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Discovery of five new massive pulsating white dwarf stars⋆

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ABSTRACT

Using the SOuthern Astrophysical Research telescope (SOAR) Optical Imager at the SOAR 4.1 m telescope, we report on the discovery of five new massive pulsating white dwarf stars. Our results represent an increase of about 20 per cent in the number of massive pulsators. We have detected both short and long periods, low and high amplitude pulsation modes, covering the whole range of the ZZ Ceti instability strip.

In this paper, we present a first seismological study of the new massive pulsators based on the few frequencies detected. Our analysis indicates that these stars have masses higher than average, in agreement with the spectroscopic determinations. In addition, we study for the first time the ensemble properties of the pulsating white dwarf stars with masses above 0.8 $M_\odot$. We found a bimodal distribution of the main pulsation period with the effective temperature for the massive DAVs, which indicates mode selection mechanisms.

Key words: white dwarfs.

1 INTRODUCTION

White dwarf stars are extremely important objects in the context of stellar evolution, as they represent the final stage of about 98 per cent of all stars, i.e. stars born with masses below 9–10 $M_\odot$. In this phase, the stars show the simplest structure compared to previous phases, because they are basically just cooling. Despite their simplicity, the study of white dwarf stars reveals information from previous phases encrypted in their internal structure.

The only way to study stellar interiors is through pulsations – asteroseismology. As white dwarf stars cool, they cross four distinct instability strips (Werner & Herwig 2006; Montgomery et al. 2008; Nitta et al. 2009; Castanheira et al. 2010), depending on their temperature and atmosphere composition, i.e. the element that drives pulsation and its excitation stage. The ZZ Ceti stars (or DAVs) are pulsating white dwarf stars with hydrogen-dominated atmosphere (DAs) and are observed in a narrow instability strip, between 10 500 and 12 300 K (e.g. Bergeron et al. 2004; Mukadam et al. 2004), with a small dependence on mass (Giovannini et al. 1998). According to theoretical calculations, the absolute position and slope of this dependence varies with the efficiency of modelling convective zones. Up to date, almost 150 ZZ Ceti stars have been discovered (Castanheira et al. 2010), mostly with temperatures close to the centre of the instability strip and with masses ∼0.6 $M_\odot$ (Gianninas, Bergeron & Fontaine 2005; Kepler et al. 2007). In addition, close to the centre of the strip, the amplitudes of the pulsations are, on average, higher than at the edges.

Pulsating white dwarf stars are powerful tools for physics at extreme conditions, including the plasma crystallization in the massive pulsator BPM 37093 (Kanaan et al. 2005) and the emission and production of exotic particles, like neutrinos (Kawaler et al. 1986) and axions (Córsico et al. 2001) – the best candidates nowadays to dark mass particles (Kim 2010; Kim & Carosi 2010). Pulsations can also be used to constrain the value of $^{12}C(\alpha,\gamma)^{16}O$ (Metcalfe 2005), which cannot be measured in laboratory for the energies comparable to those in stellar interior and has direct implications on the mechanism that triggers explosions in supernovae (SN).

Within the instability strip, as the ZZ Cetis cool, the pulsation modes change both in amplitude (energy) and period (thermal time-scale). Measuring the rate of changes for pulsation modes (Kepler et al. 2005; Costa & Kepler 2008), we are calibrating the theoretical white dwarf cooling sequence. Coupled with the white dwarf luminosity function, the cooling time-scales can be used to determine the age of Galactic components, like the disc (Winget et al. 1987) and globular clusters (Renzini et al. 1996; Hansen et al. 2002), with a method independent of metallicity. In the context of this paper, with the larger number of high mass pulsators, we can study cooling for different masses, important specially for globular cluster age determinations through white dwarfs (Kalirai et al. 2007; Winget et al. 2009).

⋆ Based on observations at the SOAR, a collaboration between CNPq-Brazil, NOAO, UNC and MSU.
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Table 1. Journal of observations for the ZZ Ceti candidates using the 4.1 m SOAR telescope. ΔT is the total length of each observing run and $t_{\rm exp}$ is the integration time of each exposure.

Star	Run start (UT)	$t_{\rm exp}$ (s)	ΔT (h)	No. of points
SDSS J034939.35+103649.9	2010-12-17 03:56	30	2.0	207
(WD J0349+1036)	2010-12-18 00:57	30	2.1	230
SDSS J094000.27+005207.1	2010-05-18 23:26	30	2.0	221
(WD J0940+0052)	2011-04-10 23:28	30	2.7	300
	2011-05-06 23:37	30	2.7	300
SDSS J120054.55−025107.0	2011-04-11 02:32	30	2.7	296
(WD J1200−0251)	2011-05-06 23:38	30	3.0	301
SDSS J161218.08+083028.1	2011-06-03 01:46	30	2.8	300
(WD J1612+0830)	2011-06-04 02:34	30	2.9	307
	2011-06-12 03:02	15	2.9	600
	2011-06-15 02:08	15	2.9	600
SDSS J220830.02+065448.7	2011-06-02 07:15	30	2.7	300
(WD J2208+0654)	2011-06-03 07:28	30	2.8	300

Table 2. Observational properties of the new ZZ Ceti stars. $T_{\rm eff}$ and log g were determined from SDSS spectra.

Star	$T_{\rm eff}$ (K)	log g	Mass ($M_\odot$)	g (mag)	Period (s)	Amplitude (mma)
WD J0349+1036	11 715 ± 41	8.40 ± 0.02	0.86 ± 0.01	16.64	184.50	3.76
WD J0940+0052	10 692 ± 75	8.42 ± 0.07	0.87 ± 0.04	18.12	254.98	17.13
					255.75	8.02
WD J1200−0251	11 986 ± 143	8.33 ± 0.06	0.82 ± 0.04	18.15	304.78	23.72
					271.30	13.09
					257.10	6.69
					294.10	6.69
WD J1612+0830	12 026 ± 126	8.46 ± 0.04	0.90 ± 0.03	17.75	115.17	5.06
					117.21	4.05
WD J2208+0654	11 104 ± 29	8.49 ± 0.03	0.92 ± 0.02	17.91	757.23	4.46
					668.07	4.05

In this paper, we report on the discovery of five massive pulsating white dwarf stars and the first asteroseismological studies of these stars. Our results represent an increase of about 20 per cent on the total number of these rare pulsators. The number of known massive white dwarf stars is small not only because of their intrinsically smaller number with respect to lower mass white dwarf stars, but also because these objects have smaller radius, and thus are less luminous. Therefore, finding these pulsators is a rather more challenging task than for normal mass white dwarf stars.

2 OBSERVATIONS AND DATA REDUCTION

Our candidate list comes from the white dwarf stars discovered by the Sloan Digital Sky Survey (SDSS) Data Release 7 (Kleinman 2013). Effective temperature ($T_{\rm eff}$) and surface gravity (log g) are derived from the SDSS photometry combined with the whole-spectrum fit (Kleinman et al. 2004) to the model grid of Koester (2010). In our candidate list, we selected the stars having a $T_{\rm eff}$ compatible with the current observed instability strip and masses above 0.8 $M_\odot$.

We observed our targets with the 4.1 m SOAR telescope, in Chile, using the SOAR Optical Imager, a mosaic of two English Electric Valve (EEV) 2048 × 4096 CCDs, thinned and back illuminated, with an efficiency of around 73 per cent at 4000 Å, at the Naysmith focus. The observations were carried out in service mode by the SOAR staff of Brazilian Resident Astronomers. The integration times were 15 and 30 s. We used fast readout mode with the CCDs binned 4 × 4 to decrease the readout+write time to 6.4 s and still achieve 0.354 arcsec pixel^{-1} resolution. All observations were obtained with a Bessel B filter to maximize the amplitude and minimize the red fringing. Table 1 shows the journal of observations.

We reduced the data using *hsp* (high speed photometry) scripts, developed by Antonio Kanaan for IRAF, with weighted apertures, for time series photometry (Kanaan et al. 2005). We extracted light curves of all bright stars that were observed simultaneously in the field. Then, we divided the light curve of the target star by either the brightest comparison or a sum of the light curves of various comparison stars to minimize sky effects and transparency fluctuations. We chose our aperture size by optimizing the noise in the resulting Fourier transform.

Our criterion for a peak to be considered as real is that it has an amplitude in the Fourier space with a 1/1000 probability of being

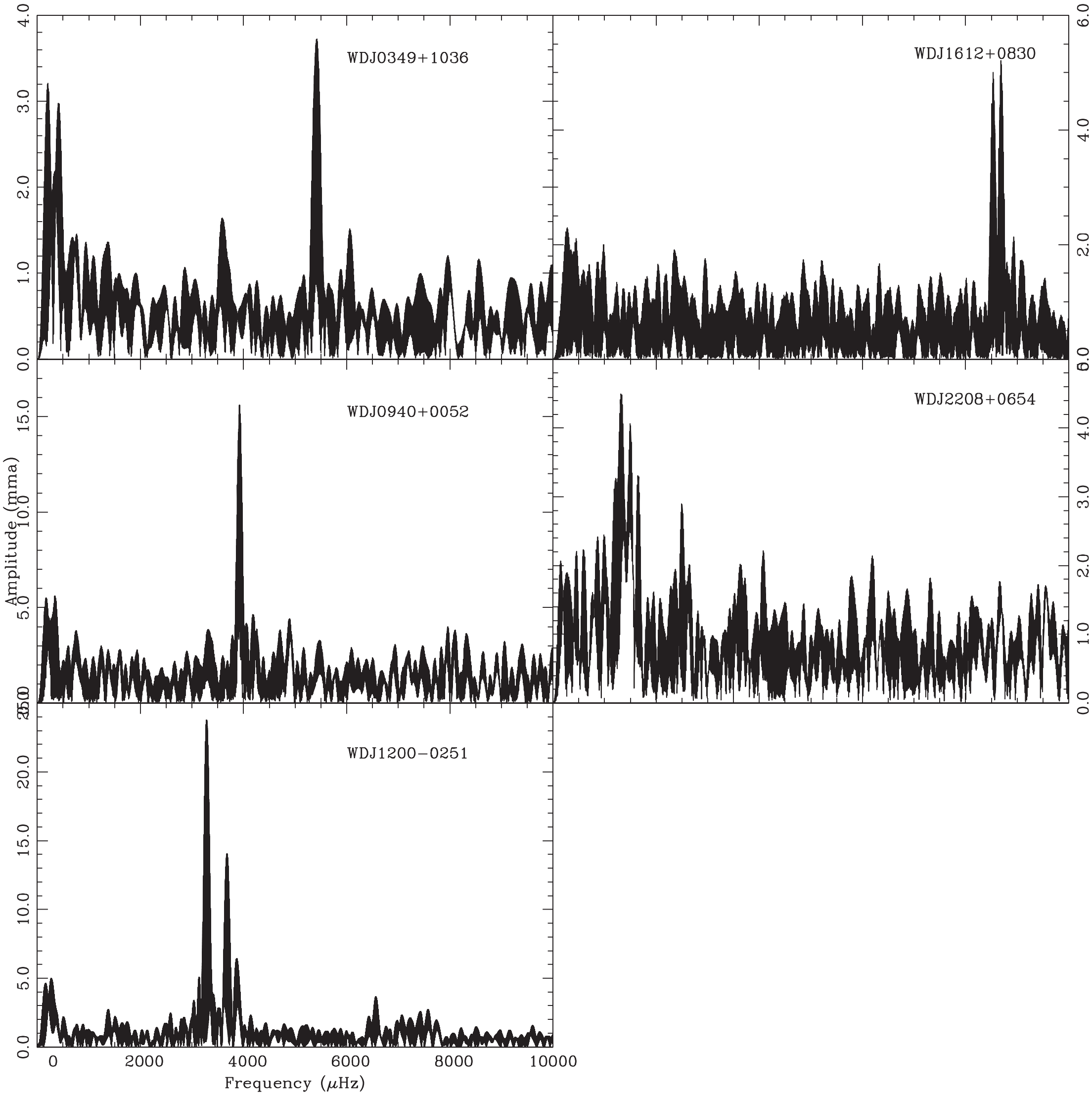

Figure 1. Fourier transform of the combined data sets for new ZZ Ceti stars. Note the *y*-axis is in mma (mili-modulation amplitude) and with a different scale for each star, as the amplitudes are different.

due to noise (Scargle 1982; Kepler 1993). We calculated the ratio $P_0/\langle P\rangle = \ln(1000{*}N)$, where P_0 is the power amplitude of a peak, $\langle P\rangle$ is the average in the power spectrum and N is the number of independent sampled frequencies.

We observed most targets in two separate nights, each for at least two hours, to look for coherent signals in the light curves, as listed in Table 1. If a significant signal was detected, we also checked if additional signals in the Fourier transform were intrinsic variations or aliases due to the spectral window. For this, we subtracted from the original light curve the sinusoid representing the highest amplitude peak (pre-whitening).

All stars that we have observed in our programme to find massive pulsators turned out to be variables. Our candidate list has few tens of stars with masses above 0.8 $M_\odot$ and temperatures within the limits of the instability strip, which we plan to observe in the near future. We have proposed observational programmes to look for variability signals in these stars.

3 NEW ZZ CETI STARS AND SEISMIC ANALYSIS

In Table 2, we list the properties of the new ZZ Ceti stars and in Fig. 1, we show their Fourier transforms.

Among our discoveries, WD J1612+0830 has the shortest observed periods at ~116 s and WD J2208+0654, the longest at ~700 s. The amplitudes vary from a few mma (1 mma = 0.1 per cent) for WD J0349+1036 to more than 20 mma in the case of WD J0940+0052.

We have detected only a few modes for each star in our discovery runs. Despite the low number of modes, we did a first seismological fit, following Castanheira & Kepler (2009). We compared the observed periodicities, weighted by amplitude, with seismological models, according to the expression

$$S = \sum_{i=1}^{n} \sqrt{\frac{[P_{\rm obs}(i) - P_{\rm model}]^2 \times w_P(i)}{\sum_{i=1}^{n} w_P(i)}}, \qquad (1)$$

Table 3. Absolute minima in S for the possible families of solutions in the seismological analysis of the new massive ZZ Ceti stars.

Star	$T_{\rm eff}$ (K)	M ($M_\odot$)	$-\log M_{\rm H}$	$-\log M_{\rm He}$	S (s)	Modes (ℓ, k)
WD J0349+1036	11 800	0.86	4.5	2.5	0.08	184.58 (1,1)
WD J0940+0052	10 600	0.84	4.5	2	0.04	255.08 (1,4)
	10 600	0.90	6	2	0.01	255.11 (1,2)
	11 100	0.87	8.5	2.5	0.01	255.11 (1,2)
	10 900	0.90	9	2.5	0.09	255.03 (1,2)
	11 000	0.86	5.5	3	0.04	254.48 (1,3)
WD J1200−0251	11 900	0.84	4	2	0.80	250.16 (2,8), 271.01 (1,4), 289.62 (2,10), 304.25 (1,5)
	12 100	0.86	8.5	2	0.63	256.00 (2,7), 270.64 (1,3), 300.70 (2,9), 305.12 (1,4)
	11 900	0.84	5	2.5	0.92	264.77 (2,8), 271.32 (1,4), 284.86 (2,9), 304.61 (1,5)
	12 500	0.80	8	2.5	0.65	252.08 (1,2), 271.08 (1,3), 290.81 (2,8), 305.26 (1,4)
	11 600	0.79	8.5	2.5	0.64	260.91 (2,6), 270.03 (1,2), 291.69 (2,7), 305.20 (1,3)
	11 900	0.80	5.5	3	0.82	248.24 (2,6), 272.03 (1,3), 291.02 (2,8), 305.16 (1,4)
	12 100	0.81	8.5	3	0.79	260.24 (2,6), 272.99 (1,2), 295.21 (1,3), 304.18 (1,4)
WD J1612+0830	11 300	0.925	5.5	2	0.01	115.96 (1,1)
	11 900	0.84	5	2.5	0.03	115.94 (1,1)
WD J2208+0654	11 400	0.93	9.5	3	0.27	668.20 (1,13), 757.57 (1,15)
	10 800	0.89	7	3.5	0.60	668.96 (1,13), 756.98 (1,15)
	10 900	0.94	8.5	3.5	1.26	666.11 (1,13), 757.07 (1,15)
	10 900	0.90	9	3.5	1.47	669.76 (1,11), 758.52 (1,13)

where n is the number of observed modes, $w_P = A^2$ is the weight given to each mode and A is the observed amplitude.

We used the spectroscopic determinations of $T_{\rm eff}$ and $\log g$ to guide our searches for the possible families of seismological solutions. We list in Table 3 the absolute minimum in S for each family of solution, and the values of ℓ (the total number of node lines on the stellar surface) and k (the number of nodes in the pulsation eigenfunction along the radial direction). Each minimum represents the results from one model fit.

In Fig. 2, we plot the comparison of temperature (upper panel) and mass (lower panel) determinations from spectroscopy (y-axis) and seismology (x-axis). Each symbol represents a different star: the filled circle for WD J0349+1036, the filled triangles for WD J0940+0052, the open circles for WD J1200−0251, the filled squares for WD J1612+0830 and the open triangles for WD J2208+0654. This comparison shows that there are indeed seismological solutions for massive pulsating white dwarf stars within 2σ of the $T_{\rm eff}$ and mass derived from spectroscopy, but the small number of detected modes prevent us from finding a unique solution.

The stars WD J0940+0052 and WD J1612+0830 pulsate with two very close modes. Assuming that in both cases, the appearance of these modes is caused by rotational splitting, we used the average as $m = 0$ to calculate the rotation period. We used the expression

$$P_{\rm rot} = \frac{1 - C_{k,\ell}}{\delta_\nu}, \tag{2}$$

where $C_{k,\ell}$ is the asymptotic overtone limit for k (Ledoux 1951). Although the modes detected in these stars seem quite far from the asymptotic regime (our best fits give $k = 1$–4), for $\ell = 1$ the models of Brassard et al. (1992) indicate for $C_{k,\ell}$ values not very different from the asymptotic (∼0.4, instead of 0.5). We find the rotational periods of 0.49 and 0.04 d for WD J0940+0052 and WD J1612+0830, respectively.

4 MASSIVE ZZ CETI STARS

Among the targets in our DAV candidate list, we selected those having $T_{\rm eff}$ compatible with the ZZ Ceti instability strip and having a high mass (see Table 2 for details). We discovered five new pulsating white dwarf stars with masses above 0.8 $M_\odot$. Compared to the total number of stars in this mass range, our findings represent an increase of about 20 per cent, as shown in Fig. 3.

One of the most exciting reasons to study massive white dwarf stars is that they are potential precursors of SN Ia. These SN explosion occurs when a nearby companion fills its Roche Lobe and transfer mass to the white dwarf, which then exceeds the Chandrasekhar mass limit, or by the merge of two white dwarf stars. The luminosity of the SN Ia, when used as standard candles, led to the important discovery of the accelerated expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999).

5 PROPERTIES OF THE MASSIVE PULSATING WHITE DWARF STARS

To our knowledge, this is the first attempt to study the ensemble properties of massive pulsating white dwarf stars. With almost 30 stars more massive than 0.8 $M_\odot$ now known, within the known ZZ Cetis, we have a sample large enough to explore some characteristics. We chose to study only the 25 stars with SDSS spectra (see Table 4) in order to have a homogeneous sample in terms of atmospheric determinations, i.e. $T_{\rm eff}$ and $\log g$ (Kleinman et al. 2004; Kleinman 2013)

The current best models predict that pulsations start when the partial ionization zone of hydrogen (H) deepens into the envelope. The base of the partial ionization zone masks the bottom of the convection zone. As the stars cool down, the depth of the convective zone increases, as well as its size. When the thermal time-scale at the bottom of the convection zone reaches the time-scale of the

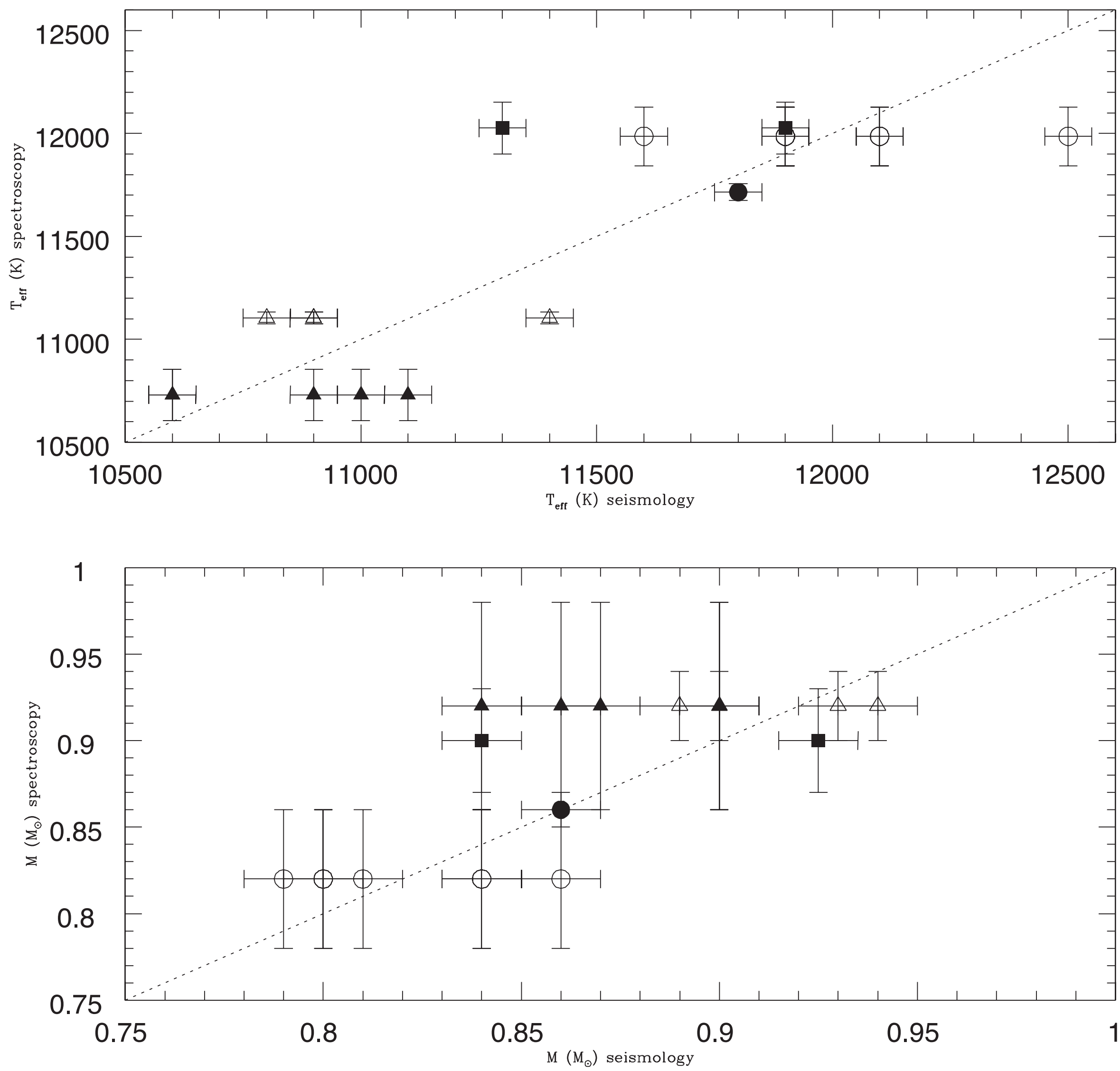

Figure 2. Comparison between temperature (upper panel) and mass (lower panel) determinations from spectroscopy (y-axis) and seismology (x-axis). Different symbols were used for different stars: the filled circle for WD J0349+1036, the filled triangles for WD J0940+0052, the open circles for WD J1200−0251, the filled squares for WD J1612+0830 and the open triangles for WD J2208+0654. The dotted lines in both panels represent the 1:1 agreements.

g-modes, pulsations are detected. Around 11 500 K, there is a sudden deepening of the convection zone in the models; the observed pulsations change in character, with more modes with long periods and high amplitudes excited. For normal mass white dwarf stars at temperatures slightly lower than 11 000 K, the stars stop to pulsate, defining the red edge of the ZZ Ceti instability strip. The observed amplitudes decrease towards the cool part of the strip, consistent with an increase of the depth of the convective zone (Brickhill 1991; Mukadam et al. 2006). These aspects will be explored in the next paragraphs.

In Fig. 4, we plot $T_{\rm eff}$ as a function of the main observed period (largest amplitude). We can see that there are two families of solutions. The best fits for these two families are for periods smaller than 500 s

$$P = 895.53\,({\rm s}) - 0.06\,({\rm s\,K^{-1}})\; T_{\rm eff} \tag{3}$$

and for periods larger than 500 s

$$P = 3186.54\,({\rm s}) - 0.21\,({\rm s\,K^{-1}})\; T_{\rm eff}. \tag{4}$$

Despite the large uncertainties in $T_{\rm eff}$ due to the model grid and/or fitting procedure reaching up to 500 K for fainter targets, the period determinations are much more precise, with uncertainties of the order of 1 s or smaller. Therefore, we can do a first seismological analysis of the massive ZZ Ceti stars by simply using these relationships to determine their $T_{\rm eff}$ from periods. For our newly discovered massive pulsators, we obtain the $T_{\rm eff}$ listed in Table 5.

In Fig. 5, we plot a histogram of the main periods observed. One very interesting feature of this histogram is that the massive ZZ Ceti stars seem to avoid to pulsate with the largest amplitude with periods around 500 s, indicating a mode selection mechanism or mode trapping. Trapped modes in a compositionally stratified

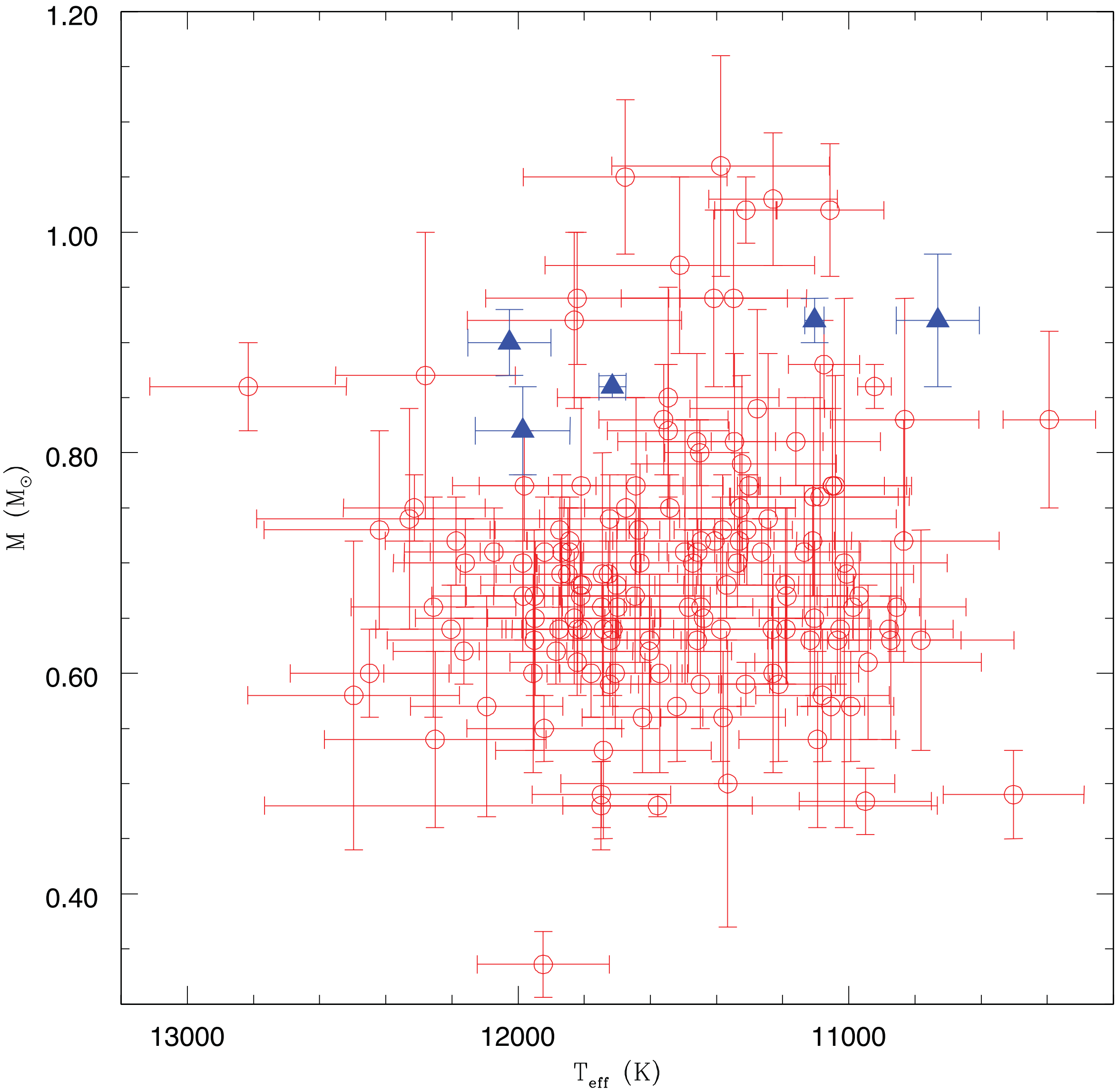

Figure 3. Position of the new massive ZZ Ceti stars (blue filled triangles) in comparison to the previously known pulsators (red open circles).

white dwarf model were discovered by (Winget, van Horn & Hansen 1981) for stellar masses around 0.6 $M_\odot$.

We also plotted a histogram for the temperature distribution of the massive ZZ Ceti stars in the SDSS (see Fig. 6). In this figure, we do not see any clump in temperature, which suggests that there is indeed a mechanism that selects the main pulsation mode, avoiding the 500 s region.

In another analysis, we looked for relations between main period and observed amplitude, as plotted in Fig. 7. There is a scatter in the observed periods versus amplitude. However, we note that the scatter increases for longer periods. Because we do not know the inclination angle of the pulsation axis a priori, the observations of the changes in the scatter indicate that the amplitudes are intrinsically smaller for shorter periods and higher for longer periods. The fact that the longest observed period has a very small amplitude is consistent with the theory: just before stopping to pulsate, stars should pulsate with small amplitudes and long periods.

6 CONCLUSIONS AND FINAL REMARKS

In this paper, we have presented our results on the searches for massive ZZ Ceti stars. We have discovered five new pulsators, which represents an increase of about 20 per cent on the total number of the massive DAVs.

We have also done for the first time an ensemble analysis of these massive DAVs, including only the ones with atmospheric determinations from the SDSS. Our goal was to test whether the previous knowledge of ensemble properties still holds for the massive pulsators. We derived the relations between periods and temperature for pulsators with short and long periods.

For the new ZZ Ceti stars, we have carried out a first seismological study, even though there are not many data available other than the discovery and confirmation runs. In the future, with the monitoring of these stars, it is likely that more modes will be revealed, allowing a more detailed seismological study.

Table 4. List of pulsating white dwarf stars with masses above 0.8 $M_{\odot}$. Temperature and mass were determined from the SDSS spectra (Kleinman et al. 2004; Kleinman 2013). In the last column, we give the reference regarding variability.

Star	$T_{\rm eff}$ (K)	Mass ($M_{\odot}$)	Main period (s)	Amplitude (mma)	Reference
WD J0000−0046	10831 ± 224	0.83 ± 0.11	611.42	23.0	Castanheira et al. (2006)
WD J0048+1521	11260 ± 139	0.82 ± 0.04	615.3	24.8	Mullally et al. (2005)
WD J0111+0018	11765 ± 92	0.81 ± 0.03	292.97	22.13	Mukadam et al. (2004)
WD J0303−0808	11408 ± 280	0.94 ± 0.08	707	4.1	Castanheira et al. (2006)
WD J0349+1036	11715 ± 41	0.86 ± 0.01	184.5	3.76	this paper
WD J0825+4119	11830 ± 324	0.92 ± 0.08	653.4	17.1	Mukadam et al. (2004)
WD J0855+0653	11075 ± 108	0.88 ± 0.04	849.88	39.09	Castanheira et al. (2006)
WD J0925+0509	10922 ± 51	0.86 ± 0.02	1378.93	5.25	Castanheira & Kepler (2009)
WD J0940+0050	10731 ± 125	0.92 ± 0.06	254.67	17.70	this paper
WD J1200−0251	11986 ± 143	0.82 ± 0.04	304.78	23.69	this paper
WD J1216+0922	11346 ± 268	0.81 ± 0.08	823	45.2	Kepler et al. 2005
WD J1222−0243	11451 ± 105	0.80 ± 0.03	396	22.0	Kepler et al. (2005)
WD J1257+0124	11546 ± 335	0.85 ± 0.10	905.8	46.7	Castanheira et al. (2006)
WD J1323+0103	11821 ± 277	0.94 ± 0.06	612.23	11.7	Kepler et al. (2012)
WD J1337+0104	11511 ± 407	0.97 ± 0.08	715	10.0	Kepler et al. (2005)
WD J1612+0830	12026 ± 126	0.90 ± 0.03	114.97	5.17	this paper
WD J1641+3521	11277 ± 203	0.84 ± 0.09	809.3	27.3	Castanheira et al. (2006)
WD J1650+3010	11057 ± 163	1.02 ± 0.06	339.06	14.71	Castanheira et al. (2006)
WD J1711+6541	11311 ± 94	1.02 ± 0.03	606.3	5.2	Mukadam et al. (2004)
WD J2128−0007	11460 ± 239	0.81 ± 0.08	302.2	17.1	Castanheira et al. (2006)
WD J2159+1322	11676 ± 308	1.05 ± 0.07	801	15.1	Mullally et al. (2005)
WD J2208+0654	11104 ± 29	0.92 ± 0.02	757.23	4.46	this paper
WD J2209−0919	11546 ± 184	0.82 ± 0.06	894.71	43.94	Castanheira & Kepler (2009)
WD J2214−0025	11560 ± 195	0.83 ± 0.05	255.2	13.1	Mullally et al. (2005)
WD J2350−0054	10394 ± 140	0.83 ± 0.08	304.3	17.0	Mukadam et al. (2004)

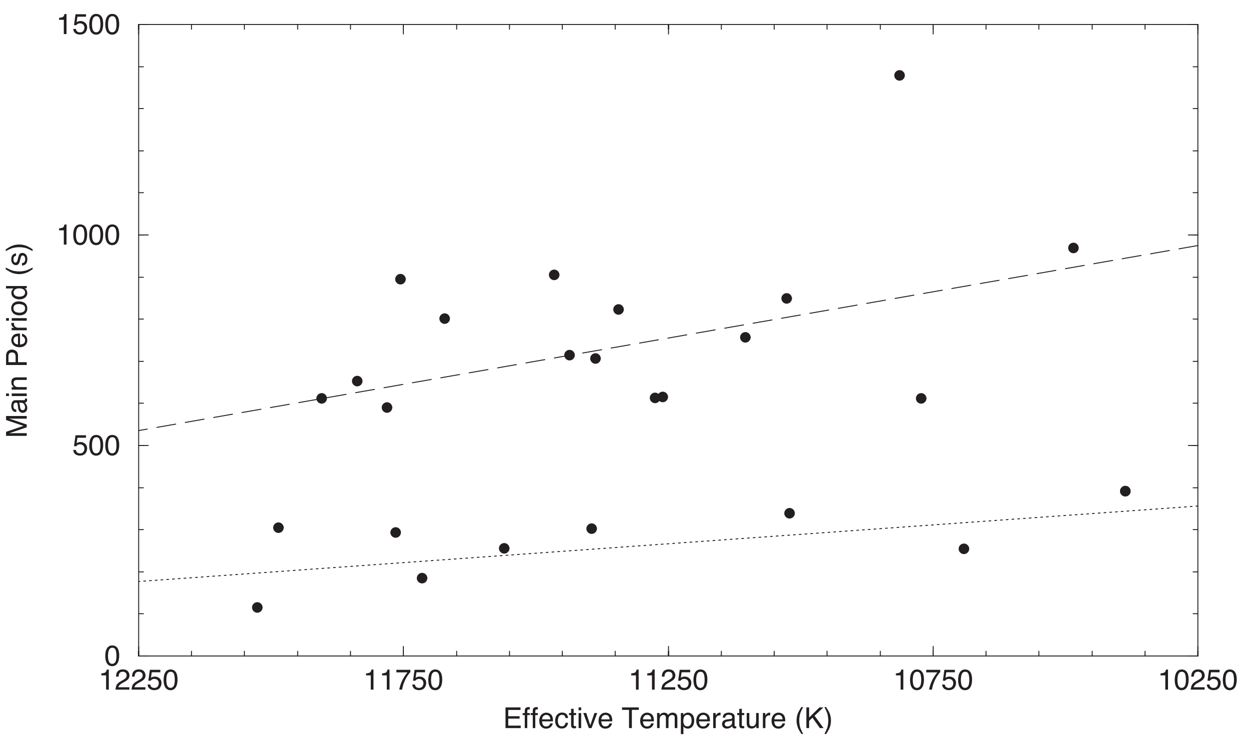

Figure 4. Main observed period as a function of effective temperature. We can see two separate families.

Table 5. $T_{\rm eff}$ derived from the relationships between main pulsation period and spectroscopic $T_{\rm eff}$ for the massive pulsating white dwarf stars. σ_T is the difference between the spectroscopic $T_{\rm eff}$ and the value obtained from equation (3) or (4).

Star	$T_{\rm eff}$	σ_T
WD J0349+1036	11 851	136
WD J0940+0052	10 674	18
WD J1200−0251	9846	2140
WD J1612+0830	12 993	967
WD J2208+0654	11 568	464

More than the simple discovery of new pulsators, our searches were crucial to populate the high mass end of the DAV instability strip.

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The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, The University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory and the University of Washington.

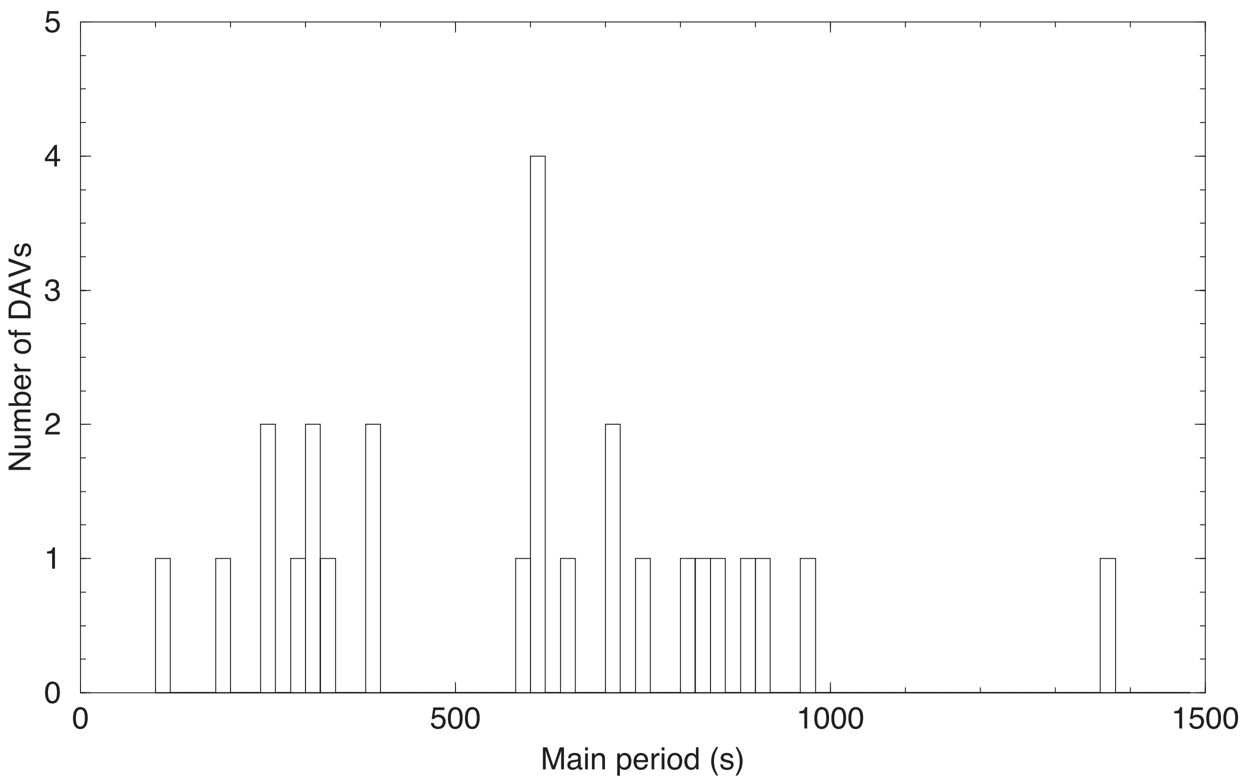

Figure 5. Histogram of the main periods observed for the massive SDSS ZZ Ceti stars.

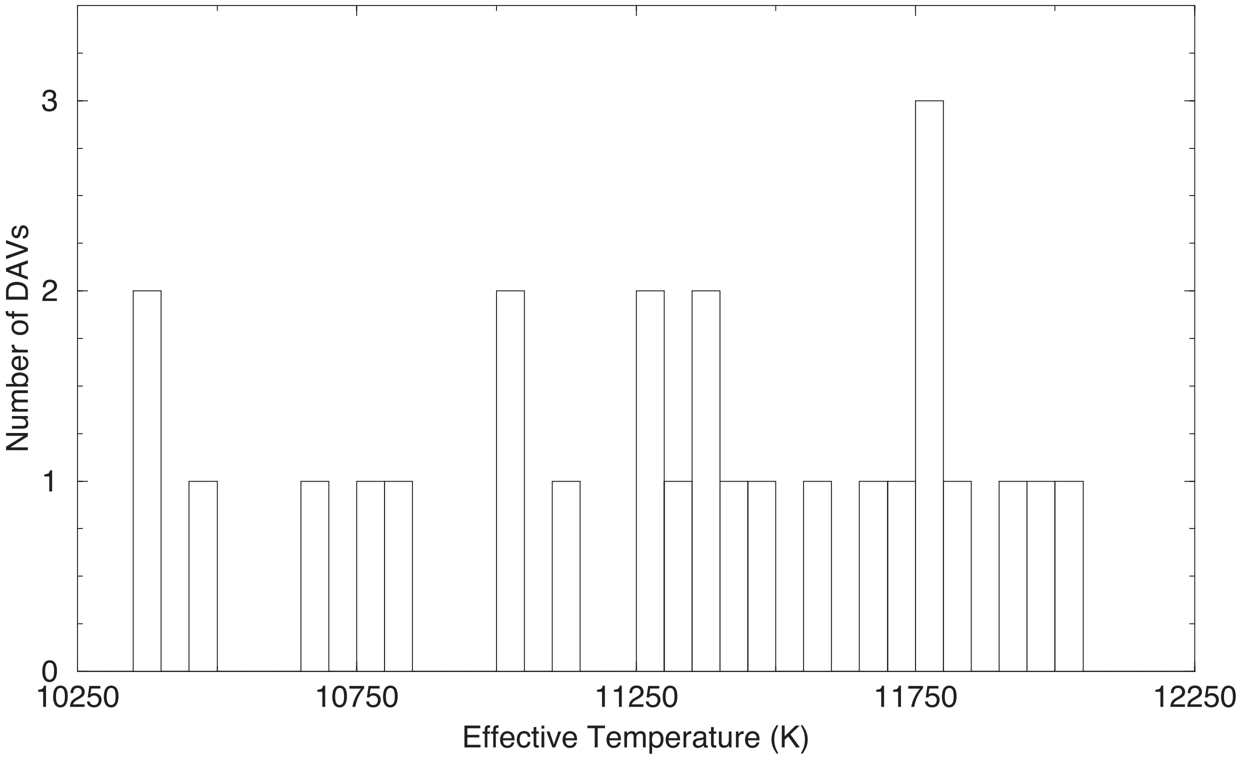

Figure 6. Histogram of the effective temperature for the massive SDSS DAVs.

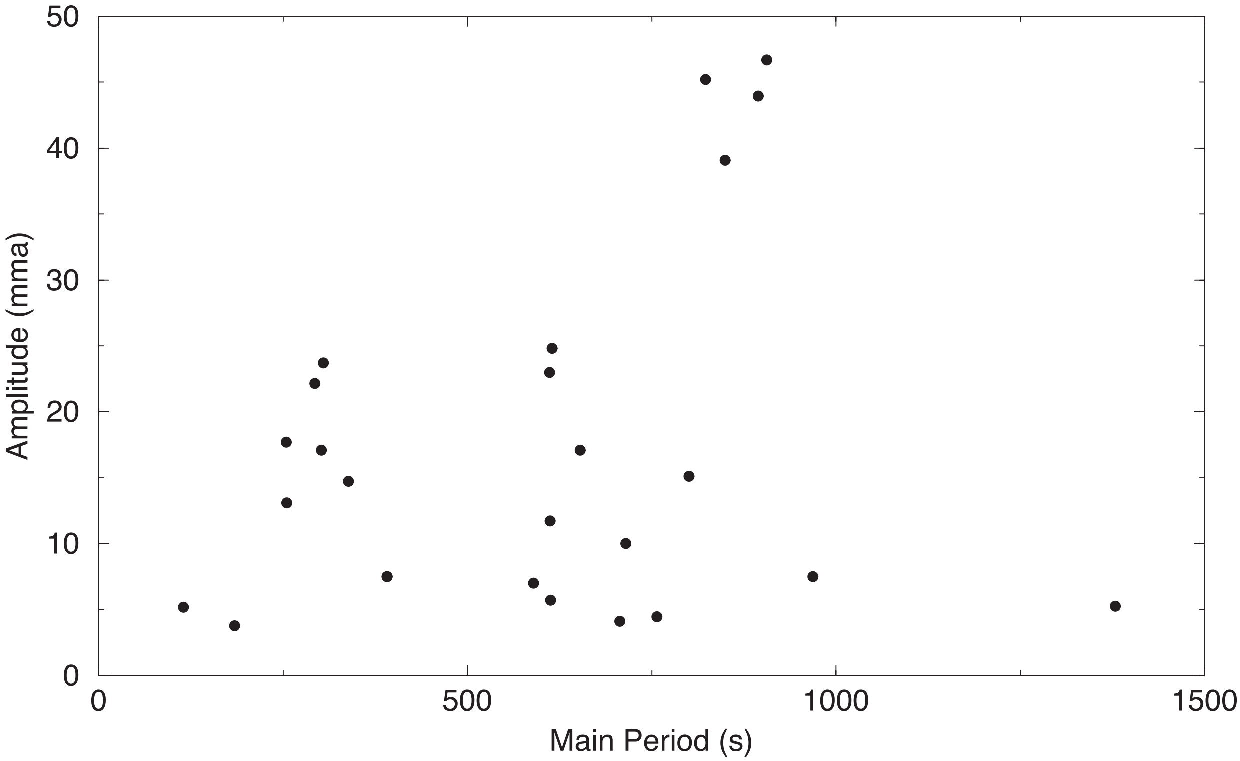

Figure 7. Observed main period versus its respective amplitude.

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