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A Study of the Newly Discovered Rapid sdO Pulsators in ω Centauri

S. K. Randall,[1] G. Fontaine,[2] A. Calamida,[3] P. Brassard,[2] P. Chayer,[4] M. L. Alonso,[5,6] M. Catelan,[5] G. Bono,[7] E. M. Green,[8] V. S. Dhillon,[9] and T. R. Marsh[10]

[1] *ESO, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany*

[2] *Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, QC H3C 3J7, Canada*

[3] *Osservatorio Astronomico di Roma, Istituto Nazionale de Astrofisica, via Frascati 33, 0040 Monte Porzio Catone, Italy*

[4] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*

[5] *Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile*

[6] *Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium*

[7] *Department of Physics, Università di Roma "Tor Vergata", via della Ricerca Scientifica 1, 00133 Rome, Italy*

[8] *Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA*

[9] *Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK*

[10] *Department of Physics, University of Warwick, Coventry CV4 7AL, UK*

Abstract. We summarise recent observational and modelling results obtained for the newly discovered rapid sdO pulsators in ω Centauri. At present, these variables have no counterpart among the field star population, and the extent and purity of the associated instability strip is not yet well defined. First non-adiabatic computations indicate that the pulsations observed are driven by the same κ-mechanism that has been invoked to explain the oscillations in the extensively studied field sdB pulsators. The ω Cen variables appear to show only a small number of independent modes down to the currently achievable detection threshold and there is evidence for significant amplitude variations over time. It remains to be seen whether these objects can be exploited for asteroseismology in the near future; this will certainly be challenging both from an observational and a modelling point of view.

1. Introduction

Pulsators among hot subdwarf (sdO and sdB) stars may hold the key to understanding the formation of the Extreme Horizontal Branch (EHB), one of the last remaining mysteries in stellar evolution theory. The asteroseismological interpretation of these stars' non-radial pulsation spectra can yield precise estimates of fundamental stellar parameters such as the total stellar mass and the thickness of the thin hydrogen-rich envelope surrounding the helium-burning core, which in turn place constraints on the evolutionary path followed.

Up until recently, all known EHB pulsators were found among the field star population and could be divided into five groups:

- Rapidly pulsating sdB stars (Kilkenny et al. 1997). Also known as EC 14026 or sdBV$_r$ stars, these objects are found in a well-defined instability strip between ~29,000 and 36,000 K and show *p*-mode pulsations on a time-scale of typically 100-200 s. The non-adiabatic pulsation properties have been modelled very successfully in terms of a classical κ-mechanism associated with a local overabundance of iron in the driving region (Charpinet et al. 1997) and asteroseismic analyses leading to a first mass distribution have now been performed for some 15 targets (see Fontaine et al. 2011, A&A, submitted, for an overview).

- Slowly pulsating sdB (sdBV$_s$) stars (Green et al. 2003). Corresponding to the cooler sdB stars with 22,000 $\lesssim T_{\rm eff} \lesssim$ 29,000 K, these pulsators exhibit *g*-mode pulsations with much longer periods on the order of one to two hours. While the modelling of their non-adiabatic properties in terms of the κ-mechanism remains challenging (Fontaine et al. 2003; Jeffery & Saio 2006), asteroseismology has recently become feasible with the advent of *Kepler*, and has already yielded highly intriguing results (van Grootel et al. 2010; Charpinet et al. 2011).

- Hybrid sdB pulsators (Schuh et al. 2005). Found at the intersection of the sdBV$_r$ and sdBV$_s$ domains, these objects exhibit both *p*- and *g*-mode pulsations.

- One Helium-rich sdB pulsator clearly located in the temperature domain of the sdBV$_r$ stars ($T_{\rm eff}$ ~ 35,000 K) was found to exhibit *g*-mode pulsations on a time-scale of 2000-5000 s (Ahmad & Jeffery 2005). It was recently proposed that these pulsations are driven by an ϵ-mechanism (Miller Bertolami et al. 2011).

- One sdO star exhibiting very rapid (P = 60-120 s) multi-periodic *p*-mode oscillations was discovered by Woudt et al. (2006). Exploratory non-adiabatic computations indicate that the pulsations observed can be qualitatively explained by the same κ-mechanism that is also at work in the sdB variables (Fontaine et al. 2008).

Several searches for counterparts to these variables in globular clusters remained inconclusive (e.g. Kaluzny & Thompson 2008; Catelan et al. 2008), until finally a promising rapid EHB pulsator candidate was identified in ω Centauri (Randall et al. 2009). The prospect of asteroseismic EHB targets in a globular cluster is particularly exciting considering the currently raging debate about EHB star formation in different stellar environments. Therefore, we made follow-up observations of this candidate pulsator a top priority.

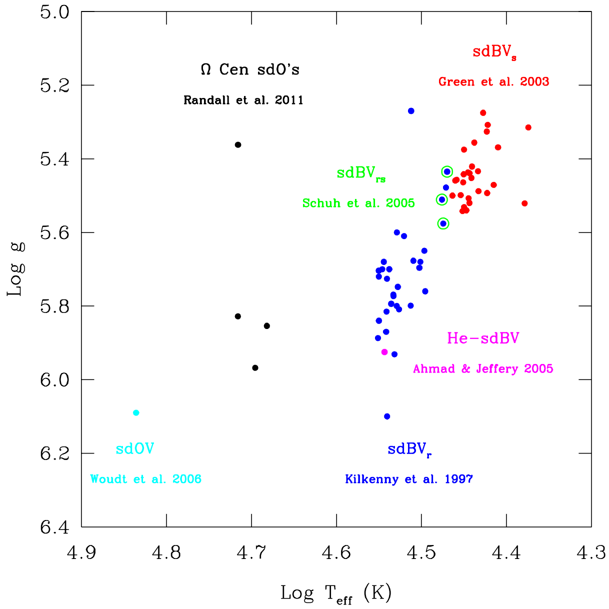

Figure 1. The distribution in $\log g$ and $T_{\rm eff}$ of the different hot subdwarf pulsators so far known.

2. Discovery of sdO Pulsators in ω Centauri

At the Fourth Meeting on Hot Subdwarfs and Related Objects held in July 2009 in Shanghai we were able to announce the discovery of three rapidly pulsating EHB stars in ω Cen (including the promising candidate previously identified) on the basis of a partial analysis of EFOSC2 time-series photometry obtained at the NTT in April 2009 (Randall et al. 2010). The analysis of the remaining data revealed another such variable, bringing the total number of known rapid EHB pulsators in ω Cen to four. These objects show multi-periodic luminosity variations in the 85-125 s timerange with amplitudes up to 2.7 % of the mean brightness, and were initially assumed to constitute the globular cluster counterparts to the well-studied rapid sdB pulsators among the field population. However, recent FORS2 spectroscopy revealed them to be significantly hotter hydrogen-rich sdO stars with effective temperatures tightly clustered around 50,000 K (Randall et al. 2011). Their location in the $\log g$-$T_{\rm eff}$ diagram with respect to the previously known EHB pulsators is shown in Fig. 1. The clear separation in temperature from both the rapid sdB pulsators and the one sdO pulsator known among the field star population appears indicative of a new class of pulsating star. This opens up new areas for exciting research, both from an observational and a modelling point of view.

A first attempt to observationally characterise the instability strip of the new ω Cen variables is illustrated in Fig. 2. We show 15 EHB stars in ω Cen for which we derived atmospheric parameters from FORS2 spectroscopy and that were also monitored with rapid photometry. From this rather small sample the instability strip appears well-defined and potentially pure, but it is obviously far too early for conclusive statements, especially considering the selection effects applied. The FORS2 spectroscopic sample was designed to include the 4 previously known variables as well as another 35 randomly selected EHB stars. Of the latter, only two are close in temperature to the

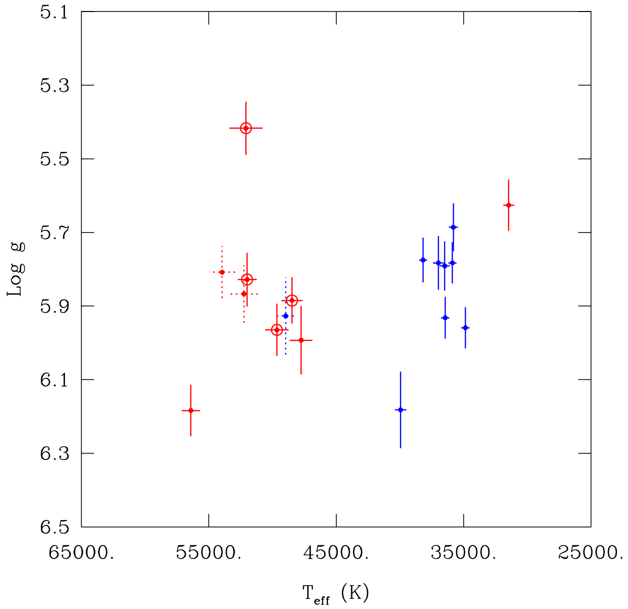

Figure 2. The instability strip for the sdO pulsators in ω Cen in $\log g - T_{\rm eff}$ space, computed on the basis of the FORS2 spectroscopy obtained. The red points with error bars refer to hydrogen-rich subdwarfs, while the blue points denote helium-rich objects. The four pulsators are marked by large open circles, while the small dots represent stars that do not exhibit rapid variability in the EFOSC2 data. We additionally show the locations of three field H-rich sdO stars that were found to be constant (dotted error bars).

variables and may or may not lie within the currently poorly defined instability strip. We plan further observations to address the issue of the purity of the instability strip in the near future.

It is intriguing to note that the ω Cen sdO variables as yet have no known counterparts among the field population. We recently monitored four field sdO's falling within the new instability strip (two H-rich, two He-rich) and found them all to be constant (the three that have reliable atmospheric parameter estimates are included in Fig. 2 for reference). The one known field sdO pulsator mentioned previously, SDSS J160043.6+074802.9, is significantly hotter at ~70,000 K (Latour et al. 2011) and moreover appears to be He-rich rather than H-rich like the ω Cen pulsators. Nevertheless, the periods observed are very similar to those detected in the ω Cen variables, indicating some kind of connection between the two groups of oscillators. This is supported by modelling, as can be seen below.

3. Exploring the Theoretical Instability Strip

We performed non-adiabatic pulsation calculations employing an extended grid of the same ”second-generation” models used for the interpretation and asteroseismological analysis of sdBV$_{\rm r}$ stars. These models are static envelope structures assuming traces of iron levitating in a pure hydrogen background with an equilibrium between gravitational settling and radiative levitation having been reached (see, e.g. Brassard et al.

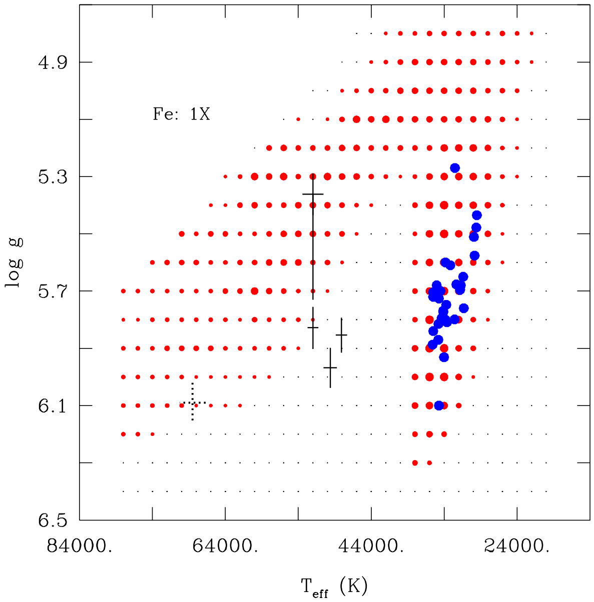

Figure 3. Results of a stability survey carried out on the basis of radial modes computed for a grid of our standard ”second generation” envelope models. The small black dots identify grid points corresponding to stable models. The larger filled red circles identify models with *p*-mode instabilities, the size of a circle being directly proportional to the number of excited modes. The observed rapid sdB pulsators are marked by the blue large dots, while the four continuous black crosses mark the sdO pulsators in ω Cen (around 50,000 K) and the dotted cross indicates the one field sdO pulsator known (~ 70,000 K). Note that the ω Cen pulsator with the large error bar in log g has a spectrum strongly contaminated by nearby stars, therefore the surface gravity inferred is thought to be severely underestimated.

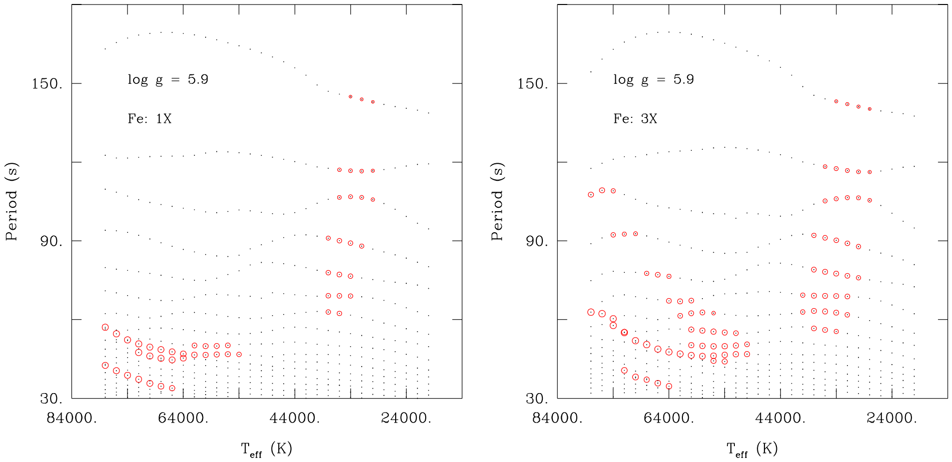

Figure 4. *Left:* Periods computed for a sequence of standard envelope models with log g=5.9 and a range of effective temperatures for low-order (the top point for each model refers to k=0) radial modes. Excited modes are marked by red circles, whose size is a logarithmic measure of the imaginary part of the complex frequency. The larger a circle, the more unstable the mode. *Right:* Similar to the left panel, but here the non-uniform iron abundance profile has been multiplied by a factor of three for each model in order to artificially boost the driving of pulsation modes.

2001, for more details). The new extended grid covers the 20,000-78,000 K temperature range and surface gravities between $\log g$=4.8 and 6.4, and was designed to encompass the entire sdB/sdO domain. These first non-adiabatic pulsation calculations focussed only on low-order radial modes with $P \sim$ 15-1200 s (depending on the value of $\log g$ of the model in question), but the non-adiabatic results obtained are representative also of higher degree modes.

Fig. 3 summarises the outcome of our stability analysis. We nicely recover the sdBV$_r$ instability strip first presented by Charpinet et al. (2001), and find that it is connected to the unstable models predicted around SDSS J160043.6+074802.9 (Fontaine et al. 2008) by a low-gravity "bridge" that merges into an extensive sdO star instability region. In fact, according to these calculations there is a complete absence of rapid sdO and sdOB pulsators only between 40,000 K and ~48,000-60,000 K, depending on the surface gravity. Unfortunately, the ω Cen variables fall right on the edge or even to the cool side of the sdO instability region and should mostly not pulsate according to these models. Matters appear even bleaker when examining the periods of the modes excited in our models at temperatures representative of the ω Cen variables: they are too short (30-60 s) compared to those observed (85-125 s), as can be seen in the left panel of Fig. 4.

Nevertheless, we believe that we have identified the driving mechanism for the ω Cen variables to be the same κ-mechanism that is at work in the pulsating sdB stars. It is clear however that our current models are lacking vital ingredients, such as the incorporation in the diffusion calculations of other heavy elements apart from iron. It will be particularly interesting to see the effect of including Nickel, which we believe will boost the pulsational driving to the extent that longer periods may also be excited. This is supported by the right hand panel of Fig. 4, where we illustrate the effect of uniformly and artificially increasing the iron abundance profile by a factor of three on pulsational mode stability. It can be seen that in this case periods completely overlapping with those observed are also excited. Since we expect the inclusion of Nickel and other heavy elements to have a similar effect on pulsation driving as artificially increasing the non-uniform iron abundance (c.f. the computations for sdBV$_s$ stars by Jeffery & Saio 2006) we are hopeful that the next generation of models will be able to reproduce the non-adiabatic pulsation properties of the ω Cen variables quite accurately.

4. Detailed Observations of Two ω Cen Variables with ULTRACAM

Two years after taking the exploratory EFOSC2 data that led to the discovery of the four ω Cen pulsators we were able to obtain more detailed time-series photometry for two of the variables (denoted V1 and V2 in Randall et al. 2011). We were allocated 6 nights of ULTRACAM time on the NTT in April 2011, and accumulated around 55 hours of data on both targets, which by chance could be fit within the same pointing. The exposure time used was between 6-7 s, ideal for detecting even pulsations as short as those predicted by the non-adiabatic calculations (~30-60 s). While a detailed reduction and photometry for all stars in the field as done for the EFOSC2 data (see Randall et al. 2010) remains to be performed, we used the ULTRACAM pipeline to obtain preliminary light curves for the two variables. Due to the extreme crowdedness of the field and the variable seeing conditions this was quite a challenge, and we were able to produce useful differential light curves only for the u' and g' bands (our targets are simply too faint and too contaminated by nearby stars in the r'). Nevertheless, the

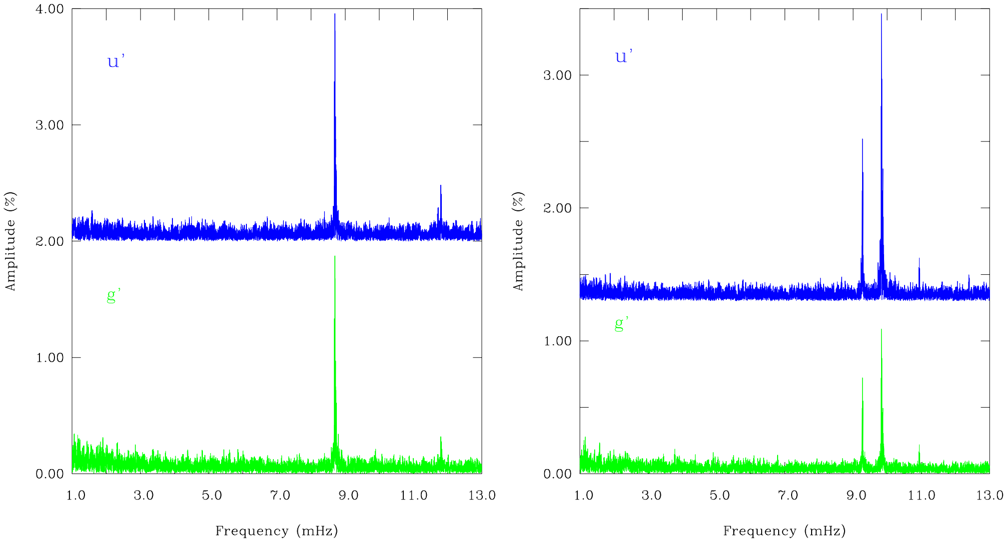

Figure 5. *Left:* u' (blue) and g' (green) Fourier amplitude spectrum for V1 computed from the ULTRACAM data. *Right:* Similar to the left panel, but here we show the corresponding Fourier amplitude spectrum for V2.

resulting Fourier amplitude spectra are of quite high quality, as can be seen in Fig. 5. The 4-σ detection threshold imposed for credible pulsations lies at ~0.3 % of the star's mean brightness for V1 and at ~0.2% for V2, and the frequency resolution is ~2.14 μHz. Pre-whitening the data down to the 4-σ threshold revealed pulsation properties as listed in Table 1. Please note that these are preliminary results and some of the values may change after the final data reduction.

The most noticeable thing about the period spectra extracted both for V1 and V2 is the splitting of the dominant frequency into several closely spaced components (4 in the case of V1, 3 in the case of V2). Some of this splitting has a similar frequency spacing as the formal resolution of the data set, indicating that it is caused by observational artifacts. Other components are placed a magnitude further apart than the formal resolution. At the present time it is not clear to us which (if any) of the split components constitute independent modes and we conservatively assume that only the dominant peak can be counted as a "real" pulsation frequency. Presumably, the lower amplitude peaks show a similar structure, but we are unable to detect the weaker components due to the limited S/N of the data.

We believe that the most likely explanation for the frequency splitting observed is amplitude variation. As explained in detail by e.g. Breger & Bischof (2002), a single pulsation mode with a variable amplitude can manifest itself as an apparent multiplet. Amplitude variations and close frequency splitting not explicable by rotation have been detected in several rapid sdB pulsators (see e.g. Kilkenny 2010), and there is ample evidence for amplitude variations occurring also in V1 and V2. Comparing the amplitudes of the periodicities present in the ULTRACAM data to those extracted from the EFOSC2 data taken two years earlier shows significant differences. It is particularly striking that for V2 the previously dominant 115-s periodicity has completely disappeared, and been replaced as the strongest peak by the previously low-amplitude 101-s

Table 1. Periodicities detected in the u' and g' ULTRACAM data for V1 and V2. Also listed for comparison are the EFOSC2 results (Randall et al. 2011).

P (s)	$A_{u'}$ (%)	$A_{g'}$ (%)	$P_{\rm EFOSC2}$ (s)	$A_{\rm EFOSC2}$ (%)
V1				
114.98	1.84	1.86	113.72	0.91
114.69	0.77	0.75	114.71	0.88
114.56	0.62	0.83	115.30	0.43
114.65	0.71	0.52	-	-
84.72	0.51	0.32	84.65	0.40
119.10	0.29	-	119.11	0.41
V2				
101.68	2.16	1.09	-	-
-	-	-	115.41	0.86
107.78	1.25	0.73	107.90	0.54
101.28	0.94	0.48	101.17	0.54
91.39	0.44	0.22	-	-
101.24	0.33	0.20	-	-

oscillation. Other pulsations have also changed in observed amplitude, but not quite as dramatically. Therefore, it does not seem too far fetched to attribute at least part of the frequency splitting observed to artifacts caused by pulsational amplitude variations. We will investigate this further when the final data reduction has been completed.

While we had hoped for the higher quality ULTRACAM photometry to reveal many more periodicities compared to the earlier data, this has unfortunately not happened, at least for the preliminary analysis presented here. Brushing aside the multiplet nature of the dominant periodicities we did not detect any modes beyond the three already known in V1, and found just one new pulsation at 91.4 s for V2. No shorter periodicities corresponding to those excited in our models were found. Apparently, the pulsation spectra of the ω Cen variables are dominated by just one or two high amplitude peaks, similarly to the case of many sdBV$_{\rm r}$ stars. Unfortunately, the faintness of the new sdO variables ($B \sim 18.5$) and the extreme crowdedness of the field conspire to make high S/N observations extremely challenging. Future asteroseismological analyses will likely have to make do with a small number of observed periods, and it will depend on the structure of the theoretical period spectra whether unique solutions can be obtained.

5. Conclusions

1. While we now know of 4 rapid H-rich sdO pulsators closely clustered around 50,000 K in ω Cen, no field star counterparts have yet been found at a similar temperature. The only known sdO pulsator among the field population is significantly hotter as well as being He-rich. It is not clear yet whether there are indeed systematic differences between sdO pulsators in the field and in globular clusters, or whether we are simply limited by small number statistics. Extensive follow-up

observations targeting sdO stars in the field, the ω Cen instability strip and other globular clusters are urgently needed to resolve this issue.

2. We believe that we have identified the mechanism responsible for exciting short-period oscillations in sdO stars to be the same κ-mechanism active in the sdB pulsators; in fact, the sdB and sdO instability regions are connected. However, some problems remain at the quantitative level, in particular concerning the red edge of the sdO star instability strip and the length of the periods excited. We are optimistic that the incorporation of other heavy elements besides iron in the diffusion calculations will resolve these issues, but the necessary computations remain to be carried out.

3. The pulsation spectra of the two ω Cen variables monitored in detail are characterised by close frequency splitting of the dominant modes, which we tentatively attribute to amplitude variations. Unfortunately, even 6 nights of ULTRACAM@NTT data did not reveal more than 3-4 periodicities interpreted as independent harmonic oscillations for each variable, implying that eventual asteroseismological analyses of these stars are likely to be limited by the observational accuracy that can be achieved. On the other hand, such analyses would be extremely rewarding as these objects constitute the only EHB pulsators so far known in a globular cluster. As such, they are currently unique probes of globular cluster EHB star evolution.

4. Given that the ω Cen variables turned out to be sdO pulsators rather than the globular cluster counterparts to the much-loved sdBV$_\mathrm{r}$ stars, the search for the latter is still on. We are hopeful that the improved accuracy of the ULTRACAM data compared to the EFOSC2 data for ω Cen will reveal such pulsators - we will know by the 6th Meeting on Hot Subdwarfs and Related Objects!

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