

## Discovery of fourteen new ZZ Ceti with SOAR<sup>★</sup>

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### ABSTRACT

We report the discovery of fourteen new ZZ Ceti with the 4.1 m Southern Astrophysical Research telescope, at Cerro Pachon, in Chile. The candidates were selected from the SDSS (Sloan Digital Sky Survey) DA white dwarf stars with  $T_{\text{eff}}$  obtained from the optical spectra fit, inside the ZZ Ceti instability strip. Considering these stars are multi-periodic pulsators and the pulsations propagate to the nucleus of the star, they carry information on the structure of the star and evolution of the progenitors. The ZZ Ceti discovered till 2003 are mainly within 100 pc from the Sun, and probe only the solar vicinity. The recently discovered ones, and those reported here, may sample a distinct population as they were selected mainly perpendicular to the galactic disk and cover a distance up to  $\approx 400$  pc.

**Key words.** stars: white dwarf – stars: variables: general – stars: oscillations

### 1. Introduction

The ZZ Ceti stars are pulsating white dwarf stars with an atmosphere of pure hydrogen (McGraw 1977; McGraw & Robinson 1977). They show multi-periodic oscillations with periods from 70 s to 1500 s and fractional amplitudes ranging from 0.4% to 30%. They undergo  $g$ -mode pulsations caused by the  $\kappa$ - $\gamma$  mechanisms and the development of a sub-surface convection zone due to the opacity bump caused by partial ionization of hydrogen that starts when the cooling white dwarf reaches effective temperatures around 12 000 K. The convection zone stores and enhances the heat exchange due to the pulsations.

The ZZ Ceti class of variable stars is also called DAVs and is the coolest of the three known instability strips in the white dwarf cooling sequence: the pulsating PG 1159 stars, around 200 000–65 000 K (Dreizler et al. 1998; Nagel & Werner 2004; Quirion et al. 2004), the DBV, around 25 000–22 000 K (Beauchamp et al. 1999; Castanheira et al. 2005a) and the DAV, around 12 270–10 850 K (Bergeron et al. 2004; Mukadam et al. 2004).

The ZZ Ceti class presents gradations between the two extremes: the hot DAVs (hDAVs), close to the blue edge of the instability strip, have sinusoidal light-curves with low amplitude ( $\leq 2\%$ ) and short periods ( $\leq 300$  s). The cool DAVs (cDAVs), close to the red edge of the instability strip, show large

amplitude ( $\leq 30\%$ ) long period pulsations ( $\leq 1500$  s), non-sinusoidal light curves because they are distorted by the extended convection zone (Brickhill 1992; Wu 2001; Ising & Koester 2001; Montgomery 2004). Another important factor in shaping the light curve and defining which periods are excited to observable amplitudes is crystallization of the core (Winget et al. 1997; Montgomery & Winget 1999; Metcalfe et al. 2004; Kanaan et al. 2005), which for the high mass (above  $1 M_{\odot}$ ) white dwarf stars occurs while the star is within the ZZ Ceti instability strip, or before it reaches the strip, depending on the mass and the core composition. Pulsations cannot propagate inside a crystallized core, distorting the period distribution and decreasing the pulsation amplitudes.

There are to date 93 known non-interacting ZZ Ceti stars (Mullally et al. 2005; Castanheira et al. 2005b) among more than 5400 spectroscopically identified white dwarf stars (McCook & Sion 2003), but McGraw (1977) and Cox (1980) already indicated they are the most common variable star known. Because they are intrinsically faint,  $M_V \approx 12$ , the published ones till 2003 are mainly within 100 pc from the Sun, and probe only the solar vicinity. The recently discovered ones, and those reported here, may sample a distinct population as they were selected mainly perpendicular to the galactic disk and cover a distance up to  $\approx 400$  pc, and the thin disk scale height extends to  $\approx 300$  pc (Majewski & Siegel 2002).

White dwarf stars are the end points of evolution of stars in the main sequence up to around  $10.5 M_{\odot}$  (e.g. Weidemann 2000), i.e., close to 98% of all stars. Taking into account

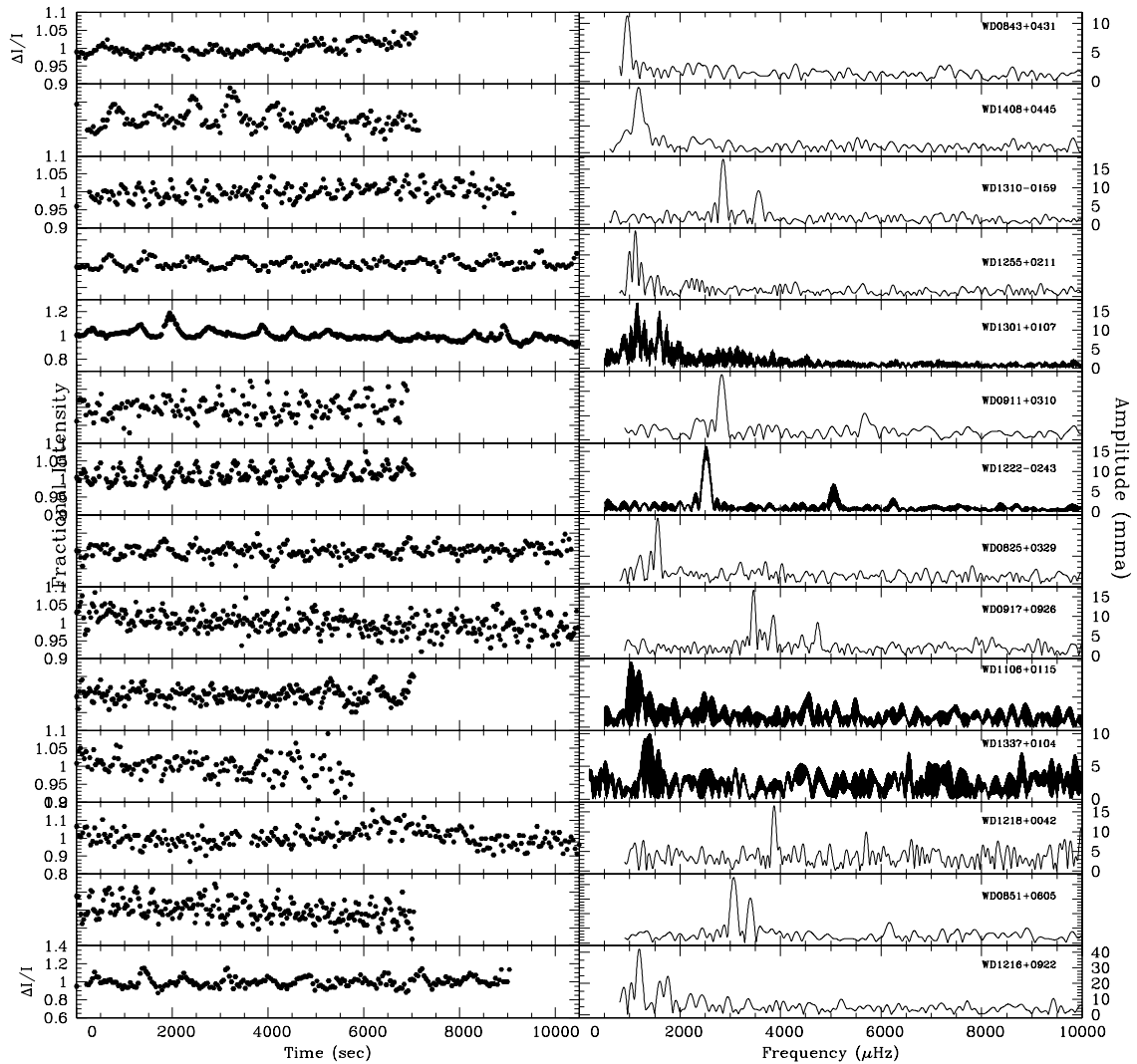
<sup>★</sup> Based on observations at the Southern Astrophysical Research telescope, a collaboration between CNPq-Brazil, NOAO, UNC and MSU.

**Table 1.** New ZZ Cetus.

SDSS spSpec MJD-Plate-Fiber	Name	$g$	$T_{\text{eff}}$ (K)	$\log g$	Main Periodicity <sup>a</sup>
52642-1185-085	WD 0825+0329	17.48	$11801 \pm 105$	$8.33 \pm 0.044$	481s@4.5 mma
52650-1188-191	WD 0843+0431	17.93	$11250 \pm 63$	$8.18 \pm 0.044$	373s@10.43 mma
52670-1190-322	WD 0851+0605	17.08	$11306 \pm 48$	$8.11 \pm 0.029$	326s@22.4 mma
52238-0566-031	WD 0911+0310	18.41	$11634 \pm 126$	$8.11 \pm 0.084$	347s@17.4 mma
52976-1301-445	WD 0917+0926	18.09	$11341 \pm 64$	$8.15 \pm 0.044$	289s@16.1 mma
51900-0278-367	WD 1106+0115	18.37	$10990 \pm 62$	$8.09 \pm 0.049$	822s@12.2 mma
52672-1230-188	WD 1216+0922	18.56	$11293 \pm 109$	$8.29 \pm 0.078$	823s@45.2 mma
52000-0288-412	WD 1218+0042	18.71	$11123 \pm 93$	$8.16 \pm 0.068$	258s@16 mma
52313-0333-077	WD 1222-0243	16.74	$11398 \pm 44$	$8.35 \pm 0.026$	396s@22.0 mma
52026-0523-186	WD 1255+0211	19.09	$11385 \pm 154$	$8.16 \pm 0.106$	897s@31.7 mma
51689-0293-603	WD 1301+0107	16.30	$11099 \pm 34$	$8.11 \pm 0.023$	879s@13 mma
51692-0339-629	WD 1310-0159	17.67	$10992 \pm 65$	$7.92 \pm 0.049$	280s@6.56 mma
51955-0298-608	WD 1337+0104	18.57	$11533 \pm 156$	$8.55 \pm 0.085$	797s@10.2 mma
52045-0582-551	WD 1408+0445	17.93	$10938 \pm 64$	$8.06 \pm 0.044$	849s@24.3 mma

<sup>a</sup> mma is milli-modulation amplitude, corresponding to  $1000 \times \Delta F/F$ , where  $F$  is the measured flux. The MJD-Plate-Fiber are the parameters necessary to access the spectra at <http://das.sdss.org>.

## New DAVs found with SOAR



**Fig. 1.** Light curves (*left panels*) and Fourier transforms (*right panels*) for the new ZZ Cetus. mma is milli-modulation amplitude, corresponding to  $1000 \times \Delta F/F$ , where  $F$  is the measured flux.

**Table 2.** Periodicities detected in the light curves.

Name	Mean noise	Period@Amplitude	Date of Obs.	Length
WD 0825+0329	$\langle A \rangle = 1.6$ mma	481s@4.5 mma = 2.8 $\langle A \rangle$ 303s@3.8 mma	10 Mar. 05	2h
	$\langle A \rangle = 3.37$ mma	664s@10.79 mma = 3.2 $\langle A \rangle$ 334s@6.9 mma	11 Mar. 05	1h
	$\langle A \rangle = 2.13$ mma	644s@12.0 mma = 5.63 $\langle A \rangle$ 704s@6.0 mma 826s@5.3 mma	13 Apr. 05	2.9h
WD 0843+0431	$\langle A \rangle = 3.75$ mma	373s@10.43 mma = 2.78 $\langle A \rangle$	21 Mar. 05	2h
	$\langle A \rangle = 2.02$ mma	1049s@11.4 mma = 5.64 $\langle A \rangle$	9 Apr. 05	2h
	$\langle A \rangle = 1.92$ mma	1085s@7.42 mma = 3.86 $\langle A \rangle$	11 Apr. 05	2.6h
WD 0851+0605	$\langle A \rangle = 4.12$ mma	326s@22.4 mma = 5.4 $\langle A \rangle$	21 Mar. 05	2h
WD 0911+0310	$\langle A \rangle = 4.3$ mma	347s@17.4 mma 757s@16.4 mma 388s@12.3 mma	10 Mar. 05	1.9h
	$\langle A \rangle = 5.1$ mma	353s@26.9 mma = 5.3 $\langle A \rangle$ 176s@11.1 mma	11 Mar. 05	1.9h
	McD $\langle A \rangle = 4.4$ mma	352s@27.7 mma = 6.2 $\langle A \rangle$ 420s@12.6 mma	11 Mar. 05	1.6h
WD 0917+0926	$\langle A \rangle = 2.7$ mma	289s@16.1 mma = 6 $\langle A \rangle$ 259s@10.2 mma 212s@8.0 mma	14 Mar. 05	2.9h
	$\langle A \rangle = 3.0$ mma	288s@14.0 mma = 4.6 $\langle A \rangle$	15 Apr. 05	2h
WD 1106+0115	$\langle A \rangle = 3.0$ mma	822s@12.2 mma = 4.1 $\langle A \rangle$ 980s@10.1 mma	15 Mar. 05	2h
	$\langle A \rangle = 3.9$ mma	937s@11.1 mma = 2.85 $\langle A \rangle$ 719s@7.7 mma 220s@8.9 mma	21 Mar. 05	2h
	all data $\langle A \rangle = 2.5$ mma	973s@10.8 mma 842s@9.4 mma		
WD 1216+0922	$\langle A \rangle = 10.7$ mma	823s@45.2 mma = 4.2 $\langle A \rangle$ 409s@30.1 mma	23 Mar. 05	1.9h
	$\langle A \rangle = 7.92$ mma	840s@42.0 mma = 5.3 $\langle A \rangle$ 570s@24.6 mma 626s@21.6 mma 967s@20.5 mma	13 Apr. 05	2.5h
WD 1218+0042	$\langle A \rangle = 4.3$ mma	258s@16 mma = 3.75 $\langle A \rangle$ 175s@10.0 mma 100s@11.0 mma	6 Apr. 05	3.4h
	$\langle A \rangle = 2.55$ mma	259s@8.2 mma = 3.2 $\langle A \rangle$ 152s@5.1 mma	15 Apr. 05	2h

the observed non-radial  $g$ -mode pulsations (e.g. Kepler 1984) are global pulsations, with each pulsation mode constraining the stellar structure in a different way, we can use the pulsations to untangle the structure of the whole star (Winget et al. 1991, 1994; Kepler et al. 2003; Metcalfe 2003) and even their rates of evolution (Winget et al. 1985; Costa et al. 1999, 2003; Kepler et al. 2000, 2005; Mukadam et al. 2003). These measured evolutionary rates have been used to calculate the age of the coolest known white dwarf stars, allowing an estimate of the age of the galactic disk (Winget et al. 1987) and of a globular cluster (Hansen et al. 2002). Even more important, pulsating white dwarf stars are excellent laboratories for testing high energy and high density physics, such as neutrino (Winget et al. 2004) and axion emission (Córscico et al. 2001; Kepler 2004), crystallization (Winget et al. 1997; Montgomery et al. 2003), and even an estimation of  $C(\alpha, \gamma)O$

reaction rate (Metcalf et al. 2003), a rate important from early Universe composition to supernova explosions, and which determines the size of the C/O core of most white dwarf stars. Crystallization, axion emission and cooling rates are mainly determined from the study of the DAVs. From evolutionary models, white dwarf stars with masses below  $0.45 M_{\odot}$  should have He cores, and those above  $1.1 M_{\odot}$  should have O-Ne-Mg cores (e.g. Weidemann 2003). Another important use of pulsations is to use the light travel time variations measurable by the phase changes in the pulsation modes to detect planetary companions to the white dwarf stars. As most planets will survive post-main sequence mass loss to the white dwarf phase (Duncan & Lissauer 1998; Mugrauer & Neuhäuser 2005), we can use the same technique used to study companions in pulsars to detect even planets smaller than the Doppler technique can, complementing their search space. But planet searches

**Table 3.** Periodicities detected in the light curves (cont.).

Name	Mean noise	Period@Amplitude	Date of Obs.	Length
WD 1222-0243	$\langle A \rangle = 3.1$ mma	396s@22.0 mma = 7.1 $\langle A \rangle$ 198s@7.3 mma	10 Mar. 05	2h
WD 1255+0211	$\langle A \rangle = 2.46$ mma	198s@6.67 mma = 2.7 $\langle A \rangle$	11 Mar. 05	1h
	$\langle A \rangle = 4.84$ mma	897s@31.7 mma = 6.55 $\langle A \rangle$ 1002s@21.7 mma 812s@16.4 mma	9 Apr. 05	3.4h
WD 1301+0107	$\langle A \rangle = 3.8$ mma	879s@13 mma = 3.4 $\langle A \rangle$	11 Mar. 05	1.9h
	$\langle A \rangle = 7.8$ mma	901s@24 mma = 3 $\langle A \rangle$	10 Mar. 05	0.6h
	$\langle A \rangle = 4.4$ mma	870s@22.3 mma = 5 $\langle A \rangle$	14 Mar. 05	2.9h
	all data $\langle A \rangle = 3.0$ mma	882s@17.6 mma 628s@15.2 mma		
WD 1310-0159	$\langle A \rangle = 2.92$ mma	280s@6.56 mma = 2.25 $\langle A \rangle$ 310s@6.4 mma	23 Mar. 05	1.25h
	$\langle A \rangle = 2.81$ mma	349.6s@17.6 mma = 6.3 $\langle A \rangle$ 280s@9.2 mma	13 Apr.	2.5h
WD 1337+0104	$\langle A \rangle = 3.7$ mma	797s@10.2 mma = 2.75 $\langle A \rangle$	15 Mar. 05	2.5h
	$\langle A \rangle = 5.75$ mma	735s@18.49 mma = 3.2 $\langle A \rangle$	21 Mar. 05	1.6h
	all data $\langle A \rangle = 3.0$ mma	715s@10.0 mma		
WD 1408+0445	$\langle A \rangle = 4.34$ mma	849s@24.3 mma = $\langle A \rangle$ 1038s@12.0 mma 764s@11.1 mma	15 Apr.	2h
	$\langle A \rangle = 0.69$ mma	NOV2	6 May	2.2h
	$\langle A \rangle = 2.4$ mma		8 May	1.1h
WD 1432+0146 <sup>a</sup>	$\langle A \rangle = 1.25$ mma	NOV3	11 Apr.	3.6h

<sup>a</sup> NOV5 Mukadam et al. (2004).

around white dwarf stars require very stable pulsations, like those found in hot DAVs (Winget et al. 2003), and only a small sample of them is known to date.

We are therefore involved in a program to find a significant number of pulsating white dwarf stars, to study their structure through asteroseismology, measure their evolutionary rates, and look for planets orbiting them.

## 2. Candidate selection

The temperatures derived from the optical spectra acquired by the Sloan Digital Sky Survey and fitted to Koester's model atmospheres (Kleinman et al. 2004) are good selection criteria to choose candidates for time series photometric searches of ZZ Ceti stars (Mukadam et al. 2004). The SDSS spectra have in general  $SNR \simeq 30$  for  $g \simeq 18$  and we fitted Koester's spectra models from 3800 Å to 7200 Å (Kleinman et al. 2004). Unlike the fitting done by Bergeron et al. (1995, 2004) and Koester & Holberg (2001), which only fit the line profiles and not the continuum, we used the whole spectra from 3800 to 7200 Å. The long wavelength baseline, coupled with the SDSS photometric data, and a low order multiplicative polynomial to allow for small flux calibration uncertainties, result in accurate  $T_{\text{eff}}$ . The selection of this limited wavelength range is to increase the weight of the region with lines, which are  $\log g$  dependent. Mukadam et al. (2004); Mullally et al. (2005) and Castanheira et al. (2005b) show that we can attain 90% probability of variability if we constrain the search range to  $11\,800\text{ K} \geq T_{\text{eff}} \geq 10\,850\text{ K}$ .

## 3. Observations

We used the SOAR Optical Imager, a mosaic of two EEV  $2048 \times 4096$  CCDs, thinned and back illuminated, with an efficiency around 73% at 4000 Å, to acquire time series photometry. It covers a field of  $5.26' \times 5.26'$  on the sky, on the bent cassegrain port of the 4.1 m SOAR telescope. We observed from March to May 2005, when the telescope and imager were still under commissioning, even lacking baffle tubes and therefore with an increased background. We observed in fast readout mode, with the CCDs binned  $2 \times 2$ , which resulted in a pixel scale of 0.153 arcsec/pixel and a readout+write time of 10.2 s. The exposure times ranged from 20 s to 40 s, longer than the overhead but still keeping the Nyquist frequency in range with the shortest pulsation periods detected to date. The data was bias subtracted and flat fielded before we obtained differential photometry through weighted apertures around  $2\text{ FWHM}$  (full width at half maximum of the seeing disk), chosen for highest SNR. We observed each star twice for around 2 h each time.

All observations were obtained with a Johnson B filter, considering Robinson et al. (1982) show the pulsation amplitude increases to the blue, and to minimize the background.

Table 1 list the new variables and their effective temperatures obtained by fitting the optical spectra to Detlev Koester's model atmospheres, as in Kleinman et al. (2004). The first pulsator we observed was also observed with Argos (Nather & Mukadam 2004) at McDonald Observatory 2.1 m telescope, to confirm all the observed periodicities we detected, and check validity of the whole observing system (the telescope, the instrument and the software).

**Table 4.** Periodicities detected for the Variable WD 1502-0001.

Name	Mean noise	Period@Amplitude	Date of Obs.	Length
WD 1502-0001	$\langle A \rangle = 7.1$ mma	603s@28.1 mma = 3.95 $\langle A \rangle$	6 Apr. 05	2.7h
		658s@27.0 mma		
		415s@16.7 mma		
		141s@14.9 mma		
		$\langle A \rangle = 7.1$ mma		
604s@35.5 mma = 5 $\langle A \rangle$	10 Apr. 05	2h		
		424s@16.4 mma		

## 4. Results

In Fig. 1, we show the light curves on the left panels and the Fourier transform of them in the right panels. In Table 2 we list all runs obtained for each star and the main periodicities detected, i.e., those with a false alarm probability smaller than 1%.  $\langle A \rangle$  is the square root of the average power, and is an estimate of the noise (Schwarzenberg-Czerny 1991, 1999; Kepler 1993).

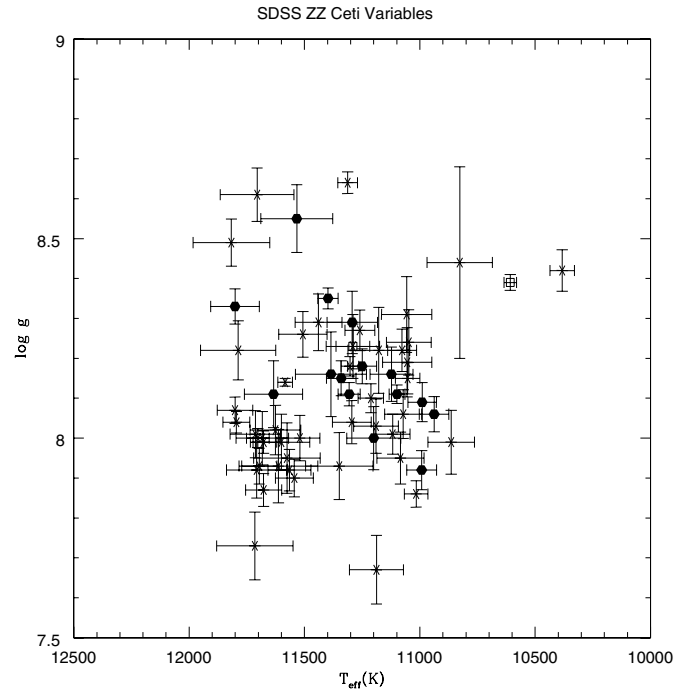
We also observed the  $g = 18.71$  variable discovered by Mukadam et al. (2004), WD 1502-0001, SDSS J150207.02-000147.1. Its SDSS spectrum spSpec-51616-0310-206 fits  $T_{\text{eff}} = 11200 \pm 117$ , and  $\log g = 8.00 \pm 0.079$  with auto23. Its spSpec-51990-0310-229 spectrum fits  $T_{\text{eff}} = 11116 \pm 096$ , and  $\log g = 8.18 \pm 0.06$ , with auto21. Auto23 is the version of the spectra fitting program and calibration published by Kleinman et al. (2004), while Mukadam et al. (2004) published values are older auto21. Mukadam et al. (2004) measured periodicities at: 687.5s@12.0 mma, 629.5s@32.6 mma, 581.9s@11.1 mma, 418.2s@14.9 mma, and 313.6s@13.1 mma, classifying it as a cDAV.

We have also found one star not observed to vary (NOV), WD1359-0034, with a detection limit of  $3\langle A \rangle = 2$  mma. Its  $T_{\text{eff}} = 10640 \pm 32$  K is outside the main strip found by Mukadam et al. (2004), but hotter than their coolest variable. We also confirmed one of the NOV's within the instability strip reported by Mukadam et al. 2004, WD 1432+0146, with  $T_{\text{eff}} = 11255 \pm 73$  K and  $\log g = 8.05 \pm 0.05$ , at the detection limit of  $3\langle A \rangle = 4$  mma.

## 5. Conclusions

We fit the optical spectra acquired by SDSS with Koester's model atmospheres, deriving the effective temperature of the DAs. Selecting to observe with time series photometry those inside the ZZ Ceti instability strip derived by Mukadam et al. (2004), we detected fourteen new ZZ Ceti, i.e., hydrogen atmosphere pulsating white dwarf stars, in the range  $11850 \text{ K} \geq T_{\text{eff}} \geq 10850 \text{ K}$ .

We do note however that there are 109 stars for which DR3 SDSS have multiple spectra, just from  $13000 \text{ K} \geq T_{\text{eff}} \geq 10000 \text{ K}$ , and the fitting results show that the mean uncertainties is  $\sigma_{T_{\text{eff}}} \approx 300 \text{ K}$ , and  $\sigma_{\log g} \approx 0.21$  dex, for the same object but different observations. This is larger than the internal uncertainty of the fits, but in general within  $3\sigma$  of each other – and mostly within 1 or  $2\sigma$ , as in Kleinman et al. (2004). The uncertainties cover a substantial fraction of the instability strip.



**Fig. 2.** Plot of effective temperature and  $\log g$  of the observed objects in this paper (filled symbols) and SDSS DAVs in general (crosses). The two NOV studied in this paper are represented by open rectangles.

To really study the purity of the instability strip we need to reduce the uncertainties to less than 200 K, but we must take into account the fact that the large amplitude pulsators at the red edge have temperature excursions of around 500 K during one pulsation cycle (Robinson et al. 1982). As the SDSS spectra on average are  $3 \times 900$  s exposures per observation, it is unlikely that pulsations are causing the 300 K differences.

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