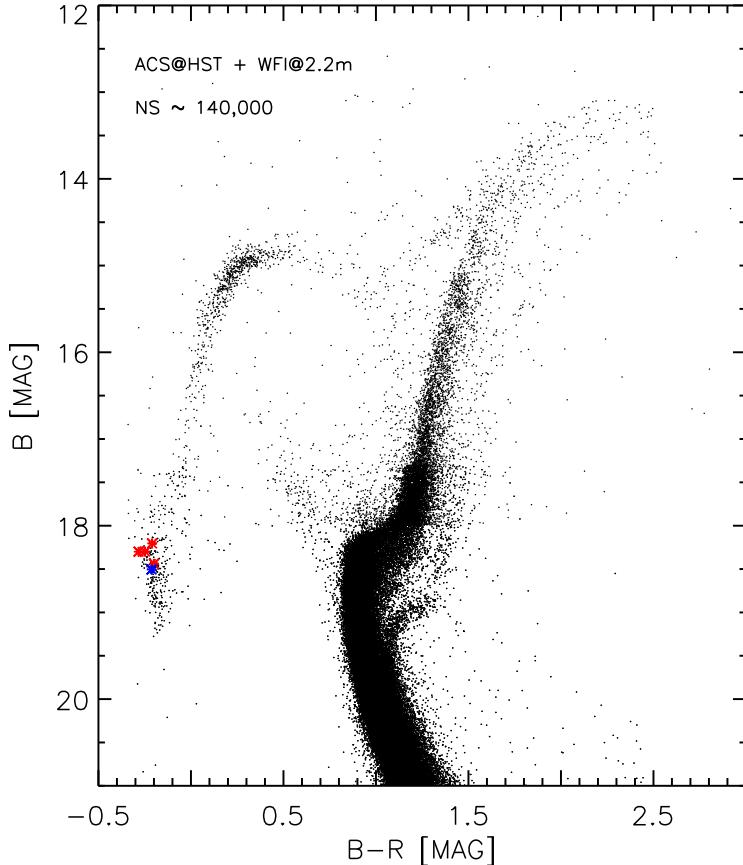
**Figure 2.** ULTRACAM  $u'$  band Fourier Transforms computed for V1,V2 and the new variable. The upper two curves have been shifted arbitrarily along the y-axis for visualisation purposes.

**Table 1.** Periodicities detected from the  $u'$  ULTRACAM data for the new EHB variable.

Rank	$P$ (s)	$\text{Amp}_{u'}\ (\%)$
1	100.50	0.50
2	99.25	0.44
3	107.49	0.41

stars in order to find just four pulsators, so it may simply be a matter of continuing the search for sdO pulsators in the Galactic field.

Concerning the apparent lack of  $\text{sdBV}_r$  pulsators in  $\omega$  Cen it is worth mentioning that compared to the sdO oscillators detected, most  $\text{sdBV}_r$  variables show smaller pulsational amplitudes that may be as low as  $\sim 0.3\text{--}0.5\%$  (compared to the 1-3% found in the  $\omega$  Cen variables). As such, they may well not have been detected in the original survey for EHB pulsators in  $\omega$  Cen, where the noise level of the data was relatively high and somewhat inhomogeneous across the sample. Therefore, we recently requested more sensitive follow-up observations of one of the EFOSC survey fields with ULTRACAM mounted on ESO/NTT at La Silla, Chile, and obtained a total of  $\sim 55$  hours of multi-colour time-series photometry. The aim was to lower the  $4\sigma$  detection threshold for credible pulsations to a level where typical  $\text{sdBV}_r$  pulsators would be detectable. While the data reduction process is still ongoing, we were already able to compute period spectra with a detection threshold  $\lesssim 0.4\%$  for some 75 EHB stars, but none of which are obviously  $\text{sdBV}_r$  pulsators (but see Section 4). It is not yet clear whether or not this is a statistically significant result. The most extensive search for blue variables among the field population to date was carried out by a group from South Africa based on the Edinburgh-Cape survey [19]. Unlike many later searches, the photometry targets were not pre-selected based on effective temperature but only on colour, and as such the sample should come close to our EHB selection, which is based purely on published WFI colours [4]. Given that the resulting fraction of  $\text{sdBV}_r$  pulsators found by the South



**Figure 3.** Colour-magnitude diagram of  $\omega$  Cen based on a WFI/ACS catalogue [4]. The four sdO variables are marked by red asterisks, while the new EHB variable is shown in blue.

African team was only 1.7%, the fact that we did not yet detect such a variable among our sample is not conclusive evidence of a lower sdBV<sub>r</sub> fraction in  $\omega$  Cen compared to the field. We hope that with the final reduction of the ULTRACAM data we will be able to present either a statistically significant null result, or – even better – the first sdBV<sub>r</sub> variable(s) in a globular cluster.

#### 4. A NEW EHB VARIABLE

The ongoing analysis of the ULTRACAM data has in fact already revealed a new candidate EHB pulsator. In Fig. 2 we show the Fourier Transform obtained on the basis of a preliminary ULTRACAM u' band light curve for this new variable compared to two of the four previously known H-sdO pulsators (labelled V1 and V2). It can be seen that, while the pulsational amplitudes for this new variable are much lower, the range of excited periods completely overlaps with that for V1 and V2. We list the periodicities extracted for the new variable in Table 1. These stars all have amplitudes above a detection threshold set to 4 times the local noise level, and can be recovered from different sub-samples of the light curve. Therefore, we regard the detection as secure, despite the relatively low amplitudes. Comparing the periodicities extracted to those published for the other H-sdO variables [10] it seems likely that this new variable is a member of this class of pulsator rather than a sdBV<sub>r</sub> pulsator, since the latter typically exhibits slightly longer periods above  $\sim 120$ –130 s.

In Fig. 3 we show the Colour-Magnitude diagram (CMD) of  $\omega$  Cen based on a composite of Wide Field Imager (WFI) B,V band photometry taken at La Silla with the 2.2-m telescope, and Hubble Space Telescope Advanced Camera for Surveys B,R-band data [4]. The locations of the four H-sdO variables are marked by red asterisks, while the new variable is shown in blue. On the plot, the new variable appears to lie on the same part of the EHB as the four other variables, however since the colour-magnitude estimates, especially from photometry obtained at visible wavelengths, are notoriously prone to errors, this does not necessarily imply that the temperatures are similar. It is only from spectroscopic measurements that we will be able to clarify whether the new variable is a member of the same class of pulsator as V1–V4, whether it is a cooler sdBV<sub>r</sub> star, or perhaps a new type of variable altogether. Given the period of the excited modes we believe the first option is the most likely, however we will not know for sure until we obtain a high-quality spectrum.

## 5. CONCLUSIONS

The study of pulsating EHB stars in globular clusters is a new field of research that is only just opening up. To date, we know of just 5 EHB pulsators in  $\omega$  Cen, which is by no means a typical globular cluster. The  $\omega$  Cen pulsators currently form a unique class of EHB variable that has yet to be detected among the Galactic field population, or in other globular clusters. Conversely, the well-understood sdBV<sub>r</sub> stars that have been used so successfully for asteroseismology remain to be discovered in a globular cluster environment. It is clear that a lot of work still needs to be done on the observational front if the EHB instability strip in  $\omega$  Cen and other globular clusters is to be quantitatively compared to that of the Galactic field.

On the theoretical side, we need more realistic models that take into account other heavy elements besides iron while at the same time including diffusion in order to better model the EHB instability strip. The discovery of sdBV<sub>r</sub> stars in a globular cluster would be most welcome, as we could then test the exact same models as used so successfully for the field sdBV<sub>r</sub> stars in a globular cluster context. Similarly, the detection of H-sdO pulsators in the Galactic field would allow a direct comparison between the same type of object among the globular cluster and the field population, and would help us solve the mystery of the different evolutionary channels at work in the two environments.

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