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# Discovery of fourteen new ZZ Cetis with SOAR*

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**ABSTRACT**

We report the discovery of fourteen new ZZ Cetis 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 $T_{\rm eff}$ 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 Cetis 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 ≈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 (≤2%) and short periods (≤300 s). The cool DAVs (cDAVs), close to the red edge of the instability strip, show large amplitude (≤30%) long period pulsations (≤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, $M_V \simeq 12$, 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 ≈400 pc, and the thin disk scale height extends to ≈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

* Based on observations at the Southern Astrophysical Research telescope, a collaboration between CNPq-Brazil, NOAO, UNC and MSU.

**Table 1.** New ZZ Cetis.

| SDSS spSpec MJD-Plate-Fiber | Name | $g$ | $T_{\rm eff}$ (K) | log $g$ | Main Periodicity[a] |
|---|---|---|---|---|---|
| 52642-1185-085 | WD 0825+0329 | 17.48 | 11801 ± 105 | 8.33 ± 0.044 | 481s@4.5 mma |
| 52650-1188-191 | WD 0843+0431 | 17.93 | 11250 ± 63 | 8.18 ± 0.044 | 373s@10.43 mma |
| 52670-1190-322 | WD 0851+0605 | 17.08 | 11306 ± 48 | 8.11 ± 0.029 | 326s@22.4 mma |
| 52238-0566-031 | WD 0911+0310 | 18.41 | 11634 ± 126 | 8.11 ± 0.084 | 347s@17.4 mma |
| 52976-1301-445 | WD 0917+0926 | 18.09 | 11341 ± 64 | 8.15 ± 0.044 | 289s@16.1 mma |
| 51900-0278-367 | WD 1106+0115 | 18.37 | 10990 ± 62 | 8.09 ± 0,049 | 822s@12.2 mma |
| 52672-1230-188 | WD 1216+0922 | 18.56 | 11293 ± 109 | 8.29 ± 0.078 | 823s@45.2 mma |
| 52000-0288-412 | WD 1218+0042 | 18.71 | 11123 ± 93 | 8.16 ± 0.068 | 258s@16 mma |
| 52313-0333-077 | WD 1222−0243 | 16.74 | 11398 ± 44 | 8.35 ± 0.026 | 396s@22.0 mma |
| 52026-0523-186 | WD 1255+0211 | 19.09 | 11385 ± 154 | 8.16 ± 0.106 | 897s@31.7 mma |
| 51689-0293-603 | WD 1301+0107 | 16.30 | 11099 ± 34 | 8.11 ± 0.023 | 879s@13 mma |
| 51692-0339-629 | WD 1310−0159 | 17.67 | 10992 ± 65 | 7.92 ± 0.049 | 280s@6.56 mma |
| 51955-0298-608 | WD 1337+0104 | 18.57 | 11533 ± 156 | 8.55 ± 0.085 | 797s@10.2 mma |
| 52045-0582-551 | WD 1408+0445 | 17.93 | 10938 ± 64 | 8.06 ± 0.044 | 849s@24.3 mma |

[a] 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`.

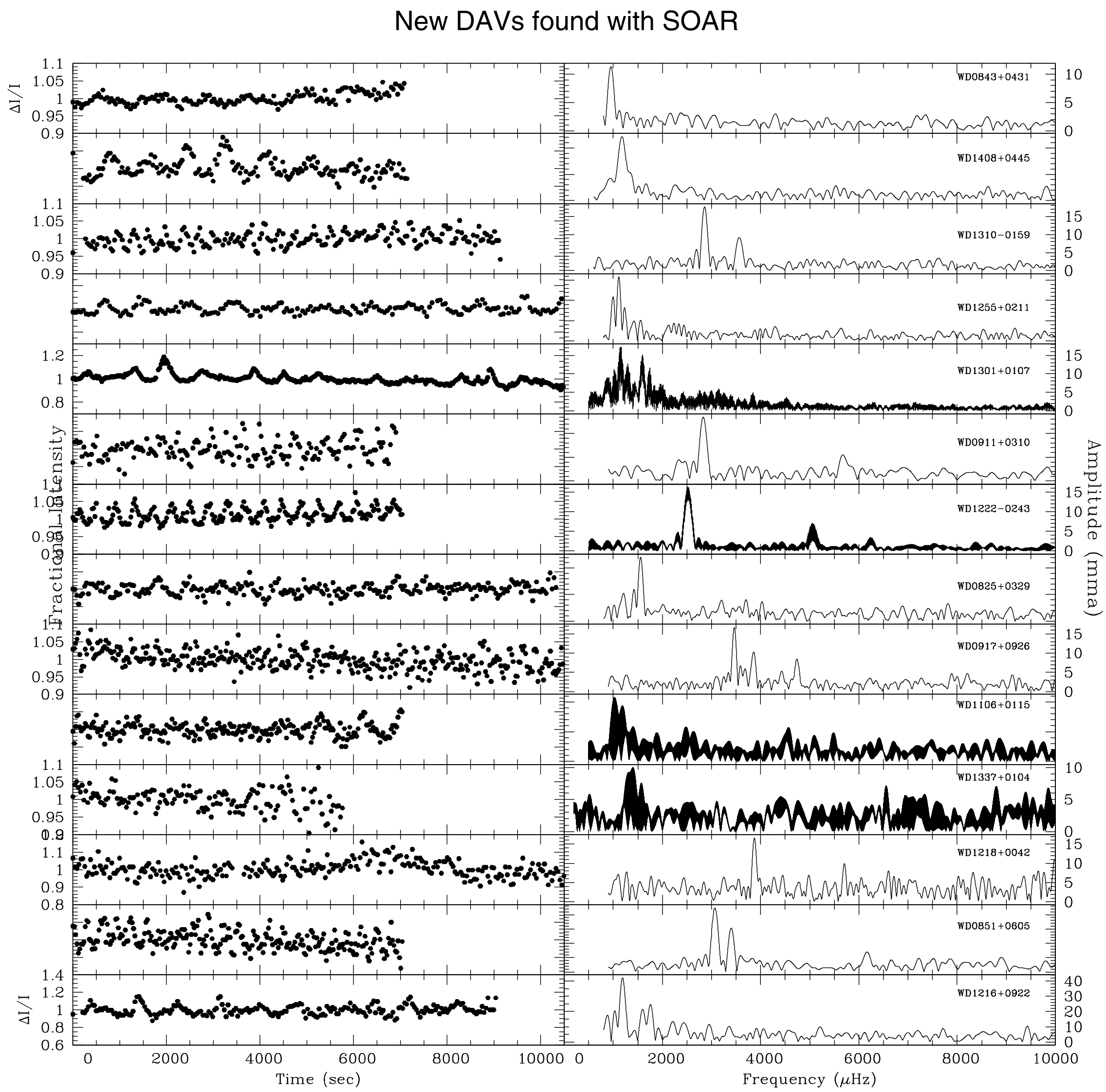


**Fig. 1.** Light curves (*left panels*) and Fourier transforms (*right panels*) for the new ZZ Cetis. mma is milli-modulation amplitude, corresponding to $1000 \times \Delta F/F$, where $F$ is the measured flux.

**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$\langle A\rangle$ | 10 Mar. 05 | 2h |
| | | 303s@3.8 mma | | |
| | $\langle A\rangle$ = 3.37 mma | 664s@10.79 mma = 3.2$\langle A\rangle$ | 11 Mar. 05 | 1h |
| | | 334s@6.9 mma | | |
| | $\langle A\rangle$ = 2.13 mma | 644s@12.0 mma = 5.63$\langle A\rangle$ | 13 Apr. 05 | 2.9h |
| | | 704s@6.0 mma | | |
| | | 826s@5.3 mma | | |
| 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 | 10 Mar. 05 | 1.9h |
| | | 757s@16.4 mma | | |
| | | 388s@12.3 mma | | |
| | $\langle A\rangle$ = 5.1 mma | 353s@26.9 mma = 5.3$\langle A\rangle$ | 11 Mar. 05 | 1.9h |
| | | 176s@11.1 mma | | |
| | McD $\langle A\rangle$ = 4.4 mma | 352s@27.7 mma = 6.2$\langle A\rangle$ | 11 Mar. 05 | 1.6h |
| | | 420s@12.6 mma | | |
| WD 0917+0926 | $\langle A\rangle$ = 2.7 mma | 289s@16.1 mma = 6$\langle A\rangle$ | 14 Mar. 05 | 2.9h |
| | | 259s@10.2 mma | | |
| | | 212s@8.0 mma | | |
| | $\langle A\rangle$ = 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$\langle A\rangle$ | 15 Mar. 05 | 2h |
| | | 980s@10.1 mma | | |
| | $\langle A\rangle$ = 3.9 mma | 937s@11.1 mma = 2.85$\langle A\rangle$ | 21 Mar. 05 | 2h |
| | | 719s@7.7 mma | | |
| | | 220s@8.9 mma | | |
| | 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$\langle A\rangle$ | 23 Mar. 05 | 1.9h |
| | | 409s@30.1 mma | | |
| | $\langle A\rangle$ = 7.92 mma | 840s@42.0 mma = 5.3$\langle A\rangle$ | 13 Apr. 05 | 2.5h |
| | | 570s@24.6 mma | | |
| | | 626s@21.6 mma | | |
| | | 967s@20.5 mma | | |
| WD 1218+0042 | $\langle A\rangle$ = 4.3 mma | 258s@16 mma = 3.75$\langle A\rangle$ | 6 Apr. 05 | 3.4h |
| | | 175s@10.0 mma | | |
| | | 100s@11.0 mma | | |
| | $\langle A\rangle$ = 2.55 mma | 259s@8.2 mma = 3.2$\langle A\rangle$ | 15 Apr. 05 | 2h |
| | | 152s@5.1 mma | | |

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 estimative 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 (Córsico 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 (Metcalfe 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$\langle A\rangle$ | 10 Mar. 05 | 2h |
| | | 198s@7.3 mma | | |
| | $\langle A\rangle$ = 2.46 mma | 198s@6.67 mma = 2.7$\langle A\rangle$ | 11 Mar. 05 | 1h |
| WD 1255+0211 | $\langle A\rangle$ = 4.84 mma | 897s@31.7 mma = 6.55$\langle A\rangle$ | 9 Apr. 05 | 3.4h |
| | | 1002s@21.7 mma | | |
| | | 812s@16.4 mma | | |
| 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$\langle A\rangle$ | 23 Mar. 05 | 1.25h |
| | | 310s@6.4 mma | | |
| | $\langle A\rangle$ = 2.81 mma | 349.6s@17.6 mma = 6.3$\langle A\rangle$ | 13 Apr. | 2.5h |
| | | 280s@9.2 mma | | |
| 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 = $\langle A\rangle$ | 15 Apr. | 2h |
| | | 1038s@12.0 mma | | |
| | | 764s@11.1 mma | | |
| WD 1359-0034 | $\langle A\rangle$ = 0.69 mma | NOV2 | 6 May | 2.2h |
| | $\langle A\rangle$ = 2.4 mma | | 8 May | 1.1h |
| WD 1432+0146[a] | $\langle A\rangle$ = 1.25 mma | NOV3 | 11 Apr. | 3.6h |

[a] 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 $T_{\rm eff}$. 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 $11\,800\,{\rm K} \geq T_{\rm eff} \geq 10\,850\,{\rm K}$.

## 3. Observations

We used the SOAR Optical Imager, a mosaic of two EEV $2048\times4096$ CCDs, thinned and back illuminated, with an efficiency around 73% at 4000 Å, to acquire time series photometry. It covers a field of $5.26'\times5.26'$ 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 $2\times2$, 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 *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 $T_{\rm eff} = 11\,200 \pm 117$, and $\log g = 8.00 \pm 0.079$ with auto23. Its spSpec-51990-0310-229 spectrum fits $T_{\rm eff} = 11\,116 \pm 096$, 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 $T_{\rm eff} = 10\,640 \pm 32$ K is outside the main strip found by Mukadam et al. (2004), but hotter than their coolest variable. We also confirmed one of the NOVs within the instability strip reported by Mukadam et al. 2004, WD 1432+0146, with $T_{\rm eff} = 11\,255 \pm 73$ 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 Cetis, i.e., hydrogen atmosphere pulsating white dwarf stars, in the range $11\,850\text{ K} \geq T_{\rm eff} \geq 10\,850$ K.

We do note however that there are 109 stars for which DR3 SDSS have multiple spectra, just from $13\,000\text{ K} \geq T_{\rm eff} \geq 10\,000$ K, and the fitting results show that the mean uncertainties is $\sigma_{T_{\rm eff}} \simeq 300$ K, and $\sigma_{\log g} \simeq 0.21$ 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.

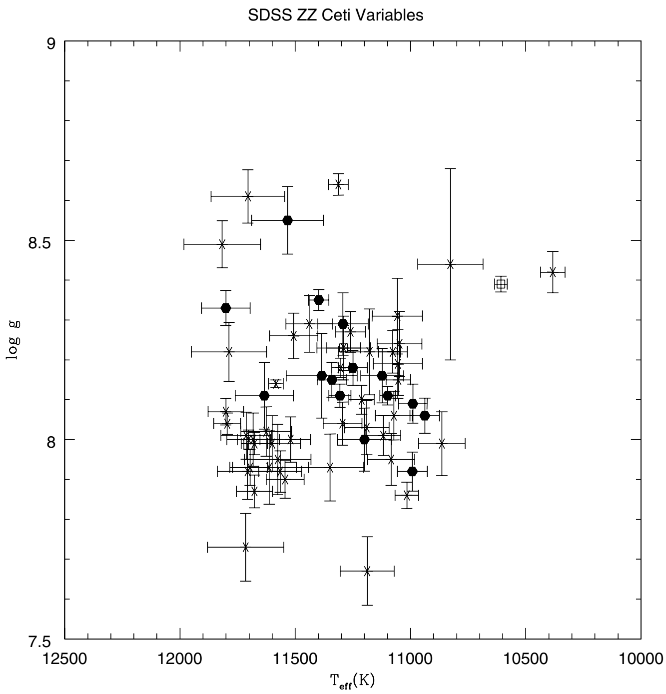


**Fig. 2.** Plot of effective temperature and log g of the observed objects in this paper (filled symbols) and SDSS DAVs in general (crosses). The two NOV studied in this paper are represented by open rectangles.

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 × 900 s exposures per observation, it is unlikely that pulsations are causing the 300 K differences.

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