Pulsating hot subdwarfs with MS companions
or: EO Ceti is an sdO pulsator!

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Abstract. About half of the hot subdwarfs are found to have spectra of composite
types, indicating a main sequence companion of spectral type F–K, and the pulsators
are no exception to this rule. The spectroscopic contamination from the main sequence
stars makes it hard to reliably establish physical parameters for the hot component, and
also makes pulsations harder to detect as the amplitudes are depressed. The binary
fraction of the observed sample of hot subdwarf pulsators is discussed, as are the biases
that are affecting it. Spectroscopic evidence is presented that clearly demonstrates that
the well known sdB pulsator, EO Ceti, is misclassified, and is actually an sdOV star.

1. Introduction

Already when the discovery of pulsations in the hot subdwarf B (sdB) stars were an-
nounced in the first papers by Kilkenny et al. (1997), Koen et al. (1997) and Stobie et al.
(1997), a strong binary fraction was evident, since all these first pulsators are in com-
posite systems. At the time it was even speculated that the binarity is somehow involved
in inducing the pulsations in these stars. Much has happened since then. It is now clear
that about 50% of sdB stars are found to be in close binaries with periods on the order
of hours or days (Copperwheat et al. 2011). The composite spectrum binaries are not
included among those. The sdB stars with main sequence F-, G- or K-type companions
are known to form through stable Roche-lobe overflow rather than common envelope
ejection, and should end up with rather long periods. As recently demonstrated from
HERMES observations (Østensen & Van Winckel, these proceedings), the periods of such
binaries are indeed exceedingly long, between one and three years. It has been demon-
strated by Reed & Stiening (2004), by computing the IR excess of the known subdwarfs
in the field, that about half of sdB stars are such composite spectrum binaries. Taken
together, these results would seem to account for ~100% of the sdBs.

When the South African group (whose most prominent member, Dave Kilkenny,
we are celebrating the 65th birthday of with this conference) initiated the rush of dis-
coversies of pulsating sdB stars, the sample they observed was fairly unbiased with
respect to binarity. The only stars excluded would have been those with main sequence
companions of type A, and possibly the occasional (sub-)giant K or M stars, where the
sdB star would be practically invisible in the optical. But when the collaboration that
I have participated in joined the fray with observations from the Nordic Optical Tele-
scope (nор), we cheated a bit, using Uli Heber’s extensive library of spectra and model
 grids to select targets most likely to be pulsators. Thus, we could increase our detection
efficiency from 1.7% to ~10% (Østensen et al. 2010). However, in the process we au-
automatically selected against composite spectrum binaries, as the contamination makes the temperature determination very uncertain, especially in low-res spectra with modest S/N. This fact was somewhat alleviated by the fact that we pretty soon ran out of targets with well-determined physical parameters, and by the time we started observing the SDSS sample we were less concerned about the contamination. Still, the consequence of these selection effects is that any attempt to check if the fraction of binaries in the observed sample of sdB pulsators is the same as in the population as a whole will be biased towards non-composite systems. Revisiting the 49 stars compiled in Table 9 of Østensen et al. (2010) reveals 18 stars that are composite, i.e. a fraction of 37%, which is close enough to the binary fraction of the field population to be consistent within 2-σ given the sample size. We list the 18 composites in Table 1.

The sdB+MS binaries are in general much more poorly studied than the rest of the sdBV sample. The complication of having a strong spectroscopic companion means several things. First of all the spectroscopic parameter determination becomes much more complicated and regardless of the care taken in correcting for the contamination, the resulting spectroscopic parameters will always be more uncertain. For asteroseismology there can be a significant suppression effect in the photometric amplitudes, an effect that is also colour dependent, since the cool companion suppresses the amplitudes in the red more than in the blue. Note also that the companion may itself be pulsating; Østensen et al. (2011) found that several of the composite systems observed with the Kepler spacecraft shows photometric variability at the 1% level with periods on order...
of days or longer, consistent with gamma Dor pulsations or rotational effects associated with spots.

I have long wanted to rectify the bias towards non-composite spectroscopic binaries among the sdBVs in order to explore the possible difference in internal structure in sdBs that form through different evolutionary channels, i.e. common envelope ejection, stable mass transfer or mergers. This was also the overarching topic of the Ph.D. thesis of Maja Vučković (2009). During the sample selection process for the long period binary study with hermes (Østensen & Van Winckel, these proceedings), I was hoping to include some sdBVs in the sample, but as can be seen from Table 1, only EO Ceti is bright enough to be observed with hermes, and even it at $V = 12.3$ is on the limit of what can be done. However, as I explored low-resolution spectra of EO Ceti and other sdB+F/G binaries kindly made available to be by Betsy Green and Uli Heber, I found an unexpected surprise, and the rest of this talk will be dedicated to this discovery.

2. Observations and analysis

The spectrum of EO Ceti provided by Betsy Green showed no trace of any He i lines typical of sdB stars, but a line at 4686 Å looked as it might be He ii. If this was the case EO Ceti would not be the second sdBV ever found, but rather the first sdOV. Pulsations in sdO stars were discovered much later than the sdBV stars by Woudt et al. (2006), and J16007+0748 remains to this date the only sdO pulsator found. However, although this spectrum have exceptionally high S/N, the low resolution ($R \approx 500$) makes it difficult to identify individual lines among the strong blends from the F-star companion. A high resolution feros spectrum obtained by Uli Heber confirmed the presence of a line at \( \sim 4686 \, \text{Å} \), but had insufficient S/N to attempt a temperature determination. We therefore obtained 3 successive deep integrations (900 s) of EO Ceti with the isis spectrograph on the William Herschel Telescope on La Palma on August 27, 2010, using the R600B grating which provides a resolution of $R \approx 2500$ in the blue. The spectra were extracted and summed, and the response was corrected by calibrating with the spectrum of a hot DA white dwarf. The resulting high S/N spectrum is shown in Figure 1. Also shown in the plot is a simple binary model produced by scaling model spectra to fit at two well separated points (here chosen to be 4050 and 5060 Å), after accounting for the estimated reddening of the system, $E(B-V) = 0.04509$ (Schlegel et al. 1998). By subtracting one model from the spectrum, the parameters of the other component could be fitted, and this procedure was iterated until the procedure converged. As can be seen from the figure, this two-component solution makes an excellent fit to practically every detail of the observed spectrum. However, as can be seen in Figure 2, the solution can hardly be called unique. For temperatures in the sdB–sdOB range (between 30 000 and 45 000 K) there is a strong correlation between the temperature of the primary and that of the secondary, whereas above $\sim 50 000 \, \text{K}$ changing the temperature of the primary does not affect the $\chi^2$ significantly. The procedure uses the whole available spectral range and is not sensitive to the strength of the He i and ii lines. In the bottom part of Figure 1 the zoom-in shows the region around the He i line 4472 Å and He ii lines at 4512 and 4686 Å. It appears that at the derived primary temperature of 52 000 K, He i at 4472 is still weaker in the observed spectrum than in the model, while He ii at 4686 appears to be stronger in the observed spectrum. This indicates that the primary temperature could be significantly higher than the derived solution, but not cooler.
EO Ceti
$T_{\text{eff}} \approx 52000$ K
$\log(g)_{\text{sdB}} = 6.05$ K
$\log(\text{He}/\text{H})_{\text{sdB}} = -1.4$ dex
$T_{\text{MS}} = 7034$ K
$\log(g)_{\text{MS}} = 4.58$ dex
$\log[Z]_{\text{MS}} = -0.61$ dex

Figure 1. WHT/ISIS spectrum of EO Ceti. Also shown are model spectra with parameters as stated on the plot. The spectrum was response corrected by calibrating the instrumental response function with a single sdB star. The models have been scaled to fit the spectrum at 4050 and 5060 Å.

We also obtained several spectra of EO Ceti with the hermes spectrograph (Raskin et al. 2011) on the Mercator Telescope, also on La Palma. These spectra have very high resolution ($R \approx 80000$) but low S/N. EO Ceti was observed on seven different occasions, using sequences of three to four exposures between 1000 and 3600 s each. The S/N in these spectra are very low (~10) and plagued by cosmic rays, but a typical S/N level of between 30 and 50 could be achieved by summing the individual spectra and reducing the resolution by a factor of 4. The final spectra were resampled to a uniform wavelength grid of 0.05 Å. This is unproblematic as the rotational broadening of the MS component is strong, and no sharp features (except a few interstellar lines) are present. The full spectrum is too extensive to show here, but in Figure 3 we show some of the most relevant regions, together with the same model spectra as in Figure 2, convolved to the appropriate resolution (0.05 Å and including a 72 km/s rotational broadening for
Figure 2. $\chi^2$ plane for model fits to the EO Ceti spectrum in Figure 1 as a function of temperature of the two stars. Acceptable solutions to the overall shape of the spectrum can be found for any temperature above $\sim 36,000$ K. Above $\sim 50,000$ K the temperature of the secondary is no longer affected by the choice of temperature for the primary.

the F-star). This spectrum is a sum of three 2700 s integrations obtained on October 30, 2010. As with the WHT spectrum, there is no trace of He I at 4472 Å, and He II at 4686 Å appears slightly stronger than in the model. At this resolution it actually appears broader than the model rather than deeper, which might well be the case as we have not made any attempt at modelling the pulsational broadening of the lines. The equivalent width of the line still points towards a primary that is more likely to be hotter than the 52,000 K model than cooler. The He I line at 5876 Å might be present in the spectrum, but is hardly significant. In the lower panels of Figure 3 we show the model fit to some of the more prominent lines from the F-star. The Ca II H and K lines are well fitted, as are the Mg I triplet and the forest of Fe I lines around 5400 Å.

### 3. Conclusions

After re-examination of new high quality spectroscopy it is clear that EO Ceti is not an sdBV but an sdOV star. Thus, as is the case with most other important discoveries in the field of hot subdwarf stars, the first sdO pulsator was actually discovered by Dave Kilkenny and his team, which I think is a very appropriate discovery to announce at this conference held in his honour.
The clear detection of the He II, together with weak or absent He I effectively forces EO Ceti to be classified as an sdO star, regardless of its actual temperature. Using the slope of the spectrum is no longer a viable option at temperatures in the sdO range, unless one has access to UV spectroscopy. So far no attempt has been made to reliably constrain the surface gravity of the component, and the analysis does not force the two stars to be at the same distance. However, since no orbit has been established, that may not actually be the case. We will continue monitoring EO Ceti with high resolution spectroscopy in the hope of detecting the orbital period of the system. That may allow us to use spectral disentangling to decompose the spectra into its two components, which will greatly simplify the parameter estimation. However, the broadening from the pulsational velocity at the surface of the sdO star and the broadening due to the rotational velocity of the F star are both higher than the expected orbital velocity, which makes this a very challenging project.

At B=12.3 EO Ceti is a much more encouraging target to study than J16007+0748, since high-precision photometry can be obtained with modest telescopes, and time-resolved spectroscopy is a lot more feasible. In fact, thanks to its early discovery, EO Ceti is one of the best studied hot subdwarf pulsators with extensive campaign observations by O’Donoghue et al. (1998), multicolor photometry by Vučković et al. (2010) and an early attempt at time-resolved photometry by Jeffery & Pollacco (2000).

Can there be other sdO pulsators in the sample of known sdBVs (Table 9 of Østensen et al. 2010)? Perhaps. I have checked the ones that I have spectroscopy on, but no clear candidates have emerged. But there are quite a few in that table that have

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Figure 3. Selected lines from a high-resolution spectrum of EO Ceti obtained with the hermes spectrograph. The model spectra shown are with the same parameters as in Figure 1.
very poor spectroscopy, and many have no established helium abundance. The spectroscopy also suffer from having been obtained with many different instruments and various resolutions and signal levels. In many cases only the original classification spectrum exists, so clearly, much more work has yet to be done.

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