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Subaru and salt spectroscopy of chemically peculiar hot subdwarfs

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Research Article

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Subaru and SALT spectroscopy of chemically peculiar hot subdwarfs

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Abstract: The majority of hot subdwarfs lie on or close to the helium main-sequence. Many have hydrogen-rich surfaces, but a substantial fraction of the hotter subdwarfs have hydrogen-depleted or hydrogen-deficient surfaces. Amongst the former, three were known to show extraordinary overabundances of heavy elements including zirconium and lead. Using Subaru/HDS, we commenced a high-resolution survey of hydrogen-depleted subdwarfs to discover new members of the class. UVO 0825+15, was found to exhibit strong lead lines, to be an intrinsic variable in K2 field 5, and to have a relatively high space motion. Two other lead-rich subdwarfs have been found in the Subaru sample. A much wider survey is in progress using SALT/HRS. Discoveries so far include one extreme helium star similar to V652 Her, and an intermediate helium star with possible comparison to HD144941. Analyses of the hotter and more compact members of the sample are continuing.

Keywords: stars: chemically peculiar, stars: subdwarfs

1 Introduction

Whilst the majority of hot subdwarfs are hydrogen-rich, to the extent that helium is strongly suppressed in their spectra, a sizable fraction (some 10%) show helium enrichments from near equity with hydrogen up to cases where hydrogen lines are hard to identify. The diversity of surface chemistry represented by the helium-rich hot subdwarfs is partially apparent in the number of spectral types identified by Drilling *et al.* (2013). The same authors also noted that low-resolution systems could not distinguish between certain classes of helium-rich hot subdwarf and extreme helium stars. Hence there is a substantial probability that unidentified extreme helium stars could be found amongst existing spectroscopic surveys. At higher resolution, the extent of very exotic chemistries was recognised by Naslim *et al.* (2011, 2013) with the discovery of extremely zirconium-rich and lead-rich subdwarfs. A possible hypothesis is that radiative levitation concentrates selected species at precise levels in the stellar photosphere; when these levels coincide with the line-forming layers, extreme overabundances are observed. Whilst much work on a theoretical framework for this hypothesis remains to be done, the extreme rarity of stars with exotic chemistries has demanded a search for additional specimens. This poster describes recent progress on a survey using the Subaru High-Dispersion Spectrograph (HDS) and the Southern African Large Telescope (SALT) High-Resolution Spectrograph (HRS). The principal aims are to identify extreme helium stars, exotic chemistry subdwarfs, and also to obtain more detailed surface chemistries for the other helium-rich subdwarfs and hence to test hypotheses for their origins.

2 Observations

Subaru/HDS

Subaru/HDS observations of five northern intermediate He-sdBs identified from the Németh *et al.* (2012) survey were obtained in service mode on 2015 June 3. Two échelle spectra of each star were reduced to one dimension, blaze

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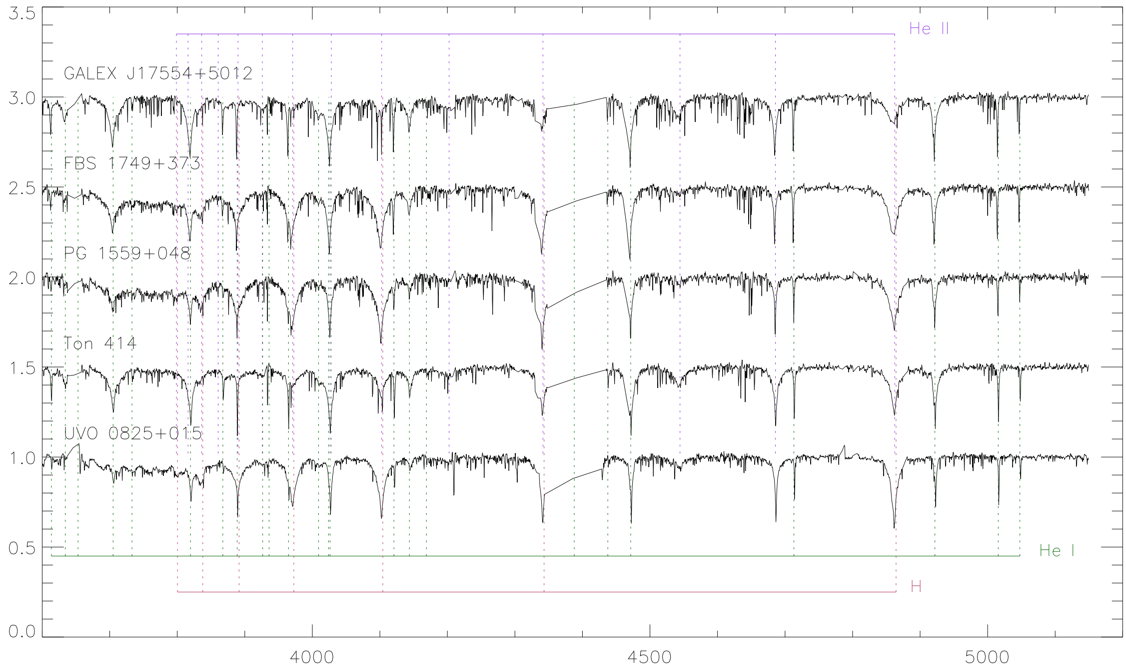

Figure 1. Subaru/HDS atlas of helium-rich hot subdwarfs binned to show major hydrogen and helium lines. Straight lines cover gaps due to CCD defects and the gap between the two CCDs.

corrected, resampled and combined to a single spectrum (Figure 1).

SALT/HRS

During 2016/17, SALT/HRS observations were obtained for some 40 southern helium-rich subdwarfs identified from low-resolution surveys, including GALEX (Németh *et al.* 2012) and Edinburgh-Cape (Stobie *et al.* 1997). The échelle spectra were reduced to one dimension (Crawford 2015), blaze corrected, resampled and stitched. Hydrogen is clearly present in seven of the 40 spectra, shown in the bottom part of Figure 2. One (J19188–3104) is a *bona fide* He-poor sdB star. Six are likely intermediate helium sdB and sdOB stars The remaining 33 stars (Figures 2,3) have helium-dominated spectra; comparison of the Balmer and Pickering lines provides clear evidence of a low hydrogen abundance. Their spectra range from those dominated by neutral helium to a few in which only ionized helium is visible.

3 Methods

The principal object is to measure the surface properties of each star, including effective temperature $T_{\rm eff}$, surface gravity g, and the abundances of hydrogen, helium and other elements. This is done by fitting the merged spectrum in a three-dimensional grid of model spectra covering $T_{\rm eff}$, g and He/H ratio. Theoretical stellar atmospheres and emergent spectra are computed with the package LTE-CODES (Jeffery 2003; Winter 2006), which includes STERNE (Behara and Jeffery 2006), SPECTRUM (Jeffery *et al.* 2001), LTE_LINES (Jeffery 1991) and SFIT (Jeffery *et al.* 2001). These assume that the atmosphere is semi-infinite, plane parallel, and in radiative, hydrostatic, and local thermodynamic equilibrium. Grids are custom built for a variety of chemistries; the choice is important because the distribution of elements heavier than helium strongly influences the atmosphere structure, especially at low hydrogen abundances. Where necessary, the choice of model grid is iterated with the chemistry determined from the next step. Once $T_{\rm eff}$, g, He/H and an approximate metal distribution are established (and then fixed), a final model atmosphere is computed. The high-resolution spectrum is renormalized to a spectrum computed from this model so that only weak lines contribute to the subsequent fit. El-

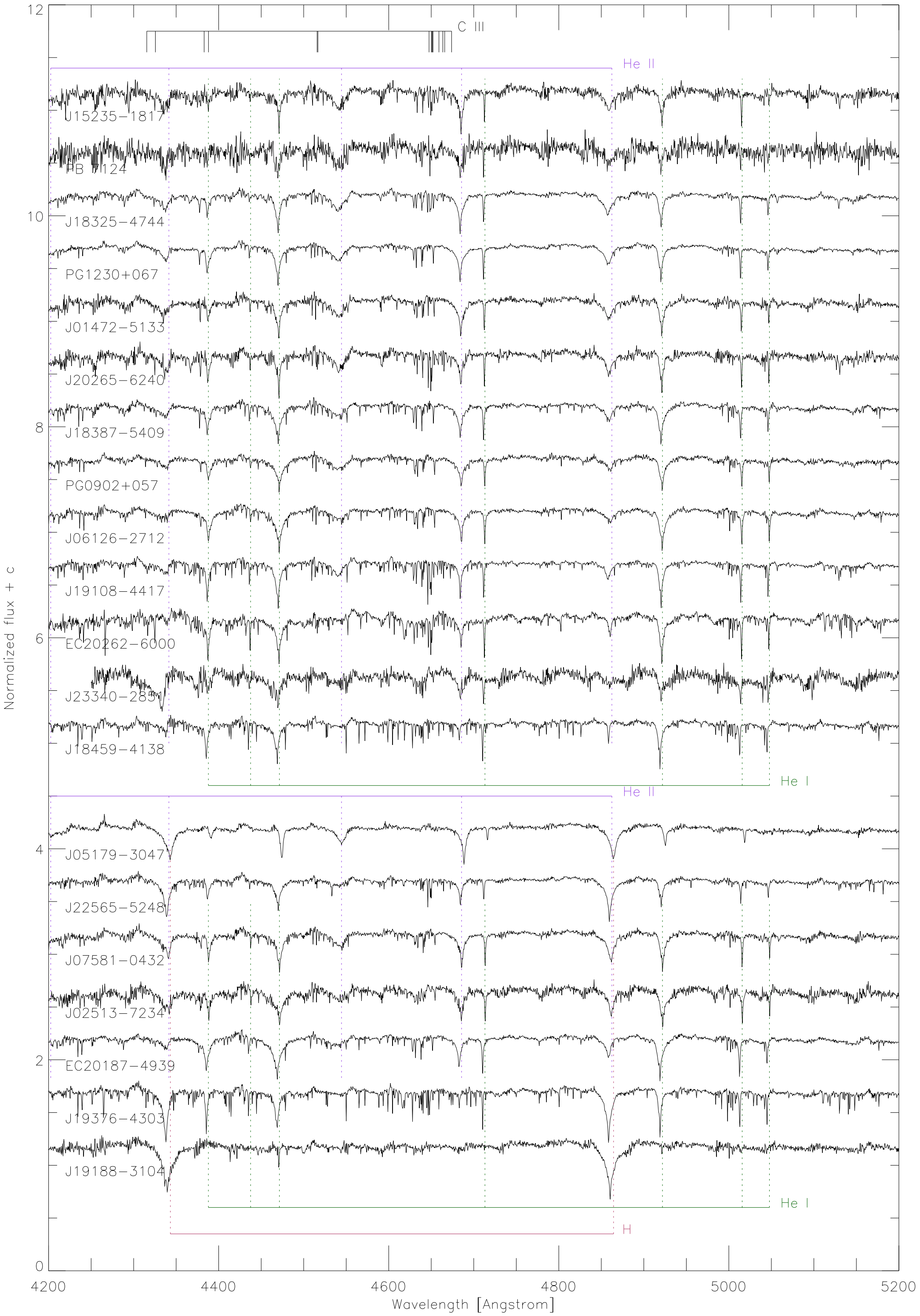

Figure 2. Blue SALT/HRS atlas of hot subdwarfs binned to show major hydrogen and helium lines. Seven stars at the bottom of the panel show significant hydrogen. Above the break, all stars are helium-rich, and have been arranged approximately in order of increasing HeII/HeI (upwards). The rest wavelengths of principal hydrogen, helium and carbon lines are indicated. The spectra have not been corrected for velocity shifts. All wavelengths are in air.

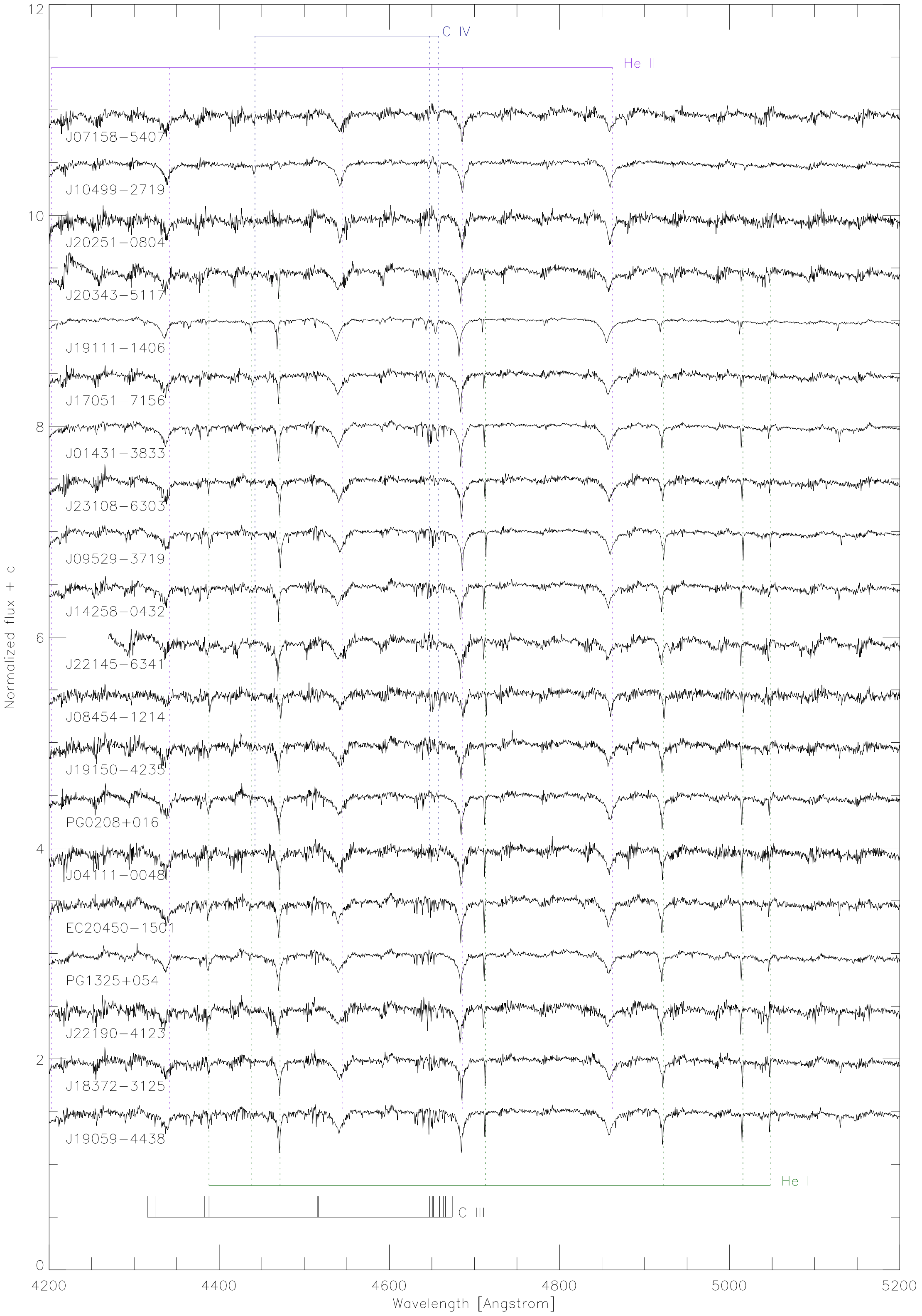

Figure 3. As Figure 2 continued. All stars in this panel are helium-rich and have been arranged approximately in order of increasing HeII/HeI (upwards).

emental abundances are obtained by minimizing the difference (χ^2) between a theoretical spectrum from the fixed model and the observed spectrum. Line-by-line analyses have been carried out in a few cases and found to agree, within errors, with the χ^2 analysis (Jeffery *et al.* 2017).

4 Results

UVO 0825+15.

UVO 0825+15 was found to be both highly variable in light (*K2* Campaign 5) and also to show strong lead lines and a high radial velocity (Subaru/HDS). The light curve has proven difficult to interpret, with peaks in the power spectrum being variable in both amplitude and frequency and at frequencies low enough to correspond to g-modes in a star that is too hot even for p-modes to be excited. The atmosphere is super-rich in lead, germanium and strontium. A detailed analysis is given by Jeffery *et al.* (2017)

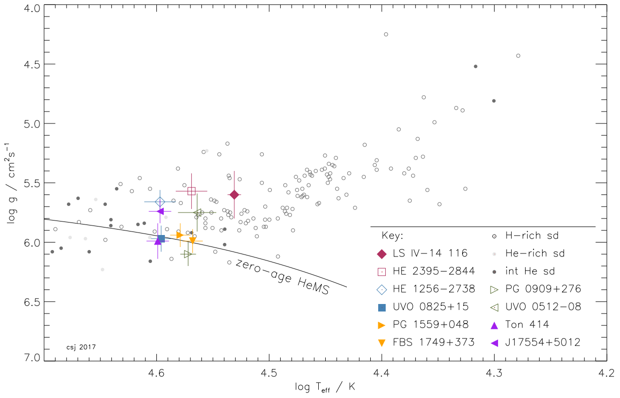

Figure 4. Surface properties of super metal-rich hot subdwarfs, including the pulsating stars LS IV–14°116 and UVO 0825+15, the iron-group CP stars UVO 0512–08 and PG 0909+276 (Wild & Jeffery: sdOB8), and the new lead-rich discoveries.

PG 1559+048 and FBS 1749+373.

Analysis of the remaining four Subaru/HDS stars is in progress (Naslim at el. in prep). Provisional $T_{\rm eff}$, g and surface abundances are shown in Figures 3 and 4. Both PG 1559+048 and FBS 1749+373 show lead lines, with abundances ≈ 3.5 dex above solar. Yttrium is detected in PG 1559+048, with marginal evidence for germanium. These lead-rich stars have helium abundances of 0.21 and 0.36 (number fraction) respectively.

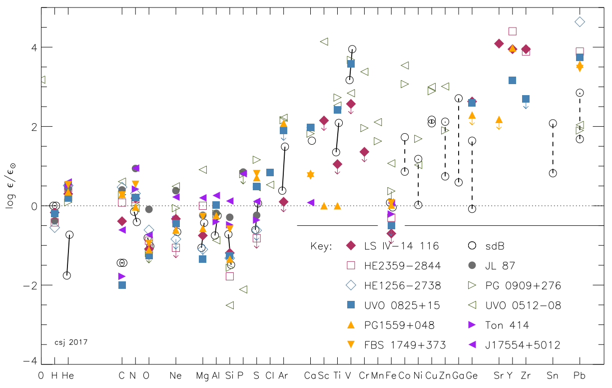

Figure 5. Surface abundances of super metal-rich hot subdwarfs, including the pulsating stars LS IV–14°116 and UVO 0825+15, the iron-group CP stars UVO 0512–08 and PG 0909+276 (Wild and Jeffery 2017), and the new lead-rich discoveries. Abundances are shown relative to solar values (dotted line). Mean abundances and ranges for normal subdwarfs are also shown. The latter are shown by connected open circles as (i) $Z \leq 26$ (solid lines): the average abundances for cool and warm sdBs (Geier 2013) and (ii) $Z \geq 27$ (broken lines): the range of abundances measured for five normal sdBs from UV spectroscopy (O'Toole and Heber 2006). Adapted from Jeffery *et al.* (2017)

J18455–4138.

Originally classified as a helium-rich subdwarf, J18455–4138 (=*GALEX* J184559.8–413827) was observed with SALT/HRS. The raw data indicated a prominent spectrum of strong sharp lines which, after reduction, were shown to be mostly due to singly-ionized nitrogen. The Balmer lines are negligible, and He II 4686 is much weaker than in other He-rich subdwarfs (Figure 2). Bearing a strong similarity to V652 Her, a fine analysis demonstrated that J18455–4138is not a hot subdwarf but, rather, a relatively high-gravity extreme helium star with $T_{\rm eff}$= 26 170 ± 750 K, $\log g/{\rm cm}^{-2}$ = 4.22 ± 0.10 and a surface characterized by CNO-processed helium with a 1% contamination from hydrogen (Jeffery 2017). Whilst the formation of such N-rich low-luminosity extreme helium stars has been strongly associated with the product of a double helium white dwarf merger (Saio and Jeffery 2000), other models are possible (Figure 6).

J19376–4303.

The raw SALT/HRS spectrum of J19376–4303 (=*GALEX* J193736.4–430300) appears similar to that of J18455–4138, prompting an equally urgent analysis. The reduced spectrum reveals much stronger Balmer lines, indicating hydrogen and helium abundances of 76% and 33% respectively. With $T_{\rm eff} \approx 26\,770$ K and $\log g/{\rm cm^{-2}} \approx 4.24 \pm 0.10$, J19376−4303 lies close to the main sequence, with only moderate helium enhancement and relatively normal CNO abundances, these provisional results await analysis of higher S/N data and careful evaluation.

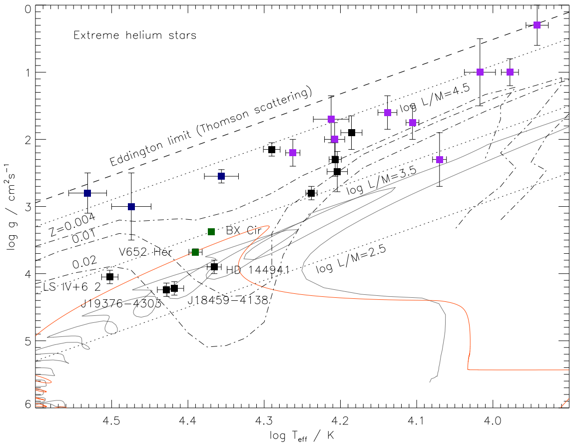

Figure 6. Surface properties of J18455−4138 and J19376−4303, compared with extreme helium stars and related objects. The positions of the Eddington limit (Thomson scattering: dashed), luminosity-to-mass contours (solar units: dotted) and lower boundaries for pulsation instability (metallicities $Z = 0.004$, 0.01, 0.03: dot-dashed) (Jeffery and Saio 1999) are also shown. Post-merger evolution tracks for models of He+He white dwarf mergers (Zhang and Jeffery 2012, 0.30+0.25 and 0.30+0.30 $M_\odot$) are shown in maroon. Part of the post-flash track of a 0.46921 $M_\odot$ 'late hot flasher' (metallicity $Z = 0.01$) is shown in orange (Miller Bertolami *et al.* 2008).

5 Challenges

It is too early for this report to reach conclusions, but major challenges are easily apparent.

– One is presented by the very sharp lines observed in all of the zirconium/lead-rich subdwarfs, implying very low projected rotation velocities (typically < 5 km·s^{-1}). Contraction following common-envelope ejection or a white-dwarf merger would imply at least some residual rotation, though efficient angular momentum loss processes are known.

– A second is the absence of zirconium/lead-rich subdwarfs in binary systems. Is this because they are all mergers, or because any companion capable of ejecting the envelope has a very low mass?

– A third challenge is the nature of the pulsations in UVO 0825+15 and LS IV−14°116. Too hot for either p- or g-mode non-radial pulsations, could they be r-modes, or something else?

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