Discovery of twelve ZZ Ceti stars

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Abstract. Using the SOAR 4.1-m telescope, we discovered low amplitude pulsations in three stars previously reported as Not–Observed–to–Vary (NOV), which are inside the ZZ Ceti instability strip. We also report the variability of nine new pulsating stars, bringing the total number of known ZZ Ceti stars to 149. In addition, we lowered the detection limit for 10 NOVs located near the edges of the instability strip. Our results are consistent with a pure mass-dependent ZZ Ceti instability strip.

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INTRODUCTION

The ZZ Ceti stars are pulsating white dwarfs with hydrogen-dominated atmosphere, observed in a narrow instability strip, between 10 800 and 12 300 K [e.g. [2, 14]], with a small dependency on mass [8].

Mukadam et al. [14] and Mullally et al. [17] reported twenty stars as Not–Observed–to–Vary (NOV) in the instability strip. Gianninas et al. [6, 7] proposed that the instability strip is pure, based on their 100% success rate in predicting variability, if temperature and surface gravity determinations are derived from S/N$>$60 spectra. They studied a bright sample, from the catalog of McCook & Sion [13]. Gianninas et al. [6, 7] claimed that the uncertainties in temperature and mass were large enough to scatter pulsators outside the instability strip and constant stars, inside. Kepler et al. [11] re-observed four stars with $T_{\rm eff} \sim 12\,000$ K from the SDSS sample with GMOS at the Gemini 8 m telescope. Fitting these S/N$\geq$60 spectra, they estimated the real uncertainties in the fits of Kleinman et al. [12] and Eisenstein et al. [5] are larger by 60% in temperature and a factor of 4 in $\log g$. However, the main component of their disagreement was systematic, with an average difference from the SDSS catalog measurements [12, 5] in temperature of 320 K, systematically lower, and in $\log g$ of 0.24 dex, systematically larger. It would appear that low S/N of the SDSS spectra are not the main explanation for the possibly contaminated instability strip. There should be also some scatter of pulsators out of the strip and constant stars inside.

We continue the effort to determine whether the ZZ Ceti instability strip is a normal evolutionary stage in the white dwarf evolution or not. We report the variability of three ZZ Ceti stars previously classified as NOVs and nine previously unobserved variables. In our searches, we also lowered the detection limit for ten NOVs near the edges of

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the strip. Since we have discovered low amplitude pulsations in *every* NOV we have observed, our observational evidence is for a pure ZZ Ceti instability strip. However, we will only be able to claim that the ZZ Ceti instability strip is truly pure when we lower the detection limits for variability of all stars within the boundaries and on the edges of the strip and have more accurate $T_{\rm eff}$ and $\log g$ determinations for all stars near the edges and inside the instability strip.

OBSERVATIONS AND DATA REDUCTION

We are looking for pulsators among the white dwarfs discovered with the SDSS [1]. Kleinman et al. [12] describes the fitting process for all SDSS white dwarfs. We chose to observe DAs with previous NOV limits higher than 1 mma [3]. along with previously un-observed DAs within the observed instability strip.

We observed with the 4.1 m SOAR telescope, in Chile, using the SOAR Optical Imager, a mosaic of two EEV 2048×4096 CCDs, thinned and back illuminated, with an efficiency around 73% at 4 000 Å, at the Naysmith focus. The integration times were 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"/pixel resolution. The Bessel *B* filter was used to maximize the amplitude and minimize the red fringing.

We reduced the data using *hsp* (high speed photometry) scripts, developed by Antonio Kanaan for IRAF, with weighted apertures, for time-series photometry [9]. We extracted light curves of all bright stars observed simultaneously in the field. Then, we divided the light curve of the target star by the sum of the comparison stars to minimize effects of sky and transparency fluctuations. We chose the aperture size by optimizing the noise in the resulting Fourier transform.

As an objective criterion, we determined a power amplitude limit such that a peak exceeding this limit has a 1/1000 probability of being due to noise (false alarm probability or FAP) [18, 10] For each light curve, we calculated the ratio $P_0/\langle P\rangle = \ln(\frac{1}{1000*N})$, 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 samples.

We observed most targets at two separate times, each for about two hours, to look for coherent signals in the light curves. We also checked if smaller peaks in the Fourier transform were intrinsic variations of the star. We subtracted from the original light curve the sinusoid representing the highest amplitude peak, re-calculated the Fourier transform and the new noise level, and continued pre-whitening until the highest remaining peak has FAP$> 1/1000$.

NEW ZZ CETI STARS

In Table 1, we list the properties of the new ZZ Ceti stars.

The star SDSS J220915.84-091942.5 is a typical red edge pulsator, the cooler end of the instability strip, with high amplitude and long periodicities. For this star, we detected two independent periodicities, as well as the first harmonic of the main mode at $\sim$895 s. SDSS J092511.60+050932.4 also pulsates with long periods, but with small amplitude.

TABLE 1. Observational properties of the new ZZ Ceti stars. $T_{\rm eff}$ and $\log g$ from SDSS spectra.

Star (SDSS J)	$T_{\rm eff}$ (K)	$\log g$	Mass ($M_\odot$)	g (mag)	Period (s)	A (mma)
004345.78+005549.9	11 820±190	7.94±0.10	0.58±0.05	18.74	258.24	6.69
012234.68+003025.8	11 800±50	7.87±0.02	0.54±0.01	17.29	121.07 200.75 358.61	1.53 1.25 1.23
012950.44-101842.0	11 910±130	8.00±0.03	0.61±0.02	18.32	193.76 147.42	2.88 2.33
030153.81+054020.0	11 470±50	8.09±0.03	0.66±0.02	18.05	300.83	24.87
092511.60+050932.4	10 880±30	8.41±0.02	0.87±0.01	15.20	1127.14 1264.29	3.17 3.05
095936.96+023828.4	11 840±110	8.05±0.06	0.64±0.04	18.15	283.41 194.68	12.95 7.23
110525.70-161328.5	11 670±90	8.23±0.03	0.75±0.02	17.54	192.66 298.25	12.09 7.09
113604.01-013658.1	11 710±70	7.96±0.04	0.59±0.02	17.84	260.79	2.45
133831.74-002328.0	11 870±80	8.13±0.04	0.69±0.02	17.09	196.93 119.72	3.97 1.75
214723.73-001358.4	11 990±290	7.92±0.11	0.57±0.06	18.98	199.77	3.88
220915.84-091942.5	11 430±110	8.33±0.06	0.82±0.04	18.93	894.71 447.94 789.31	43.94 10.80 10.37
233726.28-010110.9	11 380±190	7.90±0.12	0.56±0.06	18.85	494.66 725.49 789.52 304.17	40.07 26.09 23.32 11.71

This star could be an example of a ZZ Ceti on the verge of leaving the instability strip Mukadam et al. [16], Castanheira & Kepler [4]. The other new pulsators are closer to the blue edge of the instability strip, with low amplitude and short periods.

The stars SDSS J012234.68+003025.8, SDSS J113604.01-013658.1, and SDSS J133831.74-002328.0 were previously reported as NOV2, NOV2, and NOV4 Mukadam et al. [14] and Mullally et al. [17]. Our observations achieved a lower noise level, revealing that these stars are low amplitude pulsators, pulsating with short periods, typical of blue edge stars, consistent with our temperature determinations.

NEW ZZ CETI INSTABILITY STRIP

In the Figure 1, we plot the ZZ Ceti instability strip. There are still more than a dozen NOVs inside the current observed instability strip. The question whether all the remaining NOVs pulsate with amplitudes below the published detection limits remains, since all new low amplitude pulsators have amplitudes smaller than the previous 4 mma average limit. Our observations point towards a pure instability strip, but there is no guaran-

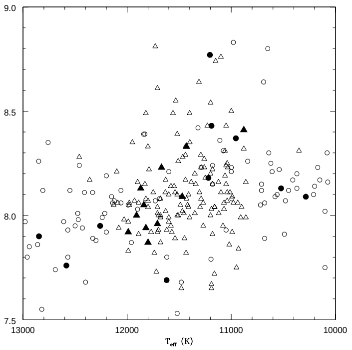

FIGURE 1: New ZZ Ceti instability strip. The full triangles are the ZZ Ceti stars we discovered, the open triangles are the previously known ZZ Ceti stars, the full circles are the NOVs for which we lowered the detection limits, and the open circles are the NOVs [14, 17, 6]. $T_{\rm eff}$ and $\log g$ are from the spectroscopic determinations.

tee that other physical mechanisms cannot shut down pulsations. Therefore, we encourage the search of variability for the stars inside and at the edges of the instability strip previously reported as NOVs, reaching a detection limit of $\sim$1 mma, before declaring them non-pulsators.

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