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The SALT survey of chemically-peculiar hot subdwarfs

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Abstract

The Southern African Large Telescope (SALT) has surveyed a sample of 300 chemically-peculiar hot subdwarfs with a view to explore evolutionary pathways and connections between a large variety of stars. Observations have been obtained for the entire sample at intermediate resolution to provide classifications and atmosphere parameters, and a smaller sample at high resolution to permit detailed chemical abundance analyses. The first has provided a substantial sample of extremely helium-rich sdO stars, but has also led to significant discoveries of hot white dwarfs, pre-white dwarfs, heavy-metal subdwarfs and extreme helium stars. This paper provides an overview of the current status of the project.

Keywords: surveys, stars: subdwarfs, stars: chemically-peculiar, stars: atmospheres, stars: evolution

MSC: 85-05 85-06 85A15

1. Overview

Half-way up the left hand side of the most modern Hertszprung-Russell diagrams, above the white dwarf sequence and below the O and B stars on the hydrogen-burning main sequence, lies a clump of hot and dim stars. These subluminous O and B stars, or hot subdwarfs, are evolved stars. They are mostly about half a solar mass, mostly converting helium to carbon in their cores, and mostly "stripped" of their hydrogen outer layers. Most have previously finished hydrogen-burning and become red giants, whereupon a nearby companion star has removed their outer layers (Han et al., 2002, 2003). In contrast, there are also many other exotic star histories that can make hot subdwarfs of different types, either as the product of a collision between two white dwarfs (Iben, 1990; Saio and Jeffery, 2000; Zhang and Jeffery, 2012), as the remnant of a star that failed to become a red giant (Byrne and Jeffery, 2020), by the mutual stripping of two stars' envelopes (Ahmad et al., 2004; Justham et al., 2011) or by means as yet unknown. Many of them lead to hot subdwarfs with peculiar surface chemistries, including some 10% of hot subdwarfs which have surfaces almost completely deficient in hydrogen (Green et al., 1986; Németh et al., 2012). A smaller fraction show surface helium fractions well above the solar value but less than $\sim 10\%$ (by number). In some cases these show extraordinary surface abundances of heavy elements including zirconium and/or lead (Naslim et al., 2011, 2013).

Since 2016, observations with the Southern African Large Telescope (SALT) have been directed at detecting and analysing the atmospheres of chemically-peculiar hot subdwarfs, both to explore connections across the entire range of hydrogen-deficient subdwarfs and to understand how the most exotic surface chemistries arise (Jeffery et al., 2017a,b; Jeffery and Miszalski, 2019; Dorsch et al., 2021). Classifications and coarse analyses of the first 100 stars observed demonstrate the wide spread in surface properties (Jeffery et al., 2021). With SALT spectroscopy of approaching 300 stars now available, we report on the current status of the project, including the discovery of new lead-rich subdwarfs and short-period binaries.

2. Observations

The SALT survey was originally motivated by evidence of a substantial population of hydrogen-deficient subdwarfs in low-resolution surveys, and a desire to identify new extreme helium stars and subdwarfs from these surveys (Jeffery et al., 2021). Stars classified He-sdB, He-sdO and He-sdOB were included by default; sdO and sdOB stars were later added because the boundary between helium-rich and helium-poor subdwarfs is indistinct. These criteria led to a sample comprising over 300 stars within the declination zone accessible to SALT. The object is be to provide precise classifications (Drilling et al., 2013) from medium-resolution (~ 1Å) spectroscopy for the complete sample, and to follow-up interesting stars with $V < 14.5$ at high resolution. Between 2017 May and 2022 May, the survey was been awarded over 260 hours of scheduled time and observed over 500 blocks. Data products for the first survey paper are available online (Jeffery et al., 2021) [1].

2.1. Medium-resolution spectroscopy (RSS)

The majority of observations with the Robert Stobie Spectrograph (RSS) were carried out with the PG2300 grating at two overlapping camera stations providing continuous wavelength

[1]Follow link to "salt_dr1" at `www.armagh.space/author/simonjeffery`

coverage in the range 3850 – 5400 Å at a resolution $R \sim 3600$. At this resolution and requiring S/N$\gtrsim$ 20, the effective limiting magnitude is $V \lesssim 16$ for a half-hour observing block. In some cases we have extended to $V < 17$. Within each observing block, two star and one arc exposures were obtained at each camera station. All individual exposures have been extracted to wavelength-calibrated sky-subtracted 1d spectra. Initially, data reduction was carried out using IRAF tasks and the LACOSMIC package (BM) (Jeffery et al., 2021). Latterly, EJS has used the TITUS_SAURES_REX software developed by Naomi Titus (formerly at University of Cape Town, South Africa). All exposures within a block are merged onto a common wavelength grid, and normalised to a continuum defined by a low-order polynomial using regions of spectrum normally free from broad H or He absorption lines. Wavelengths are given in air and corrected for earth motion. Each merged spectrum is saved as an ASCII file, labelled by the object, with a single letter suffix if more than one block is observed. The suffix 'm' is used to denote a mean spectrum. As of 7 June 2022, the survey contained 445 reduced RSS spectra, representing 294 unique stars.

2.2. High-resolution spectroscopy (HRS)

All observations with the High Resolution Spectrograph (HRS) were carried out in Medium Resolution mode ($R \sim 43\,000$). Three data reduction procedures have been available to us at different times. Up to 2018, the SALT PYHRS pipeline developed was used universally (Crawford, 2015). This pipeline was not maintained after 2018, since a viable alternative is provided by the SALT MIDAS-based pipeline (Kniazev et al., 2016, 2017). Meanwhile, we developed an IRAF-based procedure based on reduction of other échelle format data (Dorsch et al., 2021). Relative to the MIDAS-based pipeline, our IRAF-based method gives a factor of ~ 2 gain in throughput and the ability to use our own order-merging software, which is more robustthan the MIDAS procedure at low S/N ratios. However it is not automatic and therefore comes with an added cost. Wherever possible, the IRAF-based method has been used to reprocess all HRS data observed after 2018.

3. Results

3.1. Sample Characteristics

From an initial programme focused on stars classified HesdB (Stobie et al., 1997; Kilkenny et al., 1997) or sdOD (Green et al., 1986) in various catalogues, the SALT survey of chemically-peculiar hot subdwarfs has grown to include intermediate helium-rich subdwarfs, extreme helium stars and more. Initial objectives were to classify and parameterize these from RSS spectroscopy (Jeffery et al., 2021). This was essentially a sifting exercise to identify stars for detailed follow-up. The sample has grown and now, in conjunction with appropriate grids of model atmospheres, online photometry databases, and Gaia parallaxes and proper motions, offers a powerful tool for exploring population characteristics and evolutionary pathways. The classification summary from 2022 May is shown in Fig. 1. A much larger number of very hot subdwarfs with spectral type earlier than sdO5 are now known than was available for the

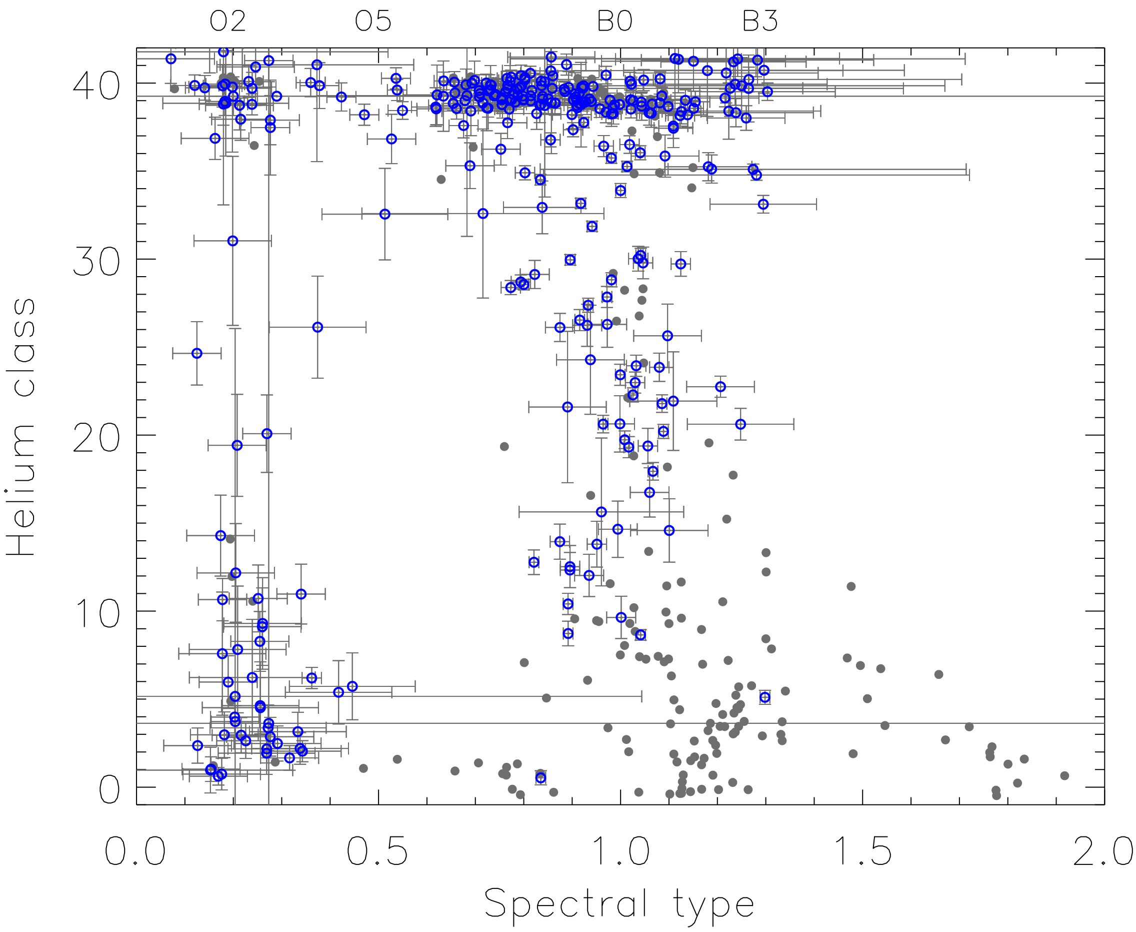

Figure 1: Drilling classifications in terms of spectral type and helium class for stars in the SALT survey of chemically-peculiar hot subdwarfs (blue circles). Classifications from Drilling et al. (2013) are shown as grey dots. Spectral type indices 0.5, 1.0 and 1.5 correspond to types sdO5, sdB0 and sdB5, respectively. Helium classes 0 and 40 correspond to non-detections of helium or hydrogen, respectively, in spectra having resolution $R \sim 2000$.

Drilling et al. (2013) classification paper. Where the helium class is small (< 10), the absence of helium lines makes the classification much less secure than, for example, where He I, He II and H lines are all present.

Immediate next steps include verification, parameterisation using a line-blanketed non-LTE model atmosphere grid, generation of spectra-energy distributions and combining all with Gaia parallaxes and proper motions.

3.2. Chemically Peculiar Hot Subdwarfs

Amongst the intermediate helium-rich subdwarfs with high overabundances of heavy metals, an early SALT discovery was the lead-rich subdwarf EC 22536–5304 (Jeffery and Miszalski, 2019). Follow-up HRS observations showed the latter to be a double-lined spectroscopic binary (Dorsch et al., 2021). The RSS spectrum of EC 22536–5304 showed that exotic metal lines can be detected in spectra with $R \sim 2000$ if their equivalent widths are ≥ 100 mÅ. We have found 3 additional lead-rich hot subdwarfs in the current survey, including SALT J001235.6-422011, SALT J191223.5-624632, and BPS CS 22956-0094. *TESS* data show that the latter, BPS CS 22956–0094, is also a short-period binary. All have Drilling et al. (2013) spectral types between sdO9.5 and sdB0.5, and helium classes in the range 23 - 27.

Zirconium is visible in the RSS spectrum of the zirconium star LS IV–14°116. We have not yet found another star with excess Zr in its RSS spectrum. With spectral type sdB1VII:He19, SALT J075448.2+014612 is a near twin of LS IV–14°109. Zirconium is not confirmed and high-resolution spectroscopy is required for follow-up.

We have identified several new extreme helium stars with $T_{\rm eff}$ and g running all the way from the extreme helium star domain ($\log g/{\rm cm\,s^{-2}} < 4$) to the true hot subdwarf domain ($\log g/{\rm cm\,s^{-2}} \approx 6$) (Fig. 2). Some have been introduced by Jeffery et al. (2017b). Analysis of the low-gravity extreme-helium subdwarf BPS CS 22940-0009 (Snowdon et al., 2022) shows it to be an intrinsically metal-poor N-rich star. Analysis of the extreme-helium subdwarf EC 20187-4939 (Scott et al, in preparation) shows it to be neon-rich as well as a member of a wide binary.

3.3. Binaries

Jeffery et al. (2021) found several He-rich subdwarfs with anomalously high radial velocities and/or line widths, suggesting possible variability or line doubling. On the other hand Geier et al. (2022) reported a very low binary fraction amongst helium-rich subdwarfs compared with classical sdB stars, based on radial-velocity variances measured in the Sloan Digital Sky Survey.

We compiled a list of ~ 250 stars identified as He-sdX in the lists compiled by the *TESS* Asteroseismic Science Operations Center Working Group 8 (Compact Pulsators)[2] of stars observed with *TESS* and with declinations accessible to SALT. Investigation of these *TESS* light curves yielded ~ 8 helium-rich subdwarfs likely to be ellipsoidal or reflection effect binaries

[2] tasoc.dk/wg8/

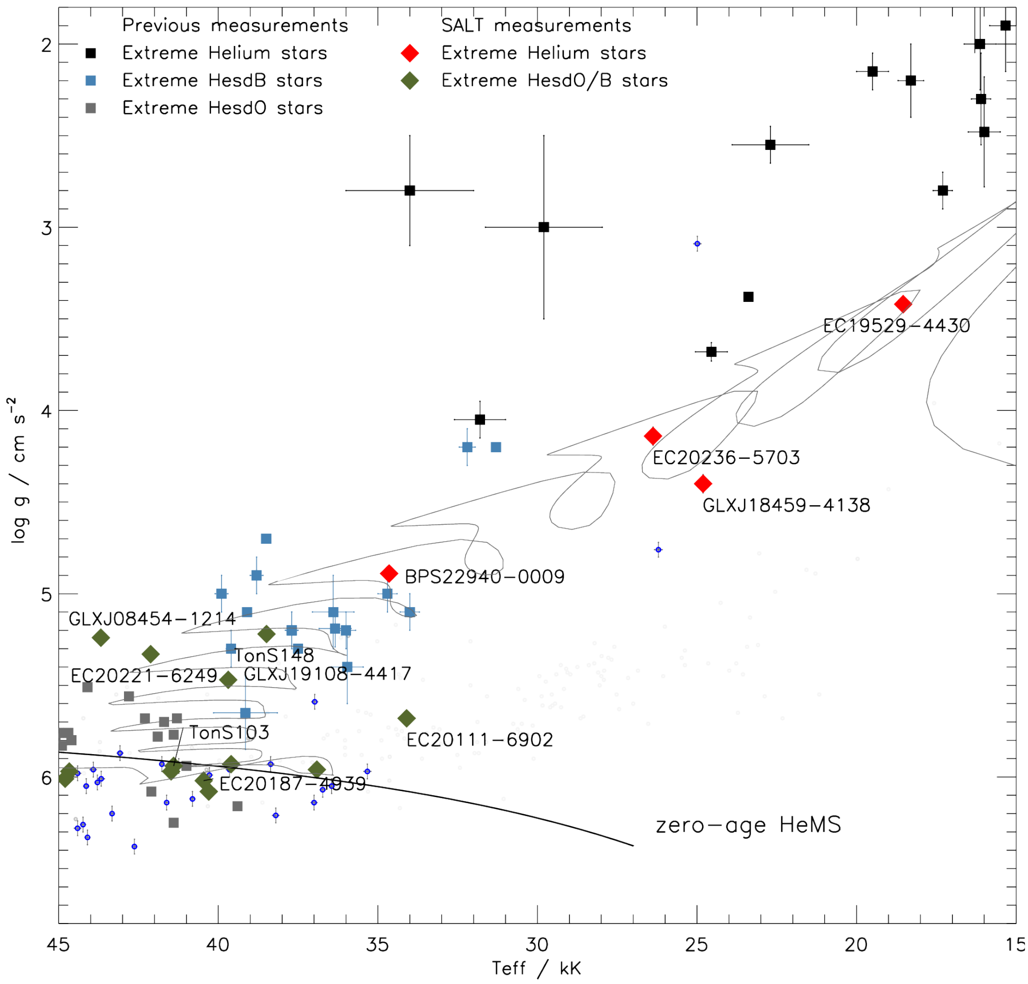

Figure 2: Surface properties of extremely helium-rich (EHe) stars and subdwarfs observed in the SALT survey (Jeffery et al., 2021, diamonds) compared with EHe stars and subdwarfs from previous work (small squares). A selection of the SALT stars are labelled. Additional stars from the SALT survey are shown as dark blue circles with error bars. The zero-age helium main-sequence (HeMS) and the evolution track for a model of a He+He white dwarf merger (Zhang and Jeffery, 2012, 0.30+0.25 $M_{\odot}$) are shown as solid lines.

(Snowdon et al. these proceedings.) We have commenced follow-up observations of these with HRS or RSS, depending on target brightness. SALT's fixed altitude permits at most two epochs per day and is therefore not optimal if the *TESS* period is close to 12 sidereal hours or some multiple thereof.

From just 3 RSS observations with velocities differing by $\sim 250\,\mathrm{km\,s^{-1}}$, the intermediate helium-rich subdwarf Ton S 415 (sdO7.5V:He28) was discovered to be a large-amplitude radial-velocity variable. *TESS* data show it to be a suspected ellipsoidal binary with orbital period $P = 5089$ s. A complete orbital analysis based on follow-up RSS and HRS observations will be presented by Snowdon et al. (in preparation).

3.4. Additional Objects

As the SALT sample has increased over the duration of the survey, targets have been selected using increasingly broad criteria, latterly including Gaia colour and absolute magnitude (Geier et al., 2019), thereby increasing the number of targets around and beyond the margins of the original survey sample. From the start, there was a roughly 5% contamination by DB white dwarfs, resulting from poor classifications in the original surveys. In more recent semesters, we have discovered eight extremely hot white dwarf and pre-white dwarfs, including two PG1159 stars, one DO white dwarf, three O(He) and two O(H) stars (Jeffery et al. 2022, submitted). One of the O(H) stars is the central star of a previously unknown planetary nebula.

The sample now also contains a significant number of early-type hydrogen-rich sdO stars with Helium class < 10 (Fig. 1).

4. Conclusion

The SALT survey of helium-rich hot subdwarfs has recorded spectra of nearly 300 unique stars. Provisional spectral classifications and parameters have been derived, but work continues to fully characterise the sample. The sample covers a volume of parameter space representing a wide variety of pathways in the late evolution of low-mass stars, many either being binary stars or the consequence of an extreme binary interaction, such as a merger. Discoveries from extremely hot white dwarf and pre-white dwarfs, to intermediate helium subdwarfs with exotic surface mixtures, including many heavy metals, to extreme helium stars. The objective of exploring the connection between the lowest mass extreme helium giants and the extreme helium subdwarfs looks realisable.

Further Information

Authors' ORCID identifiers

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Author contributions

Conceptualization (CSJ), Data curation (CSJ, BM, IM, ES, VMW), Formal Analysis (CSJ, ES, LJAS)), Funding acquisition (CSJ), Investigation (CSJ), Methodology (CSJ, BM, ES, MD), Project administration (CSJ)

Resources (CSJ), Software (CSJ, BM, ES, VMW), Supervision (CSJ), Validation (CSJ), Visualization (CSJ), Writing - original draft (CSJ), Writing - review & editing (CSJ, . . .)

Conflicts of interest

The authors declare no conflict of interest.

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