The sdA problem – II. Photometric and Spectroscopic Follow-up

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ABSTRACT

Subdwarf A star (sdA) is a spectral classification given to objects showing H-rich spectra and sub-main sequence surface gravities, but effective temperature lower than the zero-age horizontal branch. Their evolutionary origin is an enigma. In this work, we discuss the results of follow-up observations of selected sdAs. We obtained time resolved spectroscopy for 24 objects, and time-series photometry for another 19 objects. For two targets, we report both spectroscopy and photometry observations. We confirm seven objects to be new extremely-low mass white dwarfs (ELMs), one of which is a known eclipsing star. We also find the eighth member of the pulsating ELM class.

Key words: subdwarfs – white dwarfs – binaries: general – stars: evolution

1 INTRODUCTION

White dwarf stars are the most common outcome of single-star evolution, corresponding to the final observable evolutionary stage of all stars with initial mass below 7–10.6 $M_\odot$ (e.g. Woosley & Heger 2015), including the Sun and over 95 per cent of all stars in the Galaxy. Their relative abundance, combined with a simple structure and long cooling timescales, makes them the perfect laboratory for modelling stellar evolution (e.g. Kalirai et al. 2008; Romero et al. 2015), and for population synthesis studies constraining the age and star formation history of different stellar populations (e.g. Liebert et al. 2005; Tremblay et al. 2016; Kilic et al. 2017). About 25 per cent of white dwarfs in the galactic field are known to have a companion (Toonen et al. 2017), therefore white dwarfs have also the potential to put constraints into binary evolution channels.

Short-period binary white dwarfs in particular are potential progenitors of Type Ia (Webbink 1984; Iben & Tutukov 1984) and Ia supernovae (Bildsten et al. 2007). This fact motivated the first surveys for white dwarfs in close binaries (Robinson & Shafter 1987; Foss et al. 1991), which resulted on null detections. The first successful survey was performed by Marsh et al. (1995). They noticed that the catalogue of Bergeron et al. (1992) contained fourteen white dwarfs with spectroscopic mass below 0.45 $M_\odot$, which cannot be formed within a Hubble time without some form of mass-loss enhancement. They were most likely the remnants of mass transfer in post-main-sequence common-envelope binaries. Indeed, Marsh et al. (1995) confirmed five out of the seven stars they probed to be in binaries. More recent studies suggest that the binary fraction of low-mass white dwarfs ($M \lesssim 0.45 M_\odot$) is at least 70 per cent (Brown et al. 2011a). Low-mass single systems can be explained by other mass-loss enhancing mechanisms, such as high metallicity (D’Cruz et al. 1996) or supernova stripping (Wang & Han 2009), by mass ejection caused by a massive planet (Nelemans & Tauris 1998), or by merger events (Zhang & Jeffery 2012; Zhang et al. 2017).

For the currently known white dwarfs with mass below 0.3 $M_\odot$, the binary fraction seems to be close to 100 per cent (Brown et al. 2016a). These systems are known as extremely-low mass white dwarfs (ELMs).

The ELM Survey (Brown et al. 2010; Kilic et al. 2011; Brown et al. 2012a; Kilic et al. 2012; Brown et al. 2013; Gianninas et al. 2015; Brown et al. 2016a) made large progress in the study of these objects. They have found 88 systems, 76 of which were confirmed to be in binaries, mostly through the analysis of their radial velocity (RV) variations. Seven systems were found to be pulsators, eight show ellipsoidal variations, and two are eclipsing systems (Hermes et al. 2012, 2013b,a; Kilic et al. 2015; Bell et al. 2015; Brown et al. 2016a). The obtained distribution of secondary mass suggests that over 95 per cent of the sys-
tems are not Type Ia supernovae progenitors (Brown et al. 2016a). They are, nonetheless, strong gravitational wave sources (Kilic et al. 2012), given that most systems will merge within a Hubble time (Brown et al. 2016b). The gravitational wave radiation of the shortest orbital period systems ($P \lesssim 1$ h) may be directly detected by upcoming space-based missions such as the Laser Interferometer Space Antenna (LISA). Kilic et al. (2012) found three systems that should clearly be detected by missions like LISA in the first year of operations. Three other systems are above the proposed 1-$\sigma$ detection limit after one year of observations. Even when not significantly above the detection limit, ELMs are important indicators of what the Galactic foreground may look like for these detectors. Therefore understanding the space density, period distribution, and merger rate of these systems is crucial for interpreting the results of upcoming space-based gravitational wave missions, and for studying the evolution of interacting binary systems.

The target selection of the ELM Survey was initially developed to find B-type hypervelocity stars (see the MMT Hypervelocity Star Survey: Brown et al. 2009, 2012b, 2014), hence it favours the detection of hot ELMs ($T_{\text{eff}} \gtrsim 12,000$ K). Cooler objects ($T_{\text{eff}} \lesssim 10,000$ K) were targeted by Brown et al. (2012a). Yet, less than 5 per cent of the objects in the ELM Survey show $T_{\text{eff}} \lesssim 9,000$ K, while evolutionary models (Althaus et al. 2013; Córsico & Althaus 2014, 2016; Istrate et al. 2016) predict the same amount of time to be spent above and below said $T_{\text{eff}}$. Although the uncertainties in residual burning can significantly influence the cooling timescale, it is still expected that 20–50 per cent of the ELMs should show $T_{\text{eff}} < 9,000$ K (Brown et al. 2017; Pelisoli et al. 2017). Moreover, the ELM Survey selection criteria also favoured higher log $g$ objects. The low-log $g$ phases happen before the object reaches the white dwarf cooling track (the objects are hence known as pre-ELMs, see e.g. Maxted et al. 2011, 2014) and are relatively quick. However, pre-ELMs are also much brighter. Assuming a spherical distribution, we found in Pelisoli et al. (2017) that there should be about a hundred detected objects with log $g = 5$–$6$ for each object with log $g = 6$–$7$ in a magnitude-limited survey. Hence there is clearly a missing population of cool, low-mass ELMs yet to be found, as evidenced in Fig. 1.

In an effort to retrieve these missing objects, Kepler et al. (2016) extended their white dwarf catalogue down to log $g = 5.5$, revealing a population of objects which were dubbed subdwarf A stars (sdAs). Their spectra are dominated by hydrogen lines, suggestive of $T_{\text{eff}} \sim 10,000$ K and of 4.75 < log $g$ < 6.5. Brown et al. (2017) suggested they are mainly metal-poor A/F stars in the halo with an overestimated log $g$, given the pure hydrogen grid used to fit these objects in Kepler et al. (2016). However, as we showed in Pelisoli et al. (2018), the addition of metals to the models does not necessarily lower the estimated log $g$. Moreover, we identified the existence of clearly two populations within the sdAs, with overlapping but distinct colour distributions, and found that at least 7 per cent of the sdAs are more likely (pre-)ELMs than main sequence stars, given their physical and kinematic parameters. The missing (pre-)ELMs are thus likely within the sdA population.

In this work, we follow up on selected sdAs to probe their binarity with the aim of extending the population of known (pre-)ELMs to all the space of physical parameters predicted by the evolutionary models. We obtain both time-resolved spectroscopy to search for radial velocity (RV) variations indicating the presence of a close binary companion, and time-series photometry to look for eclipses, ellipsoidal variations, or pulsations typical of ELMs. Extending the sample of known ELMs to cool temperatures and lower masses will allow us to more robustly test the evolutionary models. With a more complete sample, we will also be able to make more reliable predictions as to the contribution of the gravitational wave signals from ELMs to upcoming missions.

2 METHODS

2.1 Observations

Our observing campaign targeted bright objects with $T_{\text{eff}}$ and log $g$ in the range predicted by the evolutionary models shown in Fig. 1. Targets with high proper motion and/or high radial velocities, and ELM-like colours, yielding high probability of being a (pre-)ELM according to Pelisoli et al. (2018), were prioritized. We have used the proper motions from the GPS1 catalogue (Tian et al. 2017), which contains all but one of the objects analysed here. Consistency checks were done with the Hot Stuff for One Year (HSOY, Altmann et al. 2017) and the UCAC5 (Zacharias et al. 2017) catalogues. We found the proper motions to agree within uncertainties for all the objects studied here. Priority was also given to objects showing radial velocity variations in the subspectra taken by the Sloan Digital Sky Survey (SDSS). We obtained time-resolved spectroscopy for 26 targets. We have also obtained time-series photometry for 21 targets in the vicinity of the instability strip by Tremblay et al. (2015) and Gianninas et al. (2015), which was empirically obtained taking into account 3D corrections to $T_{\text{eff}}$ and log $g$. The targets are listed in Table 1, as well as their SDSS $g$ magnitude, proper motion (ppm), distances given a MS or (pre-)ELM radius and velocities in the Galactic rest frame ($v_{\text{hel}}$).

We carried out spectroscopy mainly with the Goodman Spectrograph (Clemens et al. 2004) on the 4.1 m Southern Astrophysical Research (SOAR) Telescope. All exposures were taken with a 1.0" slit, and binned by a factor of two in both dimensions. We used a 1200 l/mm grating, with a camera angle of 30.00" and grating angle of 16.30", obtaining a wavelength coverage of 3600–4950 Å with a resolution of $\sim 2$ Å.

We also obtained spectroscopy with the GMOS spectrographs (Hook et al. 2004; Gimeno et al. 2016) on both Gemini North and Gemini South 8.1 m telescopes. The exposures were taken with a 0.75" slit. As with SOAR, we binned the CCD by a factor of two in both dimensions. We used a 1200 l/mm grating, with a camera angle of 30.00" and grating angle of 16.30", obtaining a wavelength coverage of 3580–5190 Å and 3630–5240 Å, respectively. Our data was partially affected by the bright columns issue developed by GMOS-S CCD2 and CCD3 during September 30, 2016 – February 21, 2017.

Five log $g > 5.5$ objects were observed with the medium resolution echelle spectrograph X-shooter (Vernet et al.
Figure 1. Bottom-left panel shows the $T_{\text{eff}} - \log g$ diagram for the objects in the ELM Survey, shown as red triangles, compared to two binary evolution models of Istrate et al. (2016) (blue lines), resulting on ELMs of masses 0.182 and 0.324 $M_\odot$. The white dwarfs from Kepler et al. (2016) are shown as grey dots for comparison. The top panel shows the distributions in $T_{\text{eff}}$, both for the observed ELMs (red continuous line) and obtained from the models (blue dashed line). The bottom-right panel shows the distributions for $\log g$. The distributions for the models were obtained taking into account the time spent at each bin of $T_{\text{eff}}$ or $\log g$ compared to the total evolutionary time, with a spherical volume correction to account for differences in brightness (see Pelisoli et al. 2018, for further details). Note that there is a lack of known ELMs in the low $T_{\text{eff}}$ and low $\log g$ ends of the distribution. There are also missing objects around $\log g \approx 7.0$; however, this range can also be reached through single evolution.

2.2 Data analysis

SOAR spectroscopic data were reduced using IRAF’s NOAO package. The frames were first bias-subtracted, and flattened with a quartz lamp flat. We then extracted the spectra and did the wavelength calibration with a CuHeAr lamp spectrum extracted with the same aperture. Finally, flux and extinction calibration were applied. The GEMINI IRAF package was used for data from these telescopes, and the X-shooter
pipeline for the VLT data, with equivalent steps in the reduction.

Radial velocity estimates were done with the XCSAO task from the RVSAO package (Kurtz & Mink 1998), after verifying that the intercalated HeAr lamps presented no shift, which was always the case. We cross-correlated the spectral region covering all visible Balmer lines (typically from 3750 to 4900 Å) to spectral templates from the updated model grid based on Koester (2010), described in Pelisoli et al. (2018). The values of RV were corrected to the Solar System barycentre given the time of observations and the telescope location. All our RV estimates are given in Table A1. We have not added the RV estimated from the SDSS spectra to our dataset, because it was obtained eight years before our data even in the best of cases, hence the phase might not be accurate to our recently obtained data.

We performed a Shapiro-Wilk normality test (Shapiro & Wilk 1965) to verify whether the obtained velocities displayed a behaviour which could be explained by Gaussian uncertainties. Next, we calculated the Lomb

| SDSS J | $g$ | ppm (mas/yr) | $\sigma_{ppm}$ (mas/yr) | $d_{MS}$ (pc) | $d_{(pre-)ELM}$ (pc) | $v_{los}$ (km/s) |
|--------|----|-------------|-----------------|-------------|-----------------|-----------------|
| 004227.73-010634.9 | 18.63 | 1.1 | 2.5 | 16494 | 254 | 111 |
| 011508.65+005346.1 | 18.07 | 7.5 | 1.6 | 16799 | 232 | -173 |
| 024932.84-010708.4 | 19.44 | 3.2 | 2.5 | 27852 | 405 | -146 |
| 031609.92-001338.9 | 19.95 | 19.3 | 2.0 | 6625 | 108 | 189 |
| 032109.77+003321.8 | 16.76 | 11.5 | 2.3 | 21652 | 202 | 88 |
| 041515.00-043231.0 | 16.49 | 8.8 | 2.3 | 8090 | 113 | 64 |
| 050034.37+172255.5 | 18.07 | 1.4 | 2.2 | 10429 | 173 | 4-55 |
| 060034.84+045557.6 | 17.34 | 2.7 | 1.6 | 9004 | 140 | 9 |
| 070410.00+034332.9 | 17.58 | 3.3 | 3.1 | 9697 | 153 | -128 |
| 100701.89+070806.8 | 18.25 | 6.2 | 2.9 | 17876 | 250 | 253 |
| 112261.66-010140.7 | 18.50 | 5.5 | 2.0 | 17990 | 256 | 62 |
| 112620.47+090145.5 | 18.85 | 6.2 | 2.5 | 23810 | 331 | 253 |
| 122911.49-003814.4 | 18.27 | 10.2 | 1.8 | 14079 | 218 | 380 |
| 134201.30+021425.4 | 16.93 | 22.5 | 1.8 | 30696 | 270 | 31 |
| 162624.91+162201.5 | 17.04 | 6.8 | 1.8 | 27991 | 270 | 31 |
| 164032.15+135329.2 | 16.34 | 39.1 | 1.5 | 3435 | 62 | 12 |
| 233507.13-102551.5 | 19.34 | 5.1 | 2.7 | 25993 | 378 | 95 |

Table 1. Followed-up objects and some notable kinematic properties, as well as the SDSS $g$ magnitude. The first 24 objects were followed-up spectroscopically only, next 19 only photometrically, and the last two both photometrically and spectroscopically. The quoted proper motions are from Tian et al. (2017), except for J110338.46-160617.4, which is not in this catalogue and whose proper motion was then obtained from Altmann et al. (2017). Many objects show unreliable proper motion given the relatively faint ($g \gtrsim 18$) magnitude. Note that most objects would be tens of kpc away given a MS radius.
Scargle periodogram (Lomb 1976; Scargle 1982) using the NASA Exoplanet Archive tool\(^1\). For each of the highest fifty peaks in the periodogram, we calculated an orbital solution of the form
\[
RV(t) = RV_0 + K \sin(2\pi t/T + \phi),
\]
where \(RV_0\) is the systemic velocity, \(K\) is the semi-amplitude of the RV variation, \(T\) is the period, and \(\phi\) is the phase. We selected as the best solution the one with the highest reduced \(R^2\), defined as
\[
R^2 \equiv 1 - \frac{\sum_i (y_i - \bar{y})^2}{\sum_i (y_i - \bar{y})^2},
\]
where \(y_i\) are the observed values, \(\bar{y}\) is their mean, and \(f_i\) are the adjusted values. This is equivalent to selecting the solution with the smallest reduced \(\chi^2\).

Each individual spectrum was later Doppler-corrected considering the estimated velocities, and all spectra of each object were combined to obtain a \(S/N \gtrsim 30\) spectrum (the average for the whole sample was \(S/R = 45\)). Considering the lack of strong metal lines, we fit these spectra to a grid of models assuming metallicity \(Z = 0.1 Z_\odot\), with the same input physics as described in Pelisoli et al. (2018). We caution that quoted uncertainties are formal fitting errors, and the systematic uncertainties are larger. We previously estimated it to be \(\approx 5\) per cent in \(T\) and 0.25 dex in \(\log g\) (e.g. Pelisoli et al. 2018); however, as we will show in Section 3.4, it seems that the systematic uncertainty in \(\log g\) can actually be higher in the \(T\) and \(\log g\) region of the sdAs, and reach 0.5 dex. The SDSS spectra of all objects were also fit to the same \(Z = 0.1 Z_\odot\) grid to allow a comparison. We have relied on the SDSS colours to choose between hot and cool solutions with similar \(\chi^2\), that arise due to similar equivalent width being possible with different combinations of \(T\) and \(\log g\). To estimate the mass of each object, we interpolated the models of Althaus et al. (2013). The models of Istrate et al. (2016) made a large improvement into the input physics, by taking into rotational mixing, which was shown to be an important factor in the atmosphere abundances for ELMs. However, the lowest ELM mass in the models of Istrate et al. (2016) is \(0.16 - 0.18 M_\odot\), depending on the metallicity, and most of our objects show mass lower than that. Only one object (SDSSJ1626+2622) could have its mass accurately determined with Istrate et al. (2016) models, and it agreed with the mass estimate using Althaus et al. (2013) within uncertainties. Hence, to be consistent, we used the models of Althaus et al. (2013) for all mass estimates.

All photometry images were bias-subtracted, and flat-field corrected using dome flats. Aperture photometry was done using the DAOPHOT package in IRAF. A neighbouring non-variable star of similar brightness was used to perform differential photometry. The resulting light curve was analysed with PERIOD04 (Lenz & Breger 2005), in search of pulsations with amplitude at least four times larger than the average amplitude of the Fourier transform. PERIOD04 was also used to fit the light curve and perform pre-whitening when pulsations were found, and to estimate uncertainties using the Monte Carlo method with a 1000 simulations.

3 RESULTS

We found seven objects whose RV variations indicate they are in close binaries. They show \(p\)-value smaller than 0.15 for the Shapiro-Wilk test, implying that the variations cannot be explained by Gaussian noise to a confidence level of 85 per cent. For six objects out of these seven, the \(p\)-value is smaller than 0.05, hence the confidence level is 95 per cent. The orbital solution shows \(R^2\) larger than 0.95 for all but one object. \(T_{\text{eff}}\) and \(\log g\) suggest they are new (pre-)ELMs (see Fig. 27). Their properties are given in Section 3.1.

For six other objects, the \(p\)-value is larger than 0.15, but we obtain an orbital solution with a short period (\(P \lesssim 10\) h), expected from (pre-)ELMs in the range of physical parameters for the sdAs (Brown et al. 2017), and \(R^2 \gtrsim 0.85\). Two other objects shows \(p < 0.05\), but its atmospheric parameters are compatible with both a pre-ELM and a main sequence star. More data is required to confirm the nature of these eight objects; given the distance modules or proper motion and the estimated physical parameters, we assume they are probable (pre-)ELMs and discuss their properties in Section 3.2.

Six other objects have twelve measurements or more (the average necessary to confirm binary, according to Brown et al. 2016a), in at least three different epochs and often multiple telescopes, but the Shapiro-Wilk test suggested no real variation. These objects are possibly single stars, or show either very short (\(\lesssim 1.0\) h) or long periods (\(\gtrsim 200\) days). We also found no RV variation or red companions for the five objects observed with X-shooter in three nights over a week. All these objects are detailed in Section 3.3.

In Section 3.4, we compare the values of \(T_{\text{eff}}\) and \(\log g\) obtained fitting the SDSS spectra and the SOAR or X-shooter spectra for each object. We were unable to obtain a good fit to the Gemini spectra. The Gemini reduction package interpolates between the CCD gaps before performing the flux calibration, and that seems to be affecting the output to a point where our models cannot fit the slope of the continuum.

In addition, we have found seven new pulsators among the sdAs. For other fourteen observed stars, we have obtained a detection limit \(\lesssim 10\) mmag and found no pulsations. The photometry results are discussed in Section 3.5.

3.1 New (pre-)ELMs

3.1.1 J032914.77+003218.8

The thirty RV estimates for J0329+0033, taken over seven non-consecutive nights at SOAR, yielded a Shapiro-Wilk \(p\)-value of 0.004, suggesting with a very high confidence level that the observed variations are not due to chance. We have estimated the period to be \(20.1 \pm 0.1\) h. The semi-amplitude is not well constrained by our data; we estimated it to be \(83 \pm 22\) km s\(^{-1}\). This results on an orbital fit with \(R^2 = 0.78\), shown in Fig. 2, the lowest \(R^2\) among our fits. However, when we assume a main sequence radius, the photometric parallax gives a distance larger than \(20\) kpc for this object, what is inconsistency with its proper motion of \(11.5 \pm 2.3\ mas\ yr^{-1}\) (Tian et al. 2017). The systemic velocity is also relatively high, \(153.3 \pm 18\ km\ s^{-1}\), Assuming an ELM

\(^1\) https://exoplanetarchive.ipac.caltech.edu/cgi-bin/Pgram/nph-radius, the distance drops to \(\sim 200\) pc.
The orbital solution, shown in Fig. 2, phase-folded to the 20.1 h period. Note that in this and also in the next orbital solution plots, two cycles are shown. The semi-amplitude is 83 ± 22 km s⁻¹, and the systemic velocity is 153 ± 18 km s⁻¹.

Our fit to the SOAR spectrum of J0329+0033 gives $T_{\text{eff}} = 9080 \pm 10$ K and log $g = 5.18 \pm 0.03$. Interpolating the models of Althaus et al. (2013), we obtain $M = 0.1536 \pm 0.0006 M_{\odot}$. Given this mass and the orbital parameters, the minimal mass of the companion (for an edge-on orbit) is $M_2 = 0.17 M_{\odot}$, implying a merging time shorter than 765 Gyr.

3.1.2 J073934.37+172225.5

We obtained nine spectra in three nights with SOAR for J0739+1722, whose RV variability was already suggested by its SDSS subspectra. The RV estimates from the SOAR spectra give $p = 0.1465$. We obtained a period of 6.64 ± 0.03 h, too short for a main sequence star in the sdA range of parameters (Brown et al. 2017), and $K = 82.6 \pm 6.8$ km s⁻¹. The orbital solution, shown in Fig 3, has a high $R^2$ of 0.96.

We estimated the mass of the ELM primary to be 0.145 ± 0.001 $M_{\odot}$, given the $T_{\text{eff}} = 7550 \pm 12$ K and the log $g = 5.06 \pm 0.05$ estimated from the SOAR combined spectrum. The minimum mass of the companion is $M_2 = 0.10 M_{\odot}$. For the mean inclination angle for a random stellar sample, $i = 60$, the mass is 0.12 $M_{\odot}$. Given the orbital parameters, the merging time is smaller than 68 Gyr.

3.1.3 J084034.83+045357.6

J0840+0453 was observed in three nights with SOAR, and we obtained nine spectra. A possible RV variability was first detected in the SDSS subspectra. The Shapiro-Wilk test performed in the SOAR RV data confirmed the variability. The best orbital solution (Fig. 4) gives $R^2 = 0.98$, with a semi-amplitude of 221.6±12.8 km s⁻¹ and a period of 8.13±0.01 h.

Our fit to the SOAR spectra of J0840+0453 gives $T_{\text{eff}} = 7890 \pm 32$ K and log $g = 5.07 \pm 0.09$, implying an ELM mass of $M = 0.147 \pm 0.002 M_{\odot}$. The secondary mass is $M_2 > 0.50 M_{\odot}$, hence it is probably a canonical mass white dwarf. The merging time due to gravitational wave radiation is ≤ 28 Gyr.

3.1.4 J134336.44+082639.4

J1343+0826 was found to be photometrically variable in our observations carried out with OPD (see Fig. 5), and most likely ELM by Pelisoli et al. (2018). We found a photometric period of about one hour, with an amplitude of 26.2 ± 2.3 mmag. This is consistent with the predicted values of Córsico & Althaus (2016). Unfortunately, this is the only detected period, and therefore we cannot obtain an asteroseismological fit to this object. Spectroscopic follow-up was obtained over five nights at SOAR; twenty-eight spectra were obtained. The derived velocities give $p = 0.004$, indicating variability with a high confidence level (>$99$ per cent). The dominant period was ~ 24 h, a probable alias given that four of the observed nights consisted of two sets of consecutive nights. A similar $R^2$ (only 0.5 per cent smaller) is obtained with $T = 21.39 \pm 0.01$ h, which is the period we adopt for the orbital solution shown in Fig. 6. The derived semi-amplitude is 136.2 ± 7.0 km s⁻¹. The systemic velocity is remarkably high, $RV_0 = 326.0 \pm 7.2$ km s⁻¹. If
we estimate the orbital period. We followed-up on J1424-0214 given the RV variability suggested by its SDSS subspectra. We observed it in three nights at SOAR, obtaining ten spectra. We obtained a period of 3618±55 s and amplitude of 26.1±2.4 mmag.

Figure 5. The light curve for SDSS J134336.44+082639.4, obtained at OPD. There is a lot of spread in the data due to the variation of the seeing throughout the night. The dashed black line shows the smoothed data. The red line shows the best fit obtained with PERIOD04, with a period of 3618±55 s and amplitude of 26.1±2.4 mmag.

Figure 6. Orbital solution for the photometric variable star SDSS J134336.44+082639.4, with $T = 21.39 \pm 0.01$ h, $K = 136.2 \pm 7.0$ km s$^{-1}$, $RV_0 = 326.0 \pm 7.2$ km s$^{-1}$, and $R^2 = 0.95$.

the 24.7 h period is the true one, the amplitude would be 175.5±6.8 km s$^{-1}$, and $RV_0 = 323.0 \pm 3.8$ km s$^{-1}$.

The log $g$ we estimated from its SOAR spectrum is among the highest in our sample ($5.97 \pm 0.03$), and the effective temperature is nonetheless quite low ($T_{\text{eff}} = 8120 \pm 10$ K), making it a very interesting addition to the known population of pulsating ELMs. We estimate its mass to be $M = 0.153 \pm 0.001 M_\odot$, while the companion has $M_2 > 0.43 M_\odot$. The objects will merge in less than 449 Gyr.

3.1.5 J142421.30-021425.4

We followed-up on J1424-0214 given the RV variability suggested by its SDSS subspectra. We observed it in three nights at SOAR, obtaining ten spectra. We obtained a period of 6.3±0.4 h, with a semi-amplitude of 79.7±21.8 km s$^{-1}$. The orbital solution, shown in Fig. 7, has $R^2 = 0.988$.

We derived $T_{\text{eff}} = 9300 \pm 11$ K and log $g = 5.13 \pm 0.03$ from the SOAR combined spectrum assuming one tenth of the solar metallicity, obtaining $M = 0.1558 \pm 0.0008 M_\odot$ from the evolutionary models of Althaus et al. (2013). Slightly smaller atmospheric parameters are obtained from the SDSS spectrum, $T_{\text{eff}} = 9090 \pm 24$ K and log $g = 4.53 \pm 0.04$, resulting in $M = 0.170 \pm 0.002 M_\odot$. Given the estimated period and semi-amplitude, and assuming the parameters derived from the SOAR spectrum are correct, the companion has $M_2 < 0.09 M_\odot$ ($M_2 = 0.12 M_\odot$ for $q = 60^\circ$) and the objects will merge in less than 57 Gyr.

3.1.6 J205120.67+014554.4

J2051+0145 would be at a distance of $7.42 \pm 0.03$, $M_2 = 0.148 \pm 0.001 M_\odot$. The minimal mass of the secondary is $M_2 = 0.45 M_\odot$, and the merging time due to the emission of gravitational waves is shorter than 533 Gyr.

3.1.7 J092056.09+013114.8 – An eclipsing binary

J0920+0131 is an eclipsing binary identified independently by Palaversa et al. (2013) and Drake et al. (2014). Using data from the the Catalina Real-Time Transient Survey (CRTS, Drake et al. 2009), we estimate the orbital period to be $15.742 \pm 0.003$ h. The phase-folded light curve is shown in Fig. 9. We obtained thirteen spectra in five nights at SOAR. Fixing the period to the photometric estimate, we obtain an orbital solution with $R^2 = 0.95$ (see Fig. 10) and $K = 75.7 \pm 11.5$ km s$^{-1}$.
We fit the photometry using \textsc{Jktebop} \citep{Southworth2004}, and obtain an orbital inclination of 82.7 ± 0.4 and $R_2/R_1 = 0.80 \pm 0.03$. Given this inclination, we obtain $M_2/M_1 = 0.894$ from the RV fit. Our spectroscopic fit to the spectrum of the primary gives $T_{\text{eff}} = 7480 \pm 13$ K and log $g = 4.80 \pm 0.06$, implying $M_1 = 0.149 \pm 0.002$ $M_\odot$ and $R_1 = 0.25$ $R_\odot$. Therefore the secondary mass seems to be an even lower mass ELM with $M_2 = 0.133 \pm 0.002$ $M_\odot$ and $R_2 = 0.20$ $R_\odot$. The external uncertainty in the radius, given the 0.25 dex uncertainty in log $g$, is about 0.7 $R_\odot$ (assuming a fixed mass of 0.15 $M_\odot$). Thus the radius of the secondary might be larger, as it would be expected from a lower mass white dwarf given the mass-radius relation. We estimate the secondary to show $T_{\text{eff}} \sim 4000$ K, given the ratio between fluxes estimated from the light curve.

3.2 Probable (pre-)ELMs

3.2.1 J004227.73-010634.9

J0042-0106 was followed up because of the log $g > 5.5$ that we obtained by fitting its SDSS spectrum to solar abundance models. Moreover, assuming the object has a main sequence radius, we obtain a distance of over 15 kpc. It was observed in three nights with Gemini South; two spectra were obtained at each night. Although the observed variations are consistent with Gaussian errors, we obtained an orbital solution with $R_2^2 = 0.993$ (Fig. 11). The estimated amplitude is 48 km s$^{-1}$, and the period is quite low, of only 91 min. Further observations are required to confirm these findings.

The mass of the primary, given the fit to the SDSS spectrum which resulted on $T_{\text{eff}} = 8050 \pm 24$ and log $g = 5.51 \pm 0.08$, is $M = 0.1449 \pm 0.0003$ $M_\odot$. Assuming the estimated orbital parameters, we obtain the secondary to show $M_2 > 0.028$ $M_\odot$ (for an inclination of 60°), $M_2 = 0.033$ $M_\odot$, and for 15°, $M_2 = 0.22$ $M_\odot$. Given the short period, the system would merge in less than a Hubble time ($\tau_{\text{merge}} < 4.2$ Gyr).
3.2.2 \( \text{J011508.65+005346.1} \)

\( \text{J0115+0053} \) also shows \( \log g > 5.5 \) in our solar abundance fits to its SDSS spectrum, and \( d > 15 \) kpc when a main sequence radius is assumed. Moreover, we found it to be more likely ELM in Pelisoli et al. (2018), given its space motion, colours, and physical parameters. We obtained six spectra at three nights with Gemini. The obtained RVs show real variability only at a 70 per cent confidence level, but we obtained \( R^2 = 0.97 \) for the best orbital solution, with \( T = 100 \) min and \( K = 74 \) km s\(^{-1}\) (see Fig. 12). However, all the spectra were affected by the bright columns that appeared at the Gemini South CCD during the end of 2016B, hence the uncertainties in the velocities are larger.

Given the \( T_{\text{eff}} = 8670 \pm 24 \) K and the \( g = 5.64 \pm 0.08 \), and the hinted RV variability, we propose \( \text{J0115+0053} \) is a probable ELM, but we caution that more data is needed to confirm this identification. The evolutionary models give a primary mass of \( 0.150 \pm 0.001 \, M_\odot \), and, assuming the tentative orbital parameters, the minimal secondary mass is \( 0.049 \, M_\odot \) (\( M_2 = 0.058 \, M_\odot \) for \( i = 60^\circ \), and \( M_2 = 0.54 \, M_\odot \) for \( i = 15^\circ \)), and the merging time is shorter than 3.2 Gyr.

3.2.3 \( \text{J030608.92-001338.9} \)

We found J0306-0013 to be most likely a (pre-)ELM in Pelisoli et al. (2018). It was classified as a sdA in Kepler et al. (2016). We obtained ten spectra over two nights at SOAR. Fitting the combined spectrum to our \( Z = 0.1 \, Z_\odot \) grid, we obtain \( T_{\text{eff}} = 7770 \pm 10 \) K and \( g = 5.36 \pm 0.04 \), implying \( M = 0.1433 \pm 0.0004 \, M_\odot \).

The Shapiro-Wilk test yields \( p < 0.3 \), suggesting the estimated RVs vary at the 70 per cent confidence level. With only two nights, it is hard to constrain the orbital period. We find two solutions with \( R^2 \) differing by less than two per cent for \( T = 28.6 \) h and \( T = 13.5 \) h, the former with \( K = 186 \) km s\(^{-1}\), and the latter with \( K = 88 \) km s\(^{-1}\). Both solutions are shown in Fig. 13.

For the 28.6 h period, the secondary has a relatively high minimum mass of \( \sim 1.0 \, M_\odot \). For any inclination above \( 60^\circ \), the companion would have to be a neutron star. The merging time for this period is smaller than 546 Gyr. On the other hand, for the 13.5 h period, the minimal mass is \( M_2 > 0.15 \, M_\odot \), and the merging time is shorter than 320 Gyr.

3.2.4 \( \text{J045515.00-043231.0} \)

J0455-0432 was also found to be most likely a (pre-)ELM in Pelisoli et al. (2018). Eleven spectra were obtained over two nights at SOAR. The estimated RVs suggest variability at 65 per cent confidence level. We obtain a dominant period of 4.1 h, but with a high uncertainty of 3.8 h. We estimate \( K = 60 \pm 24 \) km s\(^{-1}\). The orbital solution assuming the 4.1 h period, shown in Fig. 14, gives \( R^2 = 0.89 \).

The SOAR spectrum suggests \( T_{\text{eff}} = 8250 \pm 8 \) K and \( g = 4.15 \pm 0.03 \). These values are consistent with a pre-ELM of \( M = 0.180 \pm 0.001 \, M_\odot \), in a binary with an object of minimal mass \( 0.061 \, M_\odot \) (0.073 \( M_\odot \) for \( i = 60^\circ \), and 0.69 \( M_\odot \) for \( i = 15^\circ \)), which will merge within 25 Gyr.

3.2.5 \( \text{J122911.49-003814.4} \)

The radial velocity we derived for J1229-0038 from its SDSS spectrum was \( 472 \pm 3 \) km s\(^{-1}\), consistent with the \( 465 \pm 5 \) km s\(^{-1}\) given by the SDSS spectral pipeline fit and close to the escape velocity of the Galaxy. Moreover, a main sequence radius would place it at a distance close to 15 kpc, inconsistent with its proper motion of \( 10.2 \pm 1.8 \) mas yr\(^{-1}\) (Tian et al. 2017). Observing it for two nights at SOAR, we obtained five spectra. Although the Shapiro-Wilk test suggests the variability can be explained by Gaussian noise, we find an orbital solution with \( R^2 = 0.96 \), \( T = 3 \) h, and \( K = 47 \) km s\(^{-1}\). We estimate a very high systemic velocity of \( 510 \) km s\(^{-1}\), consistent with the SDSS spectrum, suggesting the semi-amplitude might actually be higher. More data are needed to constrain the orbit of this object.

The fit to its SOAR spectrum gives \( T_{\text{eff}} = 8300 \pm 21 \) K and \( g = 5.65 \pm 0.06 \), implying a mass \( M = 0.1476 \pm \)
0.0009 $M_\odot$ in the models of Althaus et al. (2013). Assuming the obtained orbital parameters are correct, the mass of the companion should be higher than $M_2 = 0.035 M_\odot$, or equal to $0.32 M_\odot$ for $i = 15^\circ$. The mass for most probable $i = 60^\circ$ inclination is $0.042 M_\odot$. The merging time is just above a Hubble time, $\tau_{\text{merge}} < 20$ Gyr.

3.2.6 J233606.13-102551.5

J2336-1025 would be at a distance larger than 26 kpc if it had a main sequence radius. We obtained $\log g = 5.72 \pm 0.15$ and $T_{\text{eff}} = 8330 \pm 39$ K from its SDSS spectrum using our solar abundance models. This implies $M = 0.149 \pm 0.003 M_\odot$ and $R = 0.088 \pm 0.02 R_\odot$. We followed it up for three nights with Gemini South, obtaining six spectra. The RV estimates hint a period of 2.4 h, even though the variability could also be explained by Gaussian uncertainties. The best orbital solution ($R^2 = 0.92$) gives $K = 131$ km s$^{-1}$ and is shown in Fig. 16. With these orbital parameters, we obtain $M_2 > 0.12 M_\odot$ and $\tau_{\text{merge}} < 3.73$ Gyr, shorter than a Hubble time.

3.2.7 J162624.91+162201.5

We obtained in Pelisoli et al. (2018) that J1626+1622 is most likely a (pre-)ELM. It was followed-up for two nights at SOAR, when we obtained eight spectra. At a 90 per cent confidence level, the detected RV variability cannot be explained by random uncertainty. We estimated a period of $8.2 \pm 0.1$ h and $K = 92.6 \pm 19.3$ km s$^{-1}$, obtaining an orbital solution with $R^2 = 0.88$, shown in Fig. 17.

However, J1626+1622 we derived a low log $g = 3.83 \pm 0.03$, with $T_{\text{eff}} = 7460 \pm 15$ K, from its combined SOAR spectrum. Similar parameters are obtained from the SDSS spectrum. With these parameters, we could only explain it as a pre-ELM in a CNO flash. The time scale of these flashes ranges from $10^7$ to $10^8$ years. The estimated physical parameters are consistent with the flashes of a $M = 0.34 M_\odot$ model. Given the estimated orbital parameters, $M_2 > 0.20 M_\odot$ and $\tau_{\text{merge}} < 32$ Gyr.
3.2.8 J090410.00+034332.9

We obtained eight spectra over two nights at SOAR for J0904+0343, given its RV variability in the SDSS subspectra. The normality test gave $p = 0.006$, confirming the variability. We estimated a period of 14.7 ± 0.3 h, with a low semi-amplitude of 47.7 ± 2.4 km s$^{-1}$, suggesting either a high-orbital inclination, or that the object is a main sequence binary. The orbital solution, shown in Fig. 18 gives $R^2 = 0.997$.

J0904+0343 SOAR spectrum fits $T_{\text{eff}} = 7680 ± 20$ and $\log g = 4.08 ± 0.05$, assuming 0.1 $Z_\odot$. This is compatible with a pre-ELM of mass 0.18 ± 0.05 $M_\odot$ given the models of Althaus et al. (2013). However, it could also mean that the object is a binary metal poor F star in the halo. The estimated distance given a main sequence radius is 9 kpc, and the proper motion is quite low and uncertain (3 ± 3.1 mas yr$^{-1}$). The low detected semi-amplitude results on a low minimal mass of 0.08 $M_\odot$, assuming a pre-ELM primary, given that the orbit would probably not be edge-on. For a 15° inclination, the mass is about 1.05 $M_\odot$, and for 60°, it is 0.092 $M_\odot$. The merging time would be up to 590 Gyr.

We will be able to estimate the distance for this star and others with the parallax to be released by Gaia, and therefore the difference between our preferred solution as a pre-ELM and a 9 kpc main sequence star will be clear.

3.3 No detected variation

Fig. 19 shows the RV estimates for the objects with no statistically significant RV variations, and no good orbital solutions in the probed ranges of periods, described below. We caution that periods as short as 12 min were observed for the known ELMs (Brown et al. 2011b), and theoretical models predict periods of several days (Sun & Arras 2017).

J222009.74-092709.9 was found to be a photometric variable in OPD data (see Fig. 20). Despite its reliable proper motion of $\mu = 9.6 ± 1.6$ mas yr$^{-1}$, we did not find it to be most likely ELM in Pelisoli et al. (2018) given its colours. The spectroscopic follow-up revealed no orbital periods in the range ~ 20 min to ~ 200 days. However, we obtain log $g = 6.10 ± 0.02$ and $T_{\text{eff}} = 8230 ± 6$ K for the SOAR spectra of this object, which not only places it in the region of the known ELMs, but also within the instability strip given by Tremblay et al. (2015), thus justifying the observed photometric variability. We suggest further monitoring of this object should be done to probe shorter and longer orbital periods, as well as further time series photometry to allow an asteroseismological study.

J233403.21+153829.2, J233831.91+125318.3, and J155937.48+113721.9 also have reliable proper motion according to the criteria of Pelisoli et al. (2018) (39.1 ± 1.5, 13.6 ± 1.6, and 7.4 ± 1.8 mas yr$^{-1}$, respectively, according to Tian et al. 2017), yet they were not found to be most likely ELMs. J1559+1137 has not been previously cited in the literature. Our estimated physical parameters are close.

Figure 18. The orbital solution for the SOAR data of SDSS J090410.00+034332.9, folded to the 14.7 h period (bottom), and the estimated RVs (top).

Figure 19. Velocities for the six objects observed in multiple epochs, with no statistically detected variation.
to the main sequence upper limit, $T_{\text{eff}} = 11880 \pm 41$ K and $\log g = 4.83 \pm 0.01$. The lack of RV variation and periods in the range $\sim 1$ h to $\sim 40$ days suggests it is either a short period or ELM, or possibly a halo blue straggler star.

J2337+1538 in particular was suggested to be an extremely-metal poor (EMP) star by Aoki et al. (2013). Their adopted physical parameters based on the SEGUE stellar parameter pipeline (SSPP, Lee et al. 2008), $T_{\text{eff}} = 6500$ K and $\log g = 4.0$, agree within external uncertainties with the parameters we estimate from SOAR spectra, $T_{\text{eff}} = 6710 \pm 17$ K and $\log g = 4.25 \pm 0.05$. No periods were found in the $\sim 24$ min to $\sim 180$ day range, thus the EMP explanation seems likely, although at odds with the high proper motion.

J2238+1253 was photometrically classified as a horizontal branch (HB) star by Xue et al. (2008). However, given our estimated physical parameters from its SOAR spectrum, $T_{\text{eff}} = 7870 \pm 9$ K and $\log g = 5.17 \pm 0.05$, this classification seems unlikely, considering both the low temperature and high log $g$. We find nonetheless no periods in the range $\sim 20$ min to $\sim 180$ days. The object could either be an EMP with an overestimated log $g$, or a single ELM, formed through one of the alternative paths to binary evolution described in the Introduction. Gaia parallax will allow us to determine its nature.

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J2134+1538 was photometrically classified as a horizontal branch (HB) star by Xue et al. (2008). However, given our estimated physical parameters from its SOAR spectrum, $T_{\text{eff}} = 7870 \pm 9$ K and $\log g = 5.17 \pm 0.05$, this classification seems unlikely, considering both the low temperature and high log $g$. We find nonetheless no periods in the range $\sim 20$ min to $\sim 180$ days. The object could either be an EMP with an overestimated log $g$, or a single ELM, formed through one of the alternative paths to binary evolution described in the Introduction. Gaia parallax will allow us to determine its nature.

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Table 2. Physical properties derived for the objects observed with X-shooter, with models assuming $Z = 0.1 Z_\odot$.

| SDSS J    | $T_{\text{eff}}$ (K) | $\log g$          |
|-----------|----------------------|--------------------|
| 024932.84-010708.4 | 8219 ± 13           | 4.775 ± 0.044     |
| 101701.89+070806.8  | 8746 ± 6            | 4.331 ± 0.020     |
| 112620.47+090145.5  | 8467 ± 7            | 4.640 ± 0.021     |
| 112616.66-010140.7  | 8073 ± 8            | 4.834 ± 0.025     |
| 233343.95-001502.0  | 8279 ± 6            | 4.410 ± 0.016     |

Figure 21. The top panel shows the combined X-shooter spectrum for J024932.84-010708.4. No companion can be identified in the red. The bottom panel shows the RVs obtained for the spectra taken at three different nights. The dashed lines show the weighted mean and the ±1 $\sigma$ values.

3.4 Spectral fits

Fig. 26 shows the comparison between our fit to SDSS spectra and to spectra obtained as part of this work, with the same grid of models ($Z = 0.1 Z_\odot$). The effective temperature seems to agree remarkably well between spectra obtained with different facilities, with average differences of less than 2 per cent. The log $g$, on the other hand, shows a larger spread. Considering the spectra obtained with SOAR,
Figure 22. Combined X-shooter spectrum for J101701.89+070806.8 (top), and the RVs obtained from each individual spectrum (bottom). The weighted mean and ±1σ values are indicated by the dashed lines.

Figure 23. The estimate RVs for J112620.47+090145.5 (bottom), obtained from the individual spectrum taken at three different nights. The Doppler-corrected combined spectrum is shown in the top panel.

Figure 24. X-shooter spectrum (top) and RV estimates (bottom) for J112616.66-010140.7. The RV estimates agree between the three nights.

Figure 25. Bottom panel shows the RV estimates for J233343.95-001502.0, and the top panels shows the combined Doppler-corrected spectrum for all epochs.

The sdA problem – II. Observational Follow-up

3.5 Photometry

Besides J1343+0826 and J2220-0927 described in Sections 3.1.4 and 3.3, we have found five other sdAs to show variability. Pulsation periods and amplitudes for all the average difference to SDSS, considering only objects whose fit is not at the border of our grid, is only about 0.08 dex, hence completely consistent with the uncertainties. However, comparing the four X-shooter spectra to SDSS, we obtain a large difference of −0.93 dex. The grid of models is the same, so the difference cannot be explained by metallicity as suggested by Brown et al. (2017).

The main differences between X-shooter and SDSS/SOAR spectra are the wavelength coverage and the spectral resolution. At low temperatures, the width of the lines is not very sensitive to log g, and the log g determination depends essentially on flux below 3700 Å. Spectra obtained with the SDSS spectrograph only cover above 3800 Å. More recent spectra obtained with BOSS extend the coverage down to 3600 Å, but usually with low-S/N in this wavelength range. This region is also very sensitive to flux calibration and extinction. Hence log g estimates from SDSS spectra might be affected by these uncertainties. We had previously assumed an external 0.25 dex uncertainty (Pelisoli et al. 2018), but it appears that it might be even larger, up to 0.50 dex. It is important to caution, however, that these four objects were selected on a very large sample, with tens of thousands of sdAs (Pelisoli et al. 2018), hence we should expect to find several objects with errors of 2−3σ. In short, we cannot assert that this difference between SDSS and X-shooter spectral fits is systematic, as it might result from statistical fluctuations.

The adopted physical parameters for our new and probable (pre-)ELMs are shown in Table 3, as well as their estimated orbital parameters. Fig. 27 is similar to Fig. 1, including these new objects. These additions to the known sample of ELMs improve the comparison between model predictions and observed population, by adding objects both to cool and to low-mass ends of the (pre-)ELM space of physical parameters.
Figure 26. Comparison between the physical parameters obtained by fitting SDSS spectra or SOAR/X-shooter spectra (labelled as other). The physical parameters derived from SOAR spectra are shown as black dots, while parameters derived from X-shooter spectra are shown as red squares. There is a very good agreement, to less than 2 per cent, in $T_{\text{eff}}$ (left). The dashed rectangle in the log $g$ panel (right) indicates the border of the model grid. Considering objects within this limits, SOAR and SDSS log $g$ show a low average difference of 0.08 dex. The X-shooter spectra suggest a log $g$ lower by 0.93 dex, what could be due to the better resolution and larger spectral coverage provided by X-shooter, but could also be explained by statistical fluctuations, as detailed in the text.

Figure 27. Same as Fig. 1, adding the new (pre-)ELMs (filled black circles) and probable (pre-)ELMs (open black circles). The distributions with these added objects are shown in black. Especially in $T_{\text{eff}}$, the population seems more similar to the predicted by the models. There are still missing (pre-)ELMs in the lower log $g$ end.
these seven objects are shown in Table 4. Two objects – J073505.57+175344.4 and J075519.92+091511.0 – show large amplitude variations with periods above 2 h. The estimated parameters from SDSS spectra assuming $Z = 0.1 Z_\odot$ are $T_{\text{eff}} = 36\,136\,67$ and $\log g = 6.00 \pm 0.02$ for J0739+1758. For J0755+0915, we could not obtain a good fit with the $Z = 0.1 Z_\odot$ grid — the log $g$ is too close to the lower limit of the grid. For solar metallicity, we obtain and $T_{\text{eff}} = 7470 \pm 5$ K and $\log g = 4.50 \pm 0.04$. None of these two shows significant proper motion. J0755+0915 could be explained as a metal poor A/F star, but we caution that there is at least one pre-ELM known to show RR Lyrae pulsations (Pietrzynski et al. 2012), given that during the CNO flashes the pre-ELM can reach the RR Lyrae instability strip. J0739+1758 was photometrically selected as a possible AM CVn binary by Carter et al. (2013). However, both the long period and the fact the SDSS spectrum shows no emission lines seem to rule out this possibility. Its temperature places it within the region where subdwarfs stars show pulsations (see Fig. 30), hence it could be a new variable subdwarf star. The spectroscopic fit places the object within the domain of V361 Hya stars (first discovered by Kilkenny et al. 1997, $T_{\text{eff}} \geq 28\,000$ K). However, V361 Hya stars usually show $g$-mode pulsations with short periods (100–400 s). A few were found to show also $g$-modes (e.g. Schuh et al. 2005), but the $g$-mode pulsations show low-amplitude, unlike what we found. A photometric fit to this object with fixed $\log g = 6.0$ suggests a lower temperature of $T_{\text{eff}} = 21\,745 \pm 280$. Our spectral models do not take into account line blanketing by metals or NLTE effects, which are often important for hot subdwarfs (e.g. Nemeth et al. 2014), hence in this case the spectral parameters should be only taken as a rough estimate. The photometric $T_{\text{eff}}$ places the object in the V1093 Her domain (a class first found by Green et al. 2003). V1093 Her stars show $g$-mode pulsations of the order of hours, as we have observed. The amplitude we observed is nonetheless higher than for the known V1093 Her stars. Further data is required to better determine the nature of J0739+1758.

A third object, J075738.94+144827.5 was studied in Sánchez-Arias et al. (submitted to A&A) and found to be more likely a $\delta$-Scuti star, given the spacing between periods, a result that should be confirmed by the parallax. Two other new variables, J160040.95+102511.7 and J201757.29-125615.6, are shown in Figs. 28 and 29, respectively. The derived physical parameters for the SDSS spectrum of J1600+1025 assuming $Z = 0.1 Z_\odot$ are $T_{\text{eff}} = 7816 \pm 10$ K and $\log g = 4.63 \pm 0.05$, placing it slightly above the instability strip in Fig. 30. Assuming solar metallicity, the parameters are $T_{\text{eff}} = 8050 \pm 8$ K and $\log g = 5.59 \pm 0.03$, placing it within the instability strip of Tremblay et al. (2015). Its proper motion is $7.1 \pm 1.2$ mas yr$^{-1}$. For J2017-1256, the derived physical parameters from the SDSS spectrum assuming either solar metallicity or $Z = 0.1 Z_\odot$ place it slightly above the instability strip. The $Z = 0.1 Z_\odot$ parameters are $T_{\text{eff}} = 8138 \pm 9$ K and $\log g = 5.14 \pm 0.05$. The proper motion is smaller than 5 mas yr$^{-1}$, with an uncertainty of almost 2 mas yr$^{-1}$ (Tian et al. 2017). The estimated log $g$ of both objects is too high for $\delta$-Scuti stars, which have similar spectral properties to (pre-)ELMs, but show log $g < 4.4$ (e.g., Murphy et al. 2015). However, given the uncertainties in log $g$ described in Section 3.4, the log $g$ could be lower. We obtain a distances of over 3 kpc assuming a main sequence radius, and $z > 1$ kpc given their relatively high galactic latitude. Unfortunately, the number of periods is insufficient for an asteroseismological analysis, thus conclusions on the nature of these objects require more data.

We have also observed fourteen other objects for at least 2 h, and integration times shorter than 30 s, and found no pulsations. The observing time and obtained detection limits are shown in Table 5. They are shown in Fig. 30 as not observed to vary, but we caution that this does not mean they are not variables. Beating can cause destructive interference and essentially hide the pulsations for hours.

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**Table 3.** Estimated physical and orbital properties for the new and probable (pre-)ELMs, which are separated by a horizontal line. $T_{\text{eff}}$ and log $g$ were estimated assuming $Z = 0.1 Z_\odot$. The secondary mass is the lower limit $(i = 90^\circ)$, and the time for merging is the upper limit. The uncertainties in $P$ and $K$ were calculated with a thousand Monte Carlo simulations in Period04.

| SDSS J          | $T_{\text{eff}}$ (K) | log $g$ | $M$ ($M_\odot$) | $P_{\text{orb}}$ (h) | $K$ (km/s) | $M_2$ ($M_\odot$) | $\tau_{\text{merge}}$ (Gyr) |
|-----------------|---------------------|---------|-----------------|----------------------|------------|------------------|---------------------------|
| 032914.77+003321.8 | 9077 ± 10           | 5.179 ± 0.029 | 0.1536 ± 0.0006 | 20.0 ± 0.1          | 83 ± 22    | 0.17             | 765                       |
| 073934.37+172225.5 | 7548 ± 12           | 5.056 ± 0.046 | 0.1450 ± 0.0011 | 6.64 ± 0.03          | 82.6 ± 6.8 | 0.10             | 68                        |
| 084034.83+043537.6 | 7886 ± 32           | 5.074 ± 0.091 | 0.1470 ± 0.0022 | 8.13 ± 0.01          | 222 ± 13   | 0.59             | 28                        |
| 134336.44+082639.9 | 8123 ± 10           | 5.969 ± 0.034 | 0.1527 ± 0.0011 | 24.692 ± 0.002       | 136.2 ± 7.0 | 0.43             | 410                       |
| 142421.30-021425.4 | 9299 ± 11           | 5.128 ± 0.031 | 0.1558 ± 0.0008 | 6.3 ± 0.4            | 80 ± 22    | 0.09             | 57                        |
| 205210.67+014554.4 | 7813 ± 12           | 5.004 ± 0.055 | 0.1476 ± 0.0014 | 22.9 ± 0.2           | 138 ± 14   | 0.45             | 533                       |
| 092056.09+013114.8 | 7478 ± 13           | 4.802 ± 0.044 | 0.1492 ± 0.0014 | 15.742 ± 0.003       | 75.7 ± 8.1 | 0.09             | 50                        |

* Two distinct periods are possible with the current data. Parameters for both are shown.

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Moreover, the objects can show pulsations below the detection limit or outside the probed periods.

### Table 4. Periods and amplitudes for all objects found to be photometrically variable, as well as $T_{\text{eff}}$ and $\log g$ derived from the SDSS spectra (SOAR for J134336.44+082639.4 and J222009.74-092709.9), assuming $Z = 0.1 \, Z_{\odot}$. For J160040.95+102511.7 and J075519.92+091511.0, a good fit is not obtained with $Z = 0.1 \, Z_{\odot}$; we then assumed solar metallicity.

| Object                  | $T_{\text{eff}}$ (K) | $\log g$      | Period (s) | Amplitude (mmag) |
|-------------------------|----------------------|---------------|------------|------------------|
| J134336.44+082639.4     | 8120 ± 10            | 5.97 ± 0.03   | 26.2 ± 2.4 | 7.9 ± 0.7        |
| J222009.74-092709.9     | 8230 ± 6             | 6.10 ± 0.02   | 3591.24 ± 0.03 | 2168.8 ± 0.2 |
| J075738.94+144827.5     | 8180 ± 7             | 4.75 ± 0.04   | 2437 ± 15  | 3.3 ± 0.1        |
|                         |                      |               | 2986 ± 22  | 2.2 ± 0.1        |
|                         |                      |               | 2059 ± 16  | 1.7 ± 0.1        |
|                         |                      |               | 802 ± 5    | 0.5 ± 0.1        |
| J160040.95+102511.7     | 7816 ± 10            | 4.63 ± 0.05   | 3849 ± 57  | 3.1 ± 0.2        |
|                         |                      |               | 2923 ± 32  | 1.4 ± 0.2        |
|                         |                      |               | 2133 ± 21  | 1.0 ± 0.2        |
| J201757.29-125615.6     | 8138 ± 9             | 5.14 ± 0.05   | 7171 ± 49  | 9.0 ± 0.5        |
|                         |                      |               | 3011 ± 58  | 4.1 ± 0.5        |
| J073958.57+175834.4     | 36136 ± 67           | 6.00 ± 0.02   | > 11000    | > 40             |
| J075519.92+091511.0     | 7470 ± 5             | 4.50 ± 0.04   | > 7800     | > 100            |

![Figure 28](image.png)  
**Figure 28.** SOAR light curve for 160040.95+102511.7. The grey continuous line is a fit considering the two periods above a 4 (A), 3849 ± 57 s with an amplitude of 3.1 ± 0.2 mmag, and 2923 ± 32 s with 1.4 ± 0.2 mmag. The dashed lined adds a third period, which shows an amplitude larger than 3.9 (A), 2133 ± 21 s with 1.0 ± 0.2 mmag.

![Figure 29](image.png)  
**Figure 29.** SOAR light curve for and best fit (continuous line) for 201757.29-125615.6. We find two periods, 7171 ± 49 s with and amplitude of 9.0 ± 0.5 mmag and 3011 ± 58 s and amplitude of 4.1 ± 0.5 mmag. Here the dashed line is a smoothing of the data. From 4 per cent to 20 per cent, which is consistent with the predictions by evolutionary models, considering the uncertainties behind the residual burning.

### 4 DISCUSSION

With these new pre-ELM and ELM discoveries, we add twelve objects to the $T_{\text{eff}} < 9000$ K range. With the three confirmed ELMs in this range given in Brown et al. (2016a), we reach of total of fifteen objects, compared to 75 in the $T_{\text{eff}} > 9000$ K range (73 confirmed binaries of Brown et al. 2016a, plus J032914.77+003321.8 and J142421.30-021425.4, found in this work). This raises the fraction of cool ELMs from 4 per cent to 20 per cent, which is consistent with the predictions by evolutionary models, considering the uncertainties behind the residual burning.

All of our 15 discoveries show $\log g < 6.0$. Combined with the 26 objects of the ELM Survey in this range, there are now 41 objects in the low-mass end of the ELM distribution. There are 50 objects with $\log g > 6.0$. The fraction is thus close to 1:1; however, the brightness of the lower $\log g$ objects suggests the fraction could be as high as 100:1 (Pelisoli et al. 2018). Thus, as Fig. 27 already suggested, the population of low-mass objects seems to be missing still. As we considered the estimated $\log g$ as a selection criterion during most of our follow-up, preferring objects with $\log g > 5.0$ or even $> 5.5$, the fact that this population is not unveiled by our work is not surprising, as there are still thousands of sdAs to be observed. With the upcoming data.
Figure 30. Location of the newly detected variables (filled black symbols) in the $T_{\text{eff}} - \log g$ diagram. The triangles are the two objects with high amplitude pulsations. Open black circles are objects not observed to vary. The hot (blue line) and cool (red line) edges of the ELM instability strip shown as dotted lines were extracted from Tremblay et al. (2015). Other pulsating white dwarfs are shown as in fig. 1 of Cósico & Althaus (2016): pre-ELMVs (purple), ELMVs (dark grey), DAVs (light grey, bottom right), DQVs (green, at log $T_{\text{eff}} \sim 4.3$), DBVs (yellow), and the only known hot DAV (magenta, bottom left). We have also added the sdV stars from Holdsworth et al. (2017) (orange), and the newly discovered blue large amplitude pulsators (BLAPs, shown in cyan) from Pietrukowicz et al. (2017) as comparison.

release 2 of the Gaia missing, finding this population will be a much easier task.

Out of the five observed objects found to be most likely ELM in Pelisoli et al. (2018) (J0115+0053, J0306-0013, J1626+1622, J1343+0826, J0455-0432), one was confirmed as an ELM, and the remaining four were found to be probable ELMs. Four of the objects for which we found no RV variability were also studied in Pelisoli et al. (2018), where a higher probability for the MS channel was obtained. It seems that the probability criteria of Pelisoli et al. (2018) are a good indication of the nature of the probed sdAs. On the other hand, ten of the objects we followed up spectroscopically were flagged as possible ELMs in the table 1 of Pelisoli et al. (2018) given their log $g > 5.5$ estimated from SDSS spectra, but only one was confirmed as ELM (SDSSJ1343+0826), and two others were found to be possible ELMs (SDSSJ0042-0106 and SDSSJ0115+0653). This seems to suggest that the log $g$ estimate, especially from SDSS spectra, is not a reliable criteria for selecting ELM candidates. This is in line with our findings described in Section 3.4. Spectral coverage of the $\lambda < 3700$ Å region with good S/N seems to be a requirement for a reliable estimate of the log $g$ in this $T_{\text{eff}}$ range. This might also explain the discrepancies found by Brown et al. (2017), but a study with a statistically significant sample is required to confirm this.

None of the newly discovered (pre-)ELMs has an orbital period short enough ($\lesssim 1$ h) to be above the predicted detection limit of the upcoming LISA gravitational wave detector. However, such short periods were not probed by our survey, given that most objects were observed with SOAR, a 4.1 m telescope, and required integration times close to 30 min to achieve S/N $\gtrsim 10$ in the individual spectra. Searching for this shorter periods might be interesting for the objects described Section 3.3, especially J2220-0927, which not only shows log $g > 6.0$ in our spectroscopic fit, but also photometric variability with periods in the ELM range.

The objects for which we found no RV variations could alternatively be metal-poor A/F stars in the halo, as already suggested by Brown et al. (2017) as a possible explanation for the sdAs. J2343+1538 in particular seems to be indeed an EMP star, as already suggested by Aoki et al. (2013). The five objects observed with X-shooter, which show no significant proper motion, could also be explained as such. J2134-0114 shows parameters consistent with a HB star, but the nature of the other objects remains puzzling. All show $g < 20.0$, therefore they should be included in the DR2 of Gaia, making it possible to constrain their radii and determine their nature with certainty. Follow up will still be required for the objects found to be ELMs in order to estimate their orbital parameters, given that Gaia will not be able to

Table 5. Objects not observed to vary. The physical parameters were estimated from the SDSS spectra assuming $Z = 0.1 Z_\odot$. For J233625.92+150259.6, we have assumed solar metallicity because no good fit could be obtained with $Z = 0.1 Z_\odot$.

| SDSS J              | $T_{\text{eff}}$ (K) | $\log g$ | Telescope | Exposure time (h) | 3 (Å) |
|---------------------|----------------------|----------|-----------|------------------|-------|
| 092140.37+004347.9  | 7733 ± 43            | 5.315 ± 0.179 | SOAR      | 4.0              | 5.0   |
| 14333.35+041900.00  | 8814 ± 39            | 5.404 ± 0.157 | SOAR      | 1.8              | 7.0   |
| 233625.92+150259.6  | 8246 ± 20            | 6.207 ± 0.061 | OPD       | 2.7              | 10.0  |
| 112058.97+042012.3  | 13840 ± 265          | 5.147 ± 0.065 | SOAR      | 2.4              | 9.0   |
| 204038.41-010215.7  | 7886 ± 19            | 4.833 ± 0.096 | SOAR      | 1.6              | 40.0  |
| 163625.08+113312.4  | 8538 ± 25            | 4.064 ± 0.060 | OPD       | 2.2              | 6.0   |
| 110338.46-160617.4  | 8275 ± 10            | 4.734 ± 0.051 | OPD       | 4.4              | 12.0  |
| 140353.33+164208.1  | 8062 ± 10            | 5.261 ± 0.035 | OPD       | 5.9              | 10.0  |
| 165700.89+130759.6  | 8308 ± 11            | 4.825 ± 0.047 | OPD       | 3.0              | 4.0   |
| 075133.48+101809.4  | 12954 ± 131           | 3.779 ± 0.034 | SOAR      | 5.3              | 10.0  |
| 045001.34-042712.9  | 7797 ± 35            | 4.098 ± 0.219 | SOAR      | 2.2              | 1.5   |
| 104522.80-023735.6  | 6950 ± 36            | 4.467 ± 0.086 | SOAR      | 2.1              | 7.0   |
| 094144.89+001233.8  | 7859 ± 32            | 4.689 ± 0.087 | SOAR      | 2.9              | 6.0   |
| 111041.50+132354.3  | 7859 ± 32            | 4.689 ± 0.087 | SOAR      | 3.2              | 6.0   |
resolve binaries with separations below about 20 milliarcsec (~2 AU for a distance of 100 pc).

We have also found seven new photometrically variable stars. J1334+0826 was confirmed as a $M = 0.15 M_\odot$ ELM with time-resolved spectroscopy, so the its eight member of the ELMV class, adding to the seven known pulsating ELMs (Hermes et al. 2012, 2013b,a; Kilic et al. 2015; Bell et al. 2015). We found no RV variations for J2220-0927, but its estimated log $g$ and temperature place it inside the instability strip, so it is possibly the ninth member of the class. Time-resolved spectroscopy with larger telescopes, allowing shorter integration times, should be done to probe shorter orbital periods for this object. Two other objects, J1600+1025 and J2017-1256, are also found to show pulsations, and are within the instability ELMV strip given uncertainties. Bell et al. (2017) found three pulsating stars among the objects in the ELM Survey showing no radial velocity variations, suggesting they are related to the sdA population and might be δ-Scuti stars with an overestimated log $g$, which might also be the case for these objects. Hence, as we have not obtained time resolved spectroscopy for these two stars, we make no claim about their nature given the uncertainties in the log $g$ estimated from SDSS spectra. Recently, Vos et al. (2018) found evidence of a pre-ELM in a long period binary (771 ± 3 days), likely the result of a merger of the inner binary in a hierarchical triple system. This is also a possible explanation for the systems for which we find no RV variation in short timescales. Another of the variables we discovered, J0739 +1758, seems to be a sdBV, given the $T_{\text{eff}} > 20,000$ K. Finally, J0755+0915 shows high amplitude pulsations similar to RR Lyrae stars. The estimated physical parameters and the low proper motion (3.5 ± 1.7 mas yr$^{-1}$ according to Tian et al. 2017) are consistent with a halo metal poor F star.

5 SUMMARY AND CONCLUSIONS

We present radial velocity estimates and spectral fits for 26 sdAs. We find seven to be new (pre-)ELMs, and further eight others to show most characteristics consistent with (pre-)ELMs, but requiring more data to confirm the detection, hence they are called probable (pre-)ELMs. We perform spectroscopic fits, calculate the best orbital solutions, and provide the physical and orbital parameters for each system (Table 3). With this new detections, the percentage of cool ($T_{\text{eff}} < 9000$ K) ELMs is raised from 4 to 20 per cent, which is consistent with the predictions of the evolutionary models. Nonetheless there is still a missing population of (pre-)ELMs in the low-mass end, which should be unveiled by Gaia DR2. For eleven objects, we find no RV variations, ruling out periods larger than ~1 h and shorter than ~200 days for most of them. The high rate of identified binaries in the probed sdAs (~58 per cent) suggests that this evolutionary channel indeed plays an important role in explaining the population, as already suggested in Pelisoli et al. (2018).

We have also found the eight member of the ELMV class, J1334+0826. A possible ninth member was also identified, J2220-0927, but its binarity was not confirmed by follow-up time resolved spectroscopy. We found two other sdAs within the ELM instability strip to show pulsations; however, other objects observed within the instability strip have shown no variability, suggesting the strip might not be pure. This should be further investigated when better estimates on the physical parameters of these objects are available, given the possible uncertainty in SDSS spectra that we have identified, due to the lack of good spectroscopic coverage below 3700 Å.

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Table A1. Radial velocity data for the targets in Sections 3.1, 3.2, and 3.3. The full table is available in the online version of the paper.

| Object | BJD | RV (km/s) | \( \sigma_{RV} \) (km/s) |
|--------|-----|-----------|--------------------------|
| J032914.77+003321.8 | 2457643.8079 | 247.306 | 58.121 |
| J032914.77+003321.8 | 2457643.8153 | 280.711 | 19.405 |
| J032914.77+003321.8 | 2457643.8273 | 264.793 | 23.636 |
| J032914.77+003321.8 | 2457643.8400 | 260.744 | 21.986 |
| J032914.77+003321.8 | 2457643.8521 | 268.121 | 37.191 |
| J032914.77+003321.8 | 2457643.8639 | 203.435 | 29.317 |
| J032914.77+003321.8 | 2457644.8113 | 260.744 | 21.986 |
| J032914.77+003321.8 | 2457644.8273 | 264.793 | 23.636 |
| J032914.77+003321.8 | 2457644.8351 | 139.621 | 14.224 |
| J032914.77+003321.8 | 2457644.8471 | 111.585 | 15.353 |

APPENDIX A: RADIAL VELOCITY DATA

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