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NEW PULSATING DB WHITE DWARF STARS FROM THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We are searching for new He atmosphere white dwarf pulsators (DBVs) based on the newly found white dwarf stars from the spectra obtained by the Sloan Digital Sky Survey. DBVs pulsate at hotter temperature ranges than their better known cousins, the H atmosphere white dwarf pulsators (DAVs or ZZ Ceti stars). Since the evolution of white dwarf stars is characterized by cooling, asteroseismological studies of DBVs give us opportunities to study white dwarf structure at a different evolutionary stage than the DAVs. The hottest DBVs are thought to have neutrino luminosities exceeding their photon luminosities, a quantity measurable through asteroseismology. Therefore, they can also be used to study neutrino physics in the stellar interior. So far we have discovered nine new DBVs, doubling the number of previously known DBVs. Here we report the new pulsators' light curves and power spectra.

Key words: stars: general – stars: oscillations – stars: variables: other – white dwarfs

1. INTRODUCTION

White dwarf stars (WDs) are the endpoints of evolution for most stars. Their internal structures provide key clues into their complex pre-WD evolution. As WDs, their subsequent evolution is dominated by cooling. The older they are, the cooler they become. Why then, does there exist a range of temperatures within which we hardly see any He atmosphere WDs (DBs) while we see both the H atmosphere WDs (DAs) and non-DAs (He atmosphere DOs and DBs) at both hotter and cooler temperature than this? This paradox is the so-called "DB gap" (Fontaine & Wesemael 1987). Recently, Sloan Digital Sky Survey (SDSS) data have shown us that the DB gap is not completely void of DBs, but rather deficient in the number of DBs (Eisenstein et al. 2006a). The current best explanation for this effect is based on WDs having specific layer masses (the large gravity in a WD makes it compositionally stratified) which mix and settle at certain temperatures, causing the surface "flavor" of a WD to change with time and temperature (Fontaine & Wesemael 1987). This explanation demands a thin H layer in at least a substantial fraction of DAs. However, there have been several works (Fontaine et al. 1992, 1994; Clemens 1994; Robinson et al. 1995; Kleinman et al. 1998; Benvenuto et al. 2002) suggesting that perhaps all DAs have thick H layers and if so, spectral evolution by the current model cannot happen.

Once a WD cools past the onset of its instability strip (at a temperature primarily determined by its atmospheric composition and total mass), it begins pulsating in a series of nonradial g-modes, allowing us to study its interior via the technique of asteroseismology. Asteroseismology, the study of stellar pulsations, is an important way to directly measure quantities of the stellar interior. And understanding the interior structure of the DBVs is one very important way to address some of the mysteries of DB evolution. Among the nine DBVs known prior to our work, the first DBV discovered (Winget et al. 1982), GD 358, is by far the best-studied WD pulsator. It has had its internal structure substantially explored by asteroseismology (Winget et al. 1994; Bradley & Winget 1994; Vuille et al. 2000; Metcalfe et al. 2002, 2005; Metcalfe 2003; Kepler et al. 2005a). The results from the asteroseismological investigations of GD 358 (Winget et al., 1994) are impressive: total mass of $0.61 \pm 0.03\, M_\odot$, He layer mass of $\log M_{\rm He}/M_\star = -5.7(+0.18, -0.30)$, $R_\star/R_\odot = 0.0127 \pm 0.0004$, He-to-C transition zone thickness of about 8 pressure scale heights, absolute luminosity $\log L_\star/L_\odot = -1.30(+0.09, -0.12)$ hence a distance of 42 ± 3 pc, weak magnetic field of 1300 ± 300G, and the measurements of radial differential rotation. More recent, detailed model-fitting techniques using genetic algorithms along with improvements to the models have been successful in revealing even more information. We now have a measurement of the oxygen mass fraction in the core, which places constraints on both the nuclear burning rate $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$ and even more detailed structure information, such as the extent of the He/C envelope beneath the pure He envelope (Metcalfe et al. 2002, 2005; Metcalfe 2003). Except for one other DBV, the rest of the class have not been so forthcoming in revealing their internal structures, primarily due to their lack of the abundance of pulsation modes compared to GD 358's over 100 detected frequencies. CBS 114 is a DBV which showed promise for successful asteroseismological analysis by exhibiting a rich pulsation spectrum, but earlier observational comparisons to the models produced a $\mathrm{C}(\alpha, \gamma)\mathrm{O}$ nuclear burning rate which was at odds with that obtained from GD 358 (Handler et al. 2002). After several years of additional observations of CBS 114, which lead to identifying 11 independent pulsation modes (four of which were new) along with improvements in pulsation models and fitting techniques, Metcalfe et al. (2005) have achieved new asteroseismological results for both stars, which are now in agreement with each other. The one thing CBS 114 did not show and which GD 358 did were the many fine-structure splittings of the pulsation modes caused predominantly by stellar rotation. Our understanding of the pulsation amplitude determining mechanism on these stars is incomplete, and we cannot explain why we see significant fine-structure splitting in GD 358 but not much in CBS 114. We certainly do not believe it is due to lack of rotation on CBS 114's part though it could be due to the star being observed near pole-on. So the search goes on for a third solvable pulsator to try and distinguish modes, models, fits, and reality in these objects.

Another important reason to study DBVs is that they are great cosmic laboratories for high-energy physics. Winget et al. (2004) predict that hot DBs should have significant plasmon neutrino production. Their DB models suggest that 30,000 K, 0.6 $M_\odot$ DBs have a neutrino luminosity that is 1.8 times higher than their photon luminosity. On the cool end, 22,000 K, 0.6 $M_\odot$ DBV models have a neutrino luminosity less than half of their photon luminosity. Thus the hottest DBVs should be losing energy and cooling significantly faster than the cooler ones. Since a pulsation mode's period is a function of temperature, we can directly measure a star's cooling rate by measuring a mode's rate of period change (e.g., Kepler et al. 2005b). And thus, the DBVs may be quite revealing laboratories for neutrino physics.

Finally, an increase in the number of known DBVs will help us understand their properties as a group. Clemens (1994) and Kleinman (1995, 1998) found that the DA pulsators break down nicely into two distinct classes, each subclass exhibiting common class properties, which they have used to investigate the dynamics of the pulsation mechanism in these stars. By increasing the number of known DBVs, we can search for possible subclass distinctions. Nather et al. (1981) noted that the interacting binary WD stars will each eventually form a single DB at the end of their evolution. This means that there may be more than one evolutionary channel leading to the DBs. Perhaps we will find two distinct classes, each of them retaining the evidence of their evolutionary paths in their pulsation structures.

SDSS is a photometric and spectroscopic survey of the sky covering about 10,000 $\deg^2$ around the Northern Galactic cap (York et al. 2000; Stoughton et al. 2002; Gunn et al. 1998, 2006). In SDSS's Sixth Data Release (Adelman-McCarthy et al. 2008), there are photometry of close to 10,000 $\deg^2$ in five filters (Fukugita et al. 1996) and 1.27 million spectra. Although the survey's main goal was to produce a three-dimensional map of the large-scale structure of the universe, it also contains data on many galactic stellar objects, including WDs. SDSS data provide the perfect basis set for finding new DBVs, which will eventually help solve the DB Gap mystery, measure the neutrino production rates inside the DBs, as well as answer some other questions about the WD structure and evolution. Kleinman et al. (2004) published the first WD catalog based on the spectra obtained by SDSS and doubled the number of then known WDs. The newest WD catalog from the SDSS (Eisenstein et al. 2006b, DR4 WD catalog hereafter) has almost quadrupled the number of WDs. Among the new WDs are DBs whose physical parameters determined from model fitting suggest they are inside the instability strip. Therefore, we started a project to search for new DBVs using our spectroscopic fits to SDSS spectra, originally from Kleinman et al. (2004) and later using the DR4 WD catalog, to identify likely DBV candidates and follow them up with time-series photometry. This survey is the counterpart to the search for new SDSS DAVs reported by Mukadam et al. (2004), Mullally et al. (2005), Kepler et al. (2005a), and Castanheira et al. (2006b, 2007).

2. OBSERVATIONS

We selected our DBV candidates based on the effective temperatures published in the SDSS WD catalogs (Kleinman et al. 2004; Eisenstein et al. 2006b). As described in those works, each spectrum was fitted with Detlev Koester's atmosphere models (Koester et al. 2001) to obtain an effective temperature and surface gravity. The DB models used in the catalogs are pure He models. Beauchamp et al. (1999) showed that the physical parameters of the model fit of DBs can change if He atmosphere models with trace amount of H are used. Since we do not know how much H, if any, our candidate SDSS DBs have, the pure He atmosphere model fits are as good as any other. The currently known coolest DBV being 21,800 K (Beauchamp et al. 1999; Castanheira et al. 2006a), we chose to select all DBs with effective temperatures higher than 21,000 K as DBV candidates. The blue edge of the instability strip is currently defined by EC 20058, the second hottest DB known (Beauchamp et al. 1999; Sullivan et al. 2008) prior to the new DBs discovered by the SDSS. The hottest DB known prior to the SDSS is PG0112+104 with $T_{\rm eff} = 31{,}500$ K, which defines the cool end of the DB gap. Time-series observations of this star have not detected any pulsations (J.L. Provencal 2006, private communication). Nonetheless, given a boundary determined by only one object, we decided to place no upper limit on our candidate stars' effective temperatures.

We observed our DBV candidates using the Argos CCD camera (Nather & Mukadam 2004) on the 2.1 m telescope at McDonald Observatory, SPICam on the 3.5 m telescope at Apache Point Observatory, and the Southern Astrophysical Research Telescope's (SOAR) Optical Imager (SOI). More than half of the new, H atmosphere WD variables (DAVs) reported in the past few years have been discovered using Argos (Mukadam et al. 2004; Mullally et al. 2005; Castanheira et al. 2006b). We observed and reduced the data from Argos in the same manner as described in Mukadam et al. (2004) and Mullally et al. (2005). Exposure times ranged from 5 s to 30 s, depending on the brightness of the target and condition of the sky. The readout time was negligible due to the use of a frame-transfer detector. For some of the objects, we used a BG40 filter to suppress the redder portion of the flux, which is dominated by noise. After we applied bias and flat-field corrections to all CCD frames, we extracted sky-subtracted light curves via aperture photometry for the variable candidates and at least one comparison star in the field. We then divided the target star's light curve by the sum of the comparison stars' light curves to take out any transparency variations in the sky. We normalized the result so that the average brightness of the star is equal to 0 and the light curve shows the fractional intensity variation, and applied a barycentric correction to the times. The resulting light curves for the new DBVs are shown in the left panel of Figure 1.

SPICam was not built for fast time-series data acquisition, and therefore we binned and used partial readout to achieve a reasonable duty cycle for this project. The binning and window size of the chip depended on the seeing and field of the target since we needed at least one comparison star. Once we acquired the data, we followed a similar procedure as with Argos data to produce our light curves.

We used SOI to discover our ninth DBV. SOI has also contributed to discoveries of 18 new DAVs (Kepler et al. 2005a;

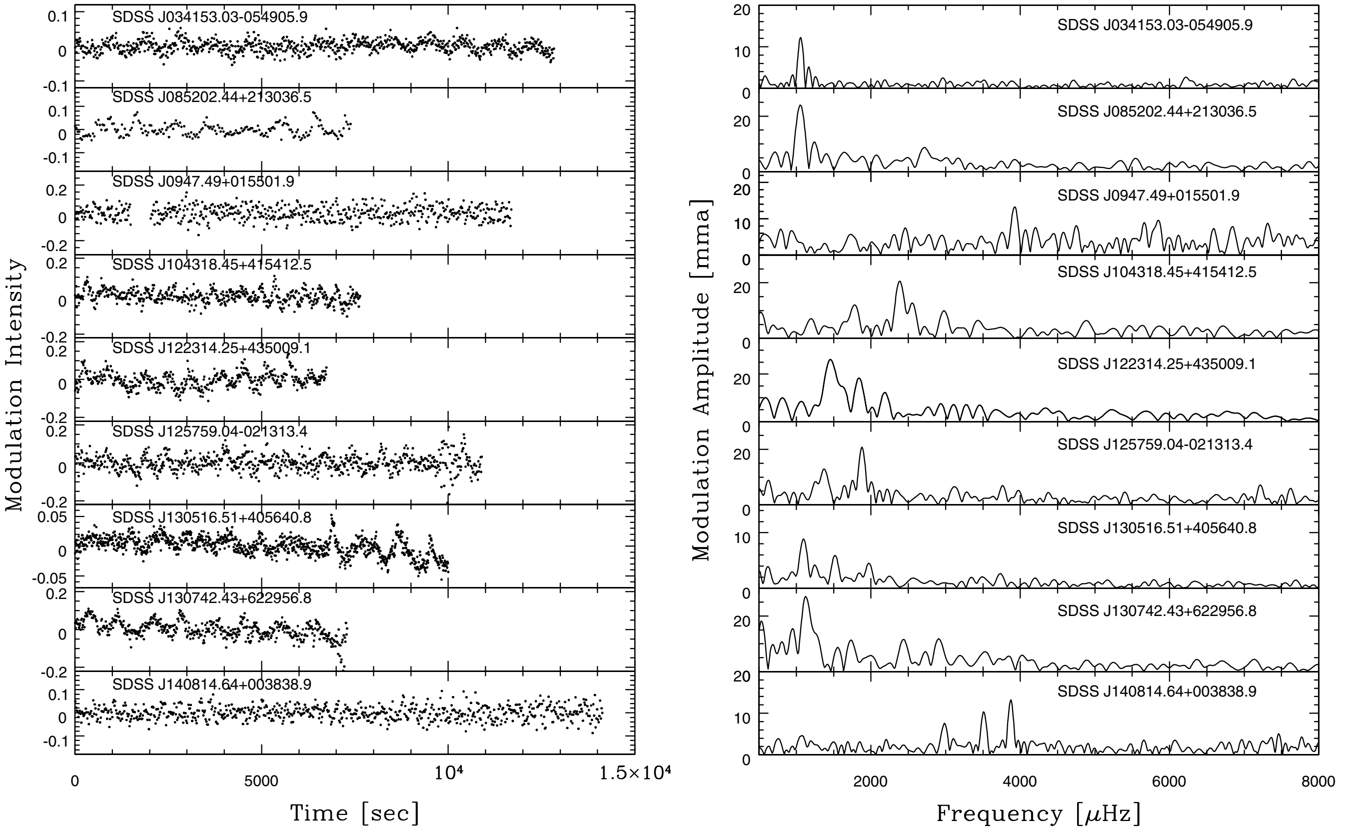

Figure 1. Light curve (the left panel) and Fourier transform (the right panel) of the nine new DBVs reported in this paper. The light curve of SDSS J140814.64+003838.9 was binned by two (i.e., changing the sampling rate from 10 s to 20 s) to show the pulsation better in the figure, but the FT was calculated from the unbinned data. SDSS J0947.49+015501.9's FT, perhaps, is not as visually convincing as other new DBVs shown here. The FT of the second observation of this target also shows the largest peak at a consistent frequency as the data shown here with similar significance.

Castanheira et al. 2006b). It is a CCD camera with reasonably fast readout time (6.3 s). We used 30 s integration time for the data we gathered on SDSS J085202.44+213036.5. Again, we followed a similar procedure as with Argos data to produce our light curves.

Table 1 is our journal of observations. We tried to observe each object for at least 2 hr on two separate occasions. The second observation is to confirm and test the results of the first observation. As you can see from Table 1, we have been able to get the second observation for five of the new DBVs, but not for all of the objects reported in this paper. For the DBs which did not show pulsations during the first observations, additional data are still very important. The lack of variability in the first observation may simply be due to amplitude modulations or beating of closely spaced modes, which are not resolved in our ∼2 hr observations. It is also important to obtain a good amplitude limit (1 mma or smaller) to which we see no variability since some currently known pulsators have similarly small amplitudes. We note that some of the DAs that had no detectable pulsations in Mukadam et al. (2004) turned out to be DAVs after additional observations lowered the detectable amplitude limit (Castanheira et al. 2006b). Both these examples suggest that more data are still needed for many of our DBs, which did not show pulsations.

3. NEW PULSATING DB WHITE DWARF STARS

Figure 1 shows the light curves and their Fourier transforms (FTs) for the nine new DBVs we have found so far. We list the frequencies, periods, and the amplitudes of the large observed peaks in the FTs in Table 2.

The g magnitudes from the SDSS imaging data, the plate, MJD and fiber number which specify unique spectra used for the model fitting, the effective temperature, surface gravity, and their uncertainties of each observed object are given in Table 3. The last column in Table 3 indicates if the object was found to vary. If we saw no variability, then this column contains the amplitude limit (in mma) that we currently have. The amplitude limit is defined as three times the average noise between 1000 and 10,000 μHz. For equally spaced data, this limit translates into a 0.1% probability of identifying a false peak as a real one (e.g., Kepler 1993). This frequency range corresponds to periods of 100 s to 1000 s where the pulsations in DBVs have been detected. We also note that some of the light curves contain noise at low frequencies (less than few hundred μHz which corresponds to several thousand seconds and longer in period), probably due to transparency variations or thin cirrus. If we included this noise in our estimate, our amplitude limits would have been higher and not reflective of our true ability to detect variation within the frequency range of interest.

In Figure 2, we plot the effective temperatures and surface gravities for DBs in the DR4 WD catalog. Newly found DBVs, represented by large solid dots with their uncertainties in effective temperature and surface gravity, cluster around $T_{\rm eff}$ ∼ 25,000 K, although many more objects still need observation (the hollow dots). We did not plot each set of error bars to avoid clutter in the figure. Many of the DBs for which we did not see any variability (represented by the squares in

Table 1
Journal of Observations

Name SDSS J	Date	Length (s)	Run Number[a]	Filter
001529.75+010521.4	2003 Nov 27	12103.06	APO	None
031609.12-062556.8	2007 Feb 13	9000.00	A1446	BG40
034153.03–054905.9*	2003 Dec 03	12832.5	A0797	None
	2003 Dec 26	4380.0	A0811	BG40
	2003 Nov 27	7575.13	APO	None
081904.19+354255.8	2007 Feb 13	12380.0	A1447	BG40
085202.44+213036.5*	2008 Mar 15	7381.15	SOAR	B
	2008 May 06	7038.50	SOAR	B
085950.30−000339.6	2003 Dec 27	10650.0	A0818	None
090409.04+012741.0	2003 Dec 26	7085.0	A0813	None
	2003 Nov 27	9026.21	APO	None
090456.13+525029.9	2003 Mar 10	9026.21	APO	None
092200.98+000834.4	2003 Dec 24	6337.5	A0804	None
094749.40+015501.9*	2003 Dec 22	8692.5	A0799	None
	2003 Dec 30	11690.0	A0828	None
095256.69+015407.7	2003 Dec 23	5505.0	A0801	None
095455.11+440330.3	2007 Feb 15	14055.0	A1451	BG40
095649.55+010812.4	2003 Apr 27	11965.58	APO	None
101131.88+050729.3	2005 Apr 01	7000.0	A1022	None
101502.95+464835.3	2005 Apr 01	6000.0	A1017	None
104318.45+415412.5*	2005 Apr 05	7635.0	A1027	None
105929.60+554039.2	2005 Apr 01	5360.0	A1018	None
122241.28−003614.4	2003 Dec 26	6547.5	A0815	None
122314.25+435009.1*	2005 Apr 05	6735.0	A1028	None
	2007 Feb 13	7240.0	A1448	BG40
125759.04−021313.4*	2003 Apr 01	10897.5	A0626	BG40
	2003 Apr 27	4968.04	APO	None
130516.51+405640.8*	2005 Apr 02	10000.0	A1019	None
130742.43+622956.8*	2005 Apr 03	7290.0	A1023	None
131148.49+053847.6	2007 Feb 13	7080.0	A1449	BG40
133215.95+640656.3	2003 May 27	10576.08	APO	None
135610.31−002230.6	2003 Dec 30	4822.5	A0829	None
140814.64+003838.9*	2003 Mar 31	14145.0	A0602	None
	2004 Apr 20	6930.0	A0868	BG40
	2003 Mar 24	17084.99	APO	None
141258.17+045602.2	2003 Apr 30	4195.0	A0623	BG40
	2003 Mar 10	5126.25	APO	None
	2003 May 27	6694.15	APO	None
	2003 Apr 27	9164.86	APO	None
231324.25−001636.8	2003 Dec 26	4552.5	A0810	None
	2003 Dec 30	5655.0	A0825	None
235322.16+002653.9	2003 Dec 22	7027.5	A0796	None

Notes. The new DBVs reported in this paper are marked with an * next to the object name.
[a] Texas data have run numbers starting with a letter A followed by a 4 digit number. APO data do not have a run number and are indicated by "APO" in this column.

Table 2
Observed Periods and Amplitudes in the New DBVs

Object SDSS J	Frequency (μHz)	Period (s)	Amplitude (mma)
034153.03−054905.8	1060.5	942.0	12.2
085202.44+213036.5	1051.9	950.7	20.8
094749.40+015501.8	3923.9	254.9	13.3
104318.45+415412.5	2382.6	419.7	20.6
122314.25+435009.1	1456.4	686.6	26.1
	1838.2	544.0	18.3
125759.03−021313.3	1371.6	729.1	13.0
	1880.6	531.7	20.8
130516.51+405640.8	1095.9	912.5	8.9
	1520.1	657.9	5.9
130742.43+622956.8	1124.1	889.6	27.0
140814.63+003838.9	2983.5	335.2	7.6
	3506.7	285.2	10.3
	3874.4	258.1	13.2

Note. We do not currently have the resolution to detect any multiplets or closely spaced modes.

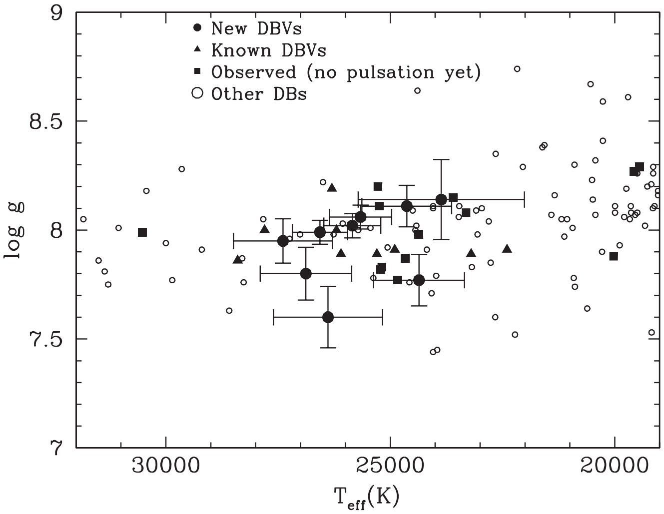

Figure 2. Here we indicate the log g vs. the T_{eff} of the DBVs we found by the black dots, the previously known DBVs by the triangles, the observed DBs by the squares and all other DBs in the SDSS DR4 by the hollow dots. We plot only the error bars of the new DBVs to avoid clutter in the diagram. The previously known DBVs' physical parameters were taken from Beauchamp et al. (1994). We only quote results from their pure He atmosphere model fits since we use pure He atmosphere models for all DBs from the SDSS. Their models and spectral-fitting techniques and ours are different. Therefore there probably are some offset/differences in the temperature and gravity scale in comparison with those from ours. Some of the observed DBs are outside the temperature range shown here.

Figure 2) have not been observed a second time, mainly because we have not yet had the time to do so. As can be seen from Table 1, only two objects (SDSS J090409.03+012740.9 and SDSS J141258.17+045602.2) were observed more than once with combined amplitude limits of 3.5 mma and 2.6 mma, respectively. These amplitude limits are by no means good enough to call them non-pulsators since some WD pulsators are known to have lower amplitudes than these. Our current results are consistent with, but do not demand, a pure DBV instability strip. We need to eventually achieve at least 1 mma detection limit for all the DBV candidates we observe before investigating the purity of the instability strip.

We observed four DBs with $T_{\mathrm{eff}} > 30{,}000$K, i.e. DBs in the "DB gap," but did not see any pulsations so far. Like the other DBs that we observed but did not detect pulsations, these objects need to be followed up before they can be declared nonpulsators. In the past, the instability strip was defined by the nine known DBVs shown by the triangles in Figure 2. The blue edge of the instability strip was defined by one DBV, EC20058. We have not found any pulsator hotter than EC20058 and hence the best chance of determining the neutrino production rates still lies with this star.

4. SUMMARY

From the DR4 WD catalog, we have about 70 DBV candidates brighter than $g = 20$ mag. To date, we have observed 29 of them and found nine new DBVs, doubling the number of known DBVs. We seek an increased number of DBVs to help us

Table 3
SDSS Data on All Observed DBs

Object SDSS J	Plate	Fiber	MJD	g (mag)	T_{eff} (K)	$\sigma_{\mathrm{T_{eff}}}$ (K)	log g	σ_{log_g}	Status
034153.03−054905.8	462	506	51909	18.25	25087	524	8.02	0.062	DBV
085202.44+213036.5	2280	604	53680	18.50	25846	6361	8.02	0.056	DBV
094749.40+015501.8	480	520	51989	19.95	23453	1659	8.13	0.192	DBV
104318.45+415412.5	1361	155	53047	18.95	26291	919	7.77	0.138	DBV(1)
122314.25+435009.1	1371	205	52821	18.98	23442	1069	7.84	0.127	DBV
125759.03−021313.3	338	436	51694	19.16	25820	1296	7.57	0.151	DBV
130516.51+405640.8	1458	21	53119	17.46	24080	414	8.14	0.056	DBV(1)
130742.43+622956.8	783	513	52325	18.83	23841	913	8.14	0.097	DBV(1)
140814.63+003838.9	302	490	51688	19.19	26073	1227	7.98	0.117	DBV
001529.74+010521.3	389	530	51795	18.94	34379	1079	7.96	0.163	8.20(1)
031609.12−062556.8	459	605	51924	19.97	24478	2520	7.96	0.222	17.0(1)
081904.19+354255.8	826	422	52295	18.22	22540	867	8.18	0.079	4.80(1)
085950.29−000339.6	469	49	51913	20.19	23729	2391	8.12	0.291	13.3(1)
090409.03+012740.9	470	442	51929	17.96	23183	533	7.95	0.062	4.28
090456.11+525029.8	552	547	51992	18.95	37584	953	7.99	0.091	10.1(1)
092200.97+000834.3	474	388	52000	18.56	22581	769	8.10	0.074	7.56(1)
095256.68+015407.6	481	513	51908	17.50	32920	323	8.16	0.041	4.84(1)
095455.11+440330.3	942	275	52703	18.18	20072	368	8.29	0.064	5.85(1)
095649.55+010812.4	481	20	51908	20.48	17125	1257	7.37	0.261	13.0(1)
101131.88+050729.3	574	331	52355	18.97	24301	984	7.71	0.115	8.98(1)
101502.95+464835.3	944	328	52614	18.61	23312	830	8.01	0.076	7.24(1)
105929.60+554039.2	908	317	52373	18.47	24742	571	8.17	0.101	8.46(1)
122241.27−003614.4	288	63	52000	18.10	24023	676	8.21	0.073	4.66(1)
131148.49+053847.6	850	522	52338	17.65	20249	268	8.30	0.041	11.7(1)
133215.93+640656.2	603	118	52056	18.41	21365	1694	7.99	0.097	9.73(1)
135610.32−002230.6	301	232	51641	19.38	18584	397	8.20	0.149	13.1(1)
141258.17+045602.2	583	432	52055	17.35	30343	329	7.97	0.038	2.88
231324.24−001636.9	381	72	51811	19.83	19588	1987	7.93	0.298	3.19
235322.16+002653.8	386	549	51788	19.71	25012	1800	8.15	0.203	13.0(1)

Notes. The top section of the table details the objects that showed variability during at least one observation. Separated by a double horizontal line, the second half of the table lists the objects for which we have not (yet?) seen significant variability. In the status section, we note new variable objects by "DBV." For objects in which we have not detected variability, we give the amplitude limit in mma in the status section. If we have observed an object only once, then we add a "(1)." Due to lack of observing time and a large number of candidates, we have not yet been able to observe all DBV candidate objects, nor all these a second time. The physical parameters here come from fitting SDSS DR6 spectral data with a denser, but otherwise consistent, model grid than that used in the DR4 WD catalog.

understand their group properties, better determine the location of the instability strip, and perhaps find hot DBVs that we can use to measure their cooling rates and place a limit on the neutrino production rate in their interiors. Based on these statistics, we can expect at least another 12 new DBVs from the DR4 sample and 20 more from the DR6. These are probably lower limits though, since we suspect that additional observations of our 29 currently observed objects will probably reveal new low-amplitude pulsators as well.

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