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Kurtz, D.W., Shibahashi, H., Dhillon, V.S. orcid.org/0000-0003-4236-9642 et al. (2 more authors) (2008) A search for a new class of pulsating DA white dwarf stars in the DB gap. Monthly Notices of the Royal Astronomical Society, 389 (4). pp. 1771-1779. ISSN 0035-8711

https://doi.org/10.1111/j.1365-2966.2008.13664.x

Mon. Not. R. Astron. Soc. **389,** 1771–1779 (2008) doi:10.1111/j.1365-2966.2008.13664.x

A search for a new class of pulsating DA white dwarf stars in the DB gap

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Accepted 2008 June 27. Received 2008 June 26; in original form 2008 May 19

ABSTRACT

While white dwarf stars are classified into many subgroups based on the appearance of hydrogen, helium, carbon, oxygen and other spectral lines – or even pure continuum with no lines in the case of the DC stars – the vast majority fall into two major subgroups: those with hydrogen atmospheres (the DA white dwarfs), and those with helium atmospheres (the DO and DB white dwarfs). Remarkably, in the range $45\,000 \geq T_{\rm eff} \geq 30\,000$ K there are only a few white dwarfs with helium atmospheres to be found – the vast majority are DAs in this temperature range – although white dwarfs with helium atmospheres are found at both hotter (DO) and cooler (DB) effective temperatures. This dearth of helium atmosphere white dwarfs in this temperature range is known as the 'DB gap' and is understood in terms convective mixing of the outer atmospheres at the hot and cool ends of the gap, while radiative stability allows the lighter hydrogen to float to the top in the DB gap, so the stars are seen to be DA hydrogen atmosphere white dwarfs. Asteroseismology is an important tool for probing stellar interiors, and white dwarf stars are the most successfully studied group using this technique. In a stability analysis of the stars in the DB gap, Shibahashi has recently predicted the existence of a new class of pulsating white dwarf stars. He finds from models that DA white dwarfs near the red edge of the DB gap have convectively stable outer atmospheres because of a steep mean molecular weight gradient, yet nevertheless have a superadiabatic layer that renders them pulsationally unstable due to radiative heat exchange. There have been very few observational tests for pulsation among stars of this type. We have initiated a survey to search for the predicted pulsators and report here our first observations of five stars with the South African Astronomical Observatory 1.9-m telescope and University of Cape Town CCD photometer, and two stars with the William Herschel Telescope 4.2-m telescope and the ULTRACAM photometer. We have two detections at formal significance levels greater then 4σ; the rest are null results with upper limits of about 6–8 mmag with the 1.9-m telescope and about 3 mmag with the 4.2-m telescope. The two formally significant detections need confirmation, but the cases for them are good. Should they be confirmed, a new class of pulsating white dwarfs will become available for asteroseismic investigation, providing new insight into white dwarfs in general and into the DB gap in particular.

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

1 INTRODUCTION

1.1 White dwarfs and the DB gap

White dwarf stars are spectroscopically classified into six major subtypes with additional classifications indicating crossover spectra. In addition, there are further subtypes that specify the presence of polarization, magnetic fields and pulsation, plus there are classes for stars that do not fit any other class! For an introduction to the white dwarf alphabet zoo, see table 1 of McCook & Sion (1999). The hottest pre-white dwarf stars that appear on the white dwarf cooling sequence in the HR diagram have effective temperatures of nearly 200 000 K, ranging down to about 80 000 K. Some of these hottest white dwarf stars are central stars of planetary nebulae, some are not; some pulsate, some do not.

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For white dwarfs cooler than $T_{\rm eff} \le 80\,000$ K there is a clear spectroscopic sequence into which the vast majority of known white dwarfs fit. The DO stars lie in the range $80\,000 \ge T_{\rm eff} \ge 45\,000$ K and show strong spectral lines of He II. It is the presence of the He II lines that gives them their 'O' subclass, in analogy with the main-sequence O stars, but note that there is not a direct correlation in temperature with the main-sequence O stars which are generally cooler. Thus the DOs are helium atmosphere white dwarfs. Much cooler than the DOs are the DB white dwarfs with approximately $30\,000 \ge T_{\rm eff} \ge 12\,000$ K. These stars are also helium atmosphere white dwarfs, where in this case the DB classification indicates that generally only spectral lines of He I are seen with little or no H or metal lines. Note again that the 'B' classification is in analogy with main-sequence B stars that show lines of neutral helium in their spectra, but that the temperatures do not necessarily correspond.

The vast majority of the rest of the white dwarfs are classified as DA stars because they show only lines of the Balmer series of hydrogen in their visible wavelength spectra. They are thus subclass 'A' in analogy to the main-sequence A stars, which by definition show the strongest Balmer lines of all main-sequence stars. However, even more so than for the DOs and DBs, the temperatures of the DAs do not in general correlate with main-sequence A stars. While there are DAs in the main-sequence A star temperature range of $10\,000 \ge T_{\rm eff} \ge 7400$ K, other DAs may be found with temperatures as hot as 170 000 K and as low as the coolest white dwarf stars known, $T_{\rm eff} \sim 4500$ K, a lower limit set by the age of the Galaxy; there has not yet been time for the first white dwarfs to cool beyond this limit.

While white dwarf stars are predicted to be the end state of evolution for main-sequence stars with $M \le 8\,{\rm M}_\odot$ and are the most common class of stars in the Galaxy, the number known is not very great as a consequence of their intrinsic faintness. Thus the study of white dwarfs is plagued by the same problem as the study of the coolest main-sequence dwarfs, brown dwarfs and especially extrasolar planets: a dearth of photons.

The number of known and studied white dwarfs has increased dramatically in recent years as a consequence of the data available from the Sloan Digital Sky Survey (SDSS; York et al. 2000). While the SDSS is primarily an extragalactic project, its uniform, relatively deep (23 mag) wide-field data set is of significant use for stellar astronomy, in particular for the discovery of new white dwarf and hot subdwarf stars. McCook & Sion (1999) presented a catalogue of 2249 white dwarfs with spectroscopic classifications; their data were complete through early 1996. Kleinman et al. (2004) increased the number of spectroscopically classified white dwarfs by 2551 stars using the first SDSS data release, thus more than doubling the number known. A subsequent more extensive work from the SDSS Data Release 4 (Eisenstein et al. 2006a) presented a catalogue of 9316 spectroscopically confirmed white dwarf stars. Thus the majority of white dwarfs now known have been found in the SDSS. A study of these SDSS white dwarfs by Kepler et al. (2007) further illuminates the temperature and mass distribution for DA and DB stars roughly in the range $40\,000 \ge T_{\rm eff} \ge 12\,000$ K.

Eisenstein et al. (2006a) confirm what was earlier known from smaller samples of white dwarfs: DA white dwarfs dominate, constituting about 86 per cent of all white dwarfs in their sample (8000 of 9316 stars). DBs are the next most numerous group comprising 8 per cent of the sample (713 of 9316 stars). All other classes comprise the remaining 6 per cent of the sample. Hence hydrogen atmosphere DA white dwarfs are 10 times more common than helium atmosphere DB white dwarfs.

While DAs can be found at all temperatures under 170 000 K down to the low temperature limit set by the age of the Galaxy, it is a remarkable and intriguing fact that few helium atmosphere white dwarfs occur in the effective temperature range between $45\,000 \ge T_{\rm eff} \ge 30,000$ K. The DOs and DBs are found on either side of this temperature range, but only a very few genuine helium atmosphere white dwarfs are found within it (see e.g. Eisenstein et al. 2006b). This exclusion is known as the 'DB gap' (Liebert 1986).

The process of atomic diffusion is important in many stellar astrophysical situations. It is a competition between gravitational settling and radiative levitation with any kind of turbulent mixing – particularly convection – potentially (usually) quenching the processes. Most importantly in the context of this discussion: gravitational settling stratifies the structure of white dwarf stars, and in the presence of such strong gravitational fields it does so quickly.

In the absence of any mixing – particularly in the absence of convection – we would expect all white dwarf stars with sufficient residual hydrogen ($>10^{-15}\,{\rm M}_\odot$ of H) to be DA stars. Some non-DA white dwarfs probably do not fulfil this condition, i.e. they lack sufficient hydrogen to be DA stars. The amount of mass loss, and in particular the amount of hydrogen loss during stellar evolution must depend on an individual star's circumstances. The major pathway to white dwarfdom is through single star evolution with envelope loss, leaving behind as the white dwarf the previous stellar core. Two other pathways are a less common one of evolution from a hot subdwarf on the extreme horizontal branch to white dwarf, and a process with unknown frequency: binary merger. It is assumed that the vast majority of white dwarfs follow the first evolutionary path.

In that context, Fontaine & Wesemael (1987) explained the DB gap as a natural consequence of the evolution of almost all white dwarfs from planetary nebulae nuclei. They supposed that a slow rise of hydrogen to the surface, as heavier nuclei sink in the strong gravitational field, eventually makes helium-rich white dwarfs appear as DA stars at the blue edge of the DB gap at about 45 000 K. Note that hydrogen is not being radiatively levitated in this case, but rises instead as a consequence of being the lightest nucleus in an environment of gravitational settling. They then explained the red edge of the DB gap as a natural consequence of the onset of a significant convection zone at the temperature where the He I/II ionization zone coincides with the upper atmosphere, thus mixing the small amount of residual hydrogen into a deeper sea of helium, so the star then appears as a DB white dwarf. The H is essentially overwhelmed by the more abundant He and becomes observationally undetectable, or at best, difficult to detect.

Shibahashi (2005) revisited this idea and proposed a different model for the onset of the blue edge of the DB gap as white dwarfs cool: the blue edge of the DB gap occurs at the effective temperature where the He III/II ionization zone becomes deep enough that the surface convection zone of the DO stars disappears. Hence in this model the stars are always potentially DAs, but convection in the He III/II ionization zone mixes the atmosphere so the dominant helium appears in the spectrum for the DO stars, then similar mixing occurs again when the stars cool to the red edge where the He I/II ionization zone again generates a convection zone, as in Fontaine & Wesemael's original suggestion. The difference between the two models is in the time-scale for gravitational settling, hence hydrogen floating to the surface. For Fontaine & Wesemael (1987) this happens slowly during the cooling of a star from a PG 1159 pre-white dwarf stage; for Shibahashi (2005) it happens quickly as soon as the convection is turned off at 45 000 K. One possible explanation for some of the small number DB stars that do appear in the DB gap is that they are truly stars for which there is virtually no residual hydrogen to form an optically thick atmosphere. However, this is inconsistent with Eisenstein et al.'s (2006b) conclusion from statistical studies that some of the DB stars in the DB gap cool to be DA white dwarfs. They conclude that the DB gap is real – and we assume this to be true here – but clearly there are mysteries concerning this gap that are still to be solved.

Based on this scenario of the spectral evolution from DA to DB at the cool end of the DB gap, Shibahashi (2005) suggested that the photospheric level of an apparently DA white dwarf – yet potentially helium atmosphere DB white dwarf in the DB gap – is superadiabatic while it is convectively stabilized by a chemical composition gradient (i.e. cooler but lighter hydrogen is stratified above hotter but heavier helium). He further pointed out that under such a condition the radiative heat exchange brings about an asymmetry in the g-mode oscillatory motion in such a way that an oscillating element overshoots its equilibrium position with increasing velocity. A local stability analysis of a white dwarf model in the DB gap by Shibahashi (2007) then suggests that g modes may be excited for stars at the cool end of the gap, i.e. with temperatures around 30 000 K. He finds higher degree, l, modes preferentially excited, but some modes with $l < 3$ are excited in the models, so may reach observable amplitudes. There have been few searches for pulsation in DA white dwarfs of this temperature. Therefore, we have begun a survey to try to find the predicted new class of pulsating stars, stars that have DA atmospheres, but are structurally close to the known DBV (DB variable) pulsating stars, the V777 Her stars. Should this search be successful – and we have some positive results that need confirmation, as we report below – this survey will open up a new temperature range and a new class of white dwarf pulsators for asteroseismic study.

1.2 White dwarf pulsation

Asteroseismology is a growing field that now gives significant constraints on both global and atmospheric structure of many types of stars. In the near future the strongest interest amongst theorists is in the prospect of years-long, high duty cycle, high signal-to-noise ratio (S/N) data sets for solar-like oscillators obtained with the CoRoT satellite which is in orbit and collecting data, and from the Kepler mission which is scheduled for launch (as of the time of this writing) in early 2009. Until those data sets become reality, the greatest successes of asteroseismology are arguably in the study of pulsating white dwarf stars.

There are three known classes of pulsating white dwarfs. The most common are the DAVs, also known as ZZ Cet stars. These are hydrogen atmosphere white dwarfs in an exclusive instability strip that ranges between $12\,500 \geq T_{\rm eff} \geq 11\,000$ K with some correlation between temperature and surface gravity, in that the more massive, higher $\log g$ stars are somewhat hotter. Since, as we pointed out in the last section, DAs comprise 86 per cent of all white dwarfs, the asteroseismic study of the ZZ Cet stars is a window to understand the vast majority of white dwarfs. Until recently, there were fewer than 40 known ZZ Cet stars, but searches for new ones using the SDSS white dwarf data base and other surveys have led to this number being more than doubled, and it is still growing in ongoing programmes (Mukadam et al. 2004; Mullally et al. 2005; Castanheira et al. 2006).

The hottest of the white dwarf pulsators are the pulsating PG 1159 stars, or GW Vir stars, of which there are fewer than a couple of dozen known; they have $170\,000 \geq T_{\rm eff} \geq 75\,000$ K. The asteroseismic record holder at the time of this writing is the prototype of this class, PG 1159−035 itself, which has 198 pulsation modes identified from which the mass is determined to very high precision; inner stratification is constrained; the rotation period is determined to high precision; the rotational inclination is constrained and the magnetic field strength has an upper limit less than 2 kG. The literature is large for this star with, in particular, five Whole Earth Telescope extended coverage campaigns for which the star was either the primary or a secondary target (Costa et al. 2008). No modes among the 198 identified for PG 1159 have a degree $l > 2$.

The pulsating white dwarfs of most interest to us in the context of our survey for a new kind of pulsator in the DB gap are the third known type of pulsating white dwarf stars, the DBV, or V777 Her stars. For his PhD thesis work Winget (1982) theoretically predicted the existence of a class of helium atmosphere white dwarf variables, then with his collaborators successfully discovered the prototype of the class, GD 358 = V 777 Her (Winget et al. 1982). Discovering more of these stars has turned out to be difficult. They are uncommon; as we pointed out in the last section, the DB white dwarfs constitute only 8 per cent of all white dwarfs. Furthermore, unlike the ZZ Cet stars for which there appears to be a exclusive instability strip in which all stars pulsate, for the DBs only some stars are V777 Her stars, while others of similar temperature and gravity do not seem to pulsate. A consequence of this – important for the survey for a new type of pulsating white dwarfs that we report here – is that a large sample needs to be tested to find a few pulsating stars. A new survey for DBVs based on the SDSS white dwarf catalogue has nearly doubled the number known, adding eight new V777 Her stars to the nine known previously (Nitta et al., in preparation). The current range in temperature of the known V777 Her stars is $27\,800 \geq T_{\rm eff} \geq 21\,800$ K.

Pulsating white dwarfs have the potential to examine astrophysics and high-energy physics as can be done in no other laboratory. Asteroseismic study of these stars gives their total stellar masses to high precision, measures the masses of stratified layers in their atmospheres, measures or constrains rotation periods and differential rotation, magnetic field strengths, the rate of evolutionary cooling and changes in radius. White dwarfs test neutrino physics, constrain possible axion mass and provide a laboratory to study crystallization and the C(α, γ)O cross-section, important for the understanding of Type Ia supernovae. White dwarfs constrain the age of the Galaxy and preserve an imprint of galactic history. For a short review of white dwarf seismology, see Kepler (2007); for extensive reviews see Fontaine & Brassard (2008) and Winget & Kepler (2008).

Clearly, white dwarf stars are important for stellar and galactic astrophysics and as high-energy physics laboratories. The discovery of a new class of pulsators could therefore have important, wide implications. We report in this paper the first results of our survey for the new type of pulsating white dwarf star at the cool end of the DB gap predicted by Shibahashi (2007).

2 OBSERVATIONS

2.1 Target selection

We used as our source for target selection the catalogue of spectroscopically identified white dwarf stars in the first data release of the SDSS (Kleinman et al. 2004). In our ongoing survey target selection has been extended to the update of this catalogue to the fourth data release of SDSS (Eisenstein et al. 2006a), from which we have taken all but one of the temperature estimates and classifications based on matching H or He models to the SDSS spectra. As our expectation from Shibahashi's (2007) stability analysis is that DA white dwarfs near the red edge of the DB gap should show observable pulsation amplitudes in low-degree g modes, we chose stars with DA spectral classifications with temperatures in the range $30\,500 \geq T_{\rm eff} \geq 28\,500$ K. The reasons for this are that the instability analysis predicts pulsation in the coolest DA stars in the DB gap, the temperatures may be more uncertain than their internal precision indicates and no searches that we know of have tested DA white dwarfs in the temperature range of the V777 Her stars, as such stars previously were not expected to pulsate.

Because the known DB stars have temperatures as hot as 31 500 K, Nitta et al. have also tested a few stars for pulsation that are in the temperature range of interest to us. They have searched for pulsation in stars classified as DB that are hot enough to be in the defined DB gap – remember that there are a few DB stars in DB gap temperature range, and that the red edge of the DB gap is not sharply defined. Their purpose was to test the blue border of the V777 Her instability strip. Thus the stars their survey is testing and the targets of our survey have overlapping temperature ranges, but their targets are classified DB, and ours are classified DA. If the theory of the DB gap that was explained in Section 1.1 is correct, then these two classes, DA and DB, have different convection zones in their atmospheres, even though the effective temperatures are similar. Obviously, another parameter is necessary, but whether that is mass (i.e. $\log g$), H mass fraction or something else is not yet known.

Pulsation amplitude in white dwarf stars can be at the limit of detection. There are pulsators with amplitudes of only a few mmag.[1] Since white dwarfs are generally faint, there are many stars that have been tested for pulsation with less sensitivity than this, thus there can be no doubt that higher S/N searches will detect more pulsators. White dwarf pulsators are generally multiperiodic, and of course it is the multiperiodicity that is sought, since frequencies (or periods) are the fundamental data for the forward problem of asteroseismology where models are matched to observations. However, multiperiodicity means that short test runs for pulsation of a few hours, or less, may not detect variation that is present because of unfavourable beat phase. Hence, proof that a star is stable to pulsation is difficult.

On the other hand, many pulsating white dwarf stars have spectacular amplitudes of tenths of a magnitude. Even relatively poor photometric S/N can detect the presence of pulsation in such stars, although the highest S/N is still desired for asteroseismic data sets. Because the instability analysis of Shibahashi (2007) was linear, it was not possible to make any prediction of amplitude, and we thus have no a priori expectation of what the amplitude might be. As a guide, the survey of SDSS DB stars and discovery of new V777 Her stars by Nitta et al. (in preparation) found amplitudes of individual modes on the order of 10–20 mmag, whereas V777 Her itself has some pulsation cycles with amplitudes 10 times that.

[1] It is common practice among those working on the photometric study of white dwarf pulsators to work with the data in intensity, and to report amplitudes in fractional intensity: i.e. mma, meaning millimodulation amplitude. We work in this paper in traditional astronomical magnitudes and report amplitudes in millimagnitudes = mmag. For low-amplitude pulsation, there is very little difference between these two systems of units. The major difference is in the processing of the data. In intensity, identified frequencies are divided out in the time domain when pre-whitening; in magnitudes, because the scale is logarithmic, the same process involves subtraction in the time domain.

2.2 SAAO data acquisition and reduction

We began our survey using the South African Astronomical Observatory (SAAO) 1.9-m telescope with the University of Cape Town (UCT) CCD photometer in frame-transfer mode (O'Donoghue 1995). The field-of-view is small on this telescope, only (50×34) arcsec^2, so that no suitably bright comparison stars were included for any target. Observations were made in white light with continuous 10-s integrations. The pixels only subtend 0.13 arcsec on this telescope, so we used 3×3 binning for the data extraction. We performed online reduction with bias subtraction and flat-field corrections. Magnitude determinations with sky correction were based on the DOPHOT program (Schechter, Mateo & Saha 1993). Extinction correction using a mean extinction coefficient was performed, some obvious outliers were removed from each data set, and one low-frequency peak was pre-whitened from each run to correct for residual transparency variations remaining after the mean extinction corrections. In most cases this latter correction was similar to the removal of a linear trend. This procedure involves frequency peaks below about 0.3 mHz, hence means that information about possible pulsation periods longer than 1 h are lost. This is an inevitable consequence of high-speed photometry for fields with no suitable comparison stars. The search for shorter periods than 1 h remains valid. The choice of 10-s integrations was driven by the range of known periods in pulsating white dwarfs which are as short as 110 s in ZZ Cet stars and 150 s in V777 Her stars.

The white dwarf stars in the SDSS spectroscopic catalogue of Kleinman et al. (2004) gave us dozens of potential candidates classified as DA stars in the temperature range of interest. The problem – as is usually the case with white dwarfs – is that they are all relatively faint for a 1.9-m telescope. Our observing run ran from 2006 December 20–25 when the brightest targets that met our criteria had SDSS $g' > 16.8$ (see Fukugita et al. 1996 for definition of the SDSS photometric passbands). High quality photometric conditions allowed us to test five candidates for 2.65–3.47 h each. Table 1 lists the candidates observed with the SAAO 1.9-m telescope and gives a journal of the observations. We report the results in Section 3.

2.3 WHT data acquisition and reduction

On the nights of 2007 October 18–19 and 19–20 we observed two targets using ULTRACAM (Dhillon et al. 2007) mounted at the Cassegrain focus of the 4.2-m William Herschel Telescope (WHT) on La Palma. ULTRACAM is a CCD camera designed to provide imaging photometry at high temporal resolution in three different colours simultaneously. The instrument provides a 5 arcmin field of view on its three 1024×1024 E2V 47-20 CCDs (i.e. 0.3 arcsec pixel^{-1}). Incident light is first collimated and then split into three different beams using a pair of dichroic beam splitters. For the observations presented here, one beam was dedicated to the SDSS u' filter, another to the SDSS g' filter and the third to the SDSS r' filter. Because ULTRACAM employs frame-transfer chips, the dead time between exposures is negligible: we used ULTRACAM in its *full-frame, no-clear mode*, providing 10-s exposure times with 24-ms dead time in the r' and g' channels; due to the low S/N in the u' band, we decided to take 20-s exposures in this channel. Each ULTRACAM data frame is time stamped to an absolute accuracy of better than 1 ms using a dedicated GPS system. The data were obtained in photometric conditions, with no moon and seeing of approximately 1.5 arcsec. A journal of observations is given in Table 1.

Table 1. A journal of observations obtained with the SAAO 1.9-m telescope and UCT CCD photometer, and with the WHT and ULTRACAM. The observers were DWK and HS at SAAO, and VSD at the WHT. The effective temperatures and spectral classifications for the stars (columns 4 and 5) have been taken from Eisenstein et al. (2006a), except for that of J020848.28+121332.4 which comes from Kleinman et al. (2004). Eisenstein et al. (2006a) describe the method of automatic fitting of the observed spectra to a grid of models to determine the effective temperatures listed here.

			SAAO observations						
Date	Star SDSS	g'	Auto T_{eff}	Class	Start BJD (245 0000+)	End BJD (245 0000+)	Δt (h)	n	σ (mmag)
2006 December 20–21	J034428.27−003814.0	16.77	30 000 ± 71 K	DA	4090.317425	4090.438142	2.90	1023	34.4
2006 December 21–22	J023520.02−093456.3	17.78	30 108 ± 252 K	DA	4091.338555	4091.449087	2.65	949	52.1
2006 December 21–22	J084742.23+000647.7	17.71	30 545 ± 241 K	DAB	4091.484995	4091.596069	2.67	953	32.8
2006 December 22–23	J033032.32+000250.1	18.12	28 833 ± 165 K	DA	4092.300941	4092.431960	3.14	1113	56.0
2006 December 24–25	J031405.83−081725.2	18.57	28 588 ± 341 K	DA	4094.294642	4094.439214	3.47	1245	44.6
			WHT observations						
Date	Star SDSS	g'	Auto T_{eff}	Class	Start HJD (245 0000+)	End HJD (245 0000+)	Δt (h)	n	σ (mmag)
2007 October 18–19	J010415.99+144857.4	18.83	29 982 ± 392 K	DA	4392.61297	4392.68863	1.82	683	15.7
2007 October 19–20	J020848.28+121332.4	18.74	31 150 ± 481 K	DA1.6_7.8	4393.61877	4393.70623	2.10	790	15.5

The data were reduced using the ULTRACAM PIPELINE reduction software. All frames were first debiased and then flat-fielded, the latter using the median of twilight sky frames taken with the telescope spiralling. We then extracted light curves of the target and the comparison stars by summing the counts in a circular aperture centred on each object, with the width of the aperture set to 1.5 times the full width at half-maximum (FWHM) of the stellar profile in each frame, and the sky determined from the clipped-mean level in an annulus surrounding the object aperture. For the two target stars, respectively, eight and nine nearby comparison stars were tested against each other for variability, then the constant star with the highest S/N was used to correct the data for transparency variations.

3 FREQUENCY ANALYSIS AND DISCUSSION OF THE SAAO DATA

For ease of discussion, SDSS star names are abbreviated in the discussion in an obvious way. The headings to each subsection leave no ambiguity about the star's full name. The Nyquist frequency for our 10-s data is 50 mHz. There are no indications of any significant peaks beyond 10 mHz. To show the noise level in the data, we choose to present amplitude spectra out to 20 mHz for null results, and, in addition, at higher frequency resolution for our possible detection in J023520. For completeness, we show the light curves, but there is no obvious pulsational variation to be seen in any of them, even for the two stars where we suggest we have made significant detections.

3.1 SDSS J084742.23+000647.7

For the SAAO data J084742 gives the best null result we obtained, so sets the limit on our precision. Fig. 1 shows an amplitude spectrum for this star. There are some residual transparency variations at low frequencies, hence we do not consider pulsation frequencies less than 1 mHz in this case, where the level of the highest peaks drops to 5.8 mmag, to have been tested in this star. The standard deviation for the amplitude of a given frequency for this data set is 1.5 mmag, thus we note that the highest peaks are at 3.9σ formally. This is not unusual for high-speed photometric data obtained without comparison stars, as a consequence of the data not being normally distributed. It also indicates the level of significance that

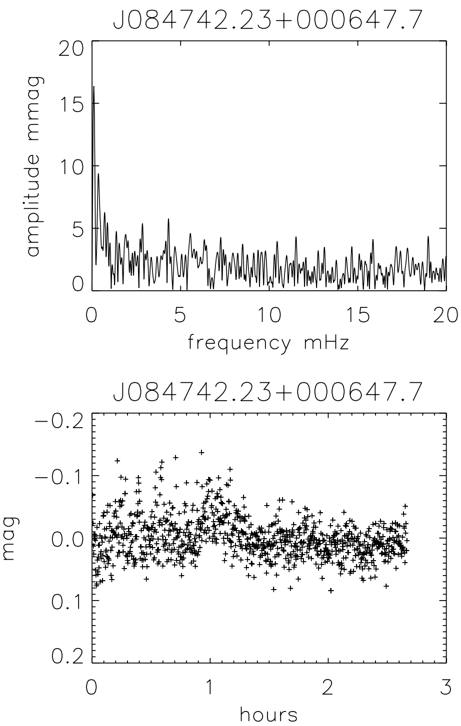

Figure 1. An amplitude spectrum and 2.7-h light curve for SDSS J084742.23+000647.7. The variations visible in the light curve are believed to be residual transparency variations and are characterized by the low-frequency peaks in the amplitude spectrum. We set an upper limit of 6 mmag to pulsational variability at frequencies higher than 1 mHz.

is not to be trusted. Note in Table 1 that this star has a hybrid classification (Eisenstein et al. 2006a) of DAB, hence it shows some He I lines in its spectrum, in addition to the dominant Balmer lines. It is the only hybrid in our sample.

3.2 SDSS J034428.27−003814.0

J034428 was our brightest target at $g' = 16.8$, hence was expected to show the lowest noise levels. As can be seen in the light curve presented in Fig. A1, the high-frequency noise increased significantly after the first 1.6 h of observations, a probable change in the upper atmospheric scintillation noise. The bottom panel of Fig. A1 therefore shows the amplitude spectrum for only the first 1.6 h of observations. As for the previous star, the highest noise peaks have amplitudes below 6 mmag, and a least-squares fit[2] shows the standard deviation in amplitude for a single frequency is $\sigma = 1.5$ mmag. Thus these data, as for the previous star, set a 6-mmag upper limit to pulsation amplitude for frequencies above 1 mHz.

3.3 SDSS J031405.83−081725.2

Fig. A2 shows amplitude spectra for the 3.5-h light curve and the first 2.7 h of the same light curve for J031405. The highest peaks for frequencies above 1 mHz are 5.4 mmag. A least-squares fit gives a standard deviation in amplitude of $\sigma = 1.7$ mmag. The upper limit for pulsation amplitude is therefore similar for this star to the two previous cases; we round it to 6 mmag.

3.4 SDSS J033032.32+000250.1

It can be seen in Fig. A3 that only the first 1 h of the 3-h run on this star had good noise characteristics. The amplitude spectrum of the entire run shows two low-frequency peaks that we believe are a result of sky transparency changes in less-than-ideal observing conditions. There is a peak at 1.88 mHz with an amplitude of 11.2 ± 2.3 mmag, suggesting within the internal errors a 4.9σ detection. We do not consider this to be significant in this case, because of the poor noise characteristics of the light curve. The bottom amplitude spectrum of Fig. A3 is for the first 1.3 h of the light curve and shows no peak at 1.88 mHz (the highest noise peak is at 2.55 mHz with an amplitude of 7.2 mmag), confirming that there is no significant signal in these data. We set the upper limit to any pulsation amplitude at 7 mmag.

3.5 SDSS J023520.02−093456.3

Fig. 2 shows amplitude spectra and the light curve for J023520. This star has a highest peak in the frequency range expected for pulsating white dwarf stars at $\nu = 1.419$ mHz ($P = 705$ s) with an amplitude of 14.4 ± 2.4 mmag, a 6σ result. The detrending of the original data for extinction has no significant impact on the frequency or amplitude of this peak; with no low-frequency data processing the peak is formally significant at the 6.3σ level. This means that there is no significant cross-talk between the spectral windows of the low frequency extinction and/or sky transparency drift, and the peak at 1.419 mHz.

This peak appears to be real; it appears that we have found the predicted type of new pulsator, a DA white dwarf with 30 108 ± 252 K in the DB gap. However, many similar claims of important discoveries of new pulsating stars, or even new classes of pulsating stars, have later proven to be overinterpretation of noisy data. We therefore remain cautious about this result until it can be confirmed independently with high S/N data. We would like to see repeatability in the detection, and we would like to have data with high enough S/N to see the variations directly in the light curve. Further observations are planned.

[2] The least-squares fits throughout this paper are of the function $\Delta m = \cos\,[2\pi f(t - t_0) + \phi]$. Δm is the variation in magnitudes where the mean has been set to zero; frequencies are given in mHz and phases in rad with respect to the time t_0.

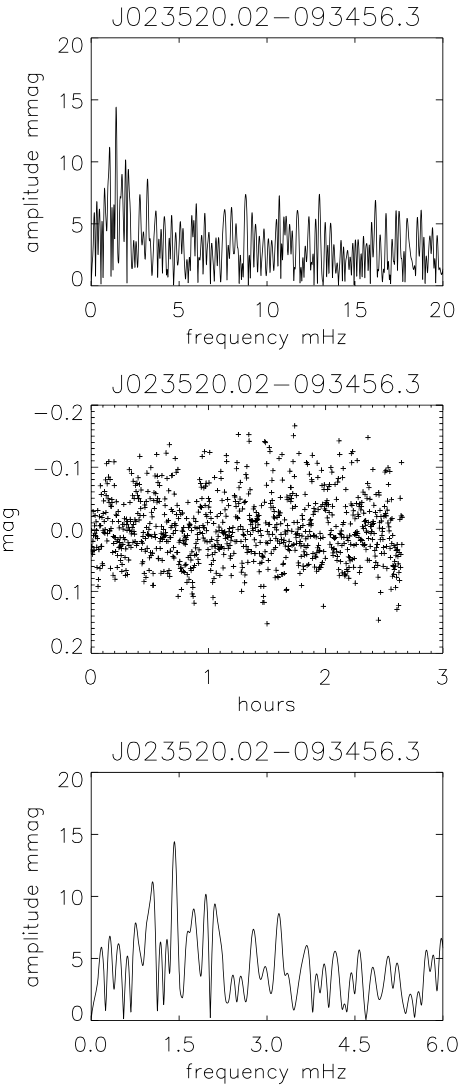

Figure 2. An amplitude spectrum and 2.7-h light curve for SDSS J023520.02−093456.3. The bottom panel shows a higher frequency resolution amplitude spectrum. The highest peak at 1.419 mHz ($P = 705$ s) appears to be significant. A least-squares fit of the frequency to the data yields an amplitude of 14.4 ± 2.4 mmag for a significance level of 6σ.

One test already possible with the data we have is to break the 2.7-h data set into two halves to see if a signal is present in both. Fig. A4 shows the results of that test. They are inconclusive. Clearly the same peak is not present in both halves of the light curve. The first half has a highest peak at $\nu = 1.016$ mHz ($P = 884$ s) with an amplitude of 19.9 ± 3.2 mmag (6.2σ); the second half has a highest peak at $\nu = 1.692$ mHz ($P = 591$ s) with an amplitude of 19.0 ± 3.4 mmag (5.6σ). Nevertheless, this result is plausibly consistent with white dwarf pulsation with multiple frequencies in the range ∼500–900 s.

4 FREQUENCY ANALYSIS AND DISCUSSION OF THE WHT DATA

All comparison stars were constant with respect to each other at frequencies of interest for the WHT data, although some showed low amplitude, low-frequency peaks when their light curves were subtracted from each other. These small drifts are most likely caused by differential extinction between stars of different colour, rather than real variability, but the latter cannot be ruled out on the longer time-scale of the low-frequency peaks. In any case, these are not of interest to our discussion here, and low-frequency peaks are substantially suppressed for the target star when corrected by the best comparison star.

Count rates were so low in the u' filter that longer, 20-s integration had to be used to avoid excessive readout noise. Even then, the S/N was too poor to be useful. Count rates were best in the g' filter because of the spectral energy distribution of the white dwarfs. We found that little was gained by adding the counts in the noisier, lower count rate r' filter to those in the g' filter. Our discussion here, therefore, will be for the data obtained in g'.

4.1 SDSS J020848.28+121332.4

Fig. A5 shows a finding chart for J020848. Star 7 is saturated in g' and r'. It was included to get a good count rate for the u' filter. The best two comparison stars are star 8 and star 5. An amplitude spectrum is shown in the top panel of Fig. A6 for the difference between the two light curves of these comparison stars. Because star 8 is the brighter of the two, we use it as the comparison star for J020848. Adding all of the comparison stars together did not significantly improve the S/N for J020848, so we have kept the analysis simple, using only one comparison star (proved to be constant with respect to the others) and one colour, g'.

The middle and bottom panels of Fig. A6 show the amplitude spectrum and light curve for J020848. There is no signal indicating pulsation. The noise level is higher than for the differential comparison stars in the top panel as a consequence of the fainter magnitude of J020848. The highest noise peak has an amplitude of 3 mmag, but in general the peaks are lower than this. The least squares determined amplitude standard deviation is $\sigma = 0.8$ mmag, so at the same 4σ level that we used for the SAAO data, we rule out pulsation with amplitude greater than 3.2 mmag, at least during the 1.8 h of our observations.

4.2 SDSS J010415.99+144857.4

Fig. 3 shows a finding chart for J010415. Stars 7 and 8 are saturated in g' and r'. They were included to get a good count rate for the u' filter. The best two comparison stars are star 6 and star 5. An amplitude spectrum is shown in the top panel of Fig. 4 for the difference between the two light curves. Because star 5 is the brighter of the two by 0.63 mag in g', we use it as the comparison star for J010415. As for the last star, we have kept the analysis simple, using only one comparison star (proved to be constant with respect to the others) and one colour, g'.

The middle and bottom panels of Fig. 4 show the amplitude spectrum and light curve for J010415. The noise level is higher than for the differential comparison stars in the top panel as a consequence of the fainter magnitude of J010415. The highest peak is at $\nu = 6.304$ mHz ($P = 159$ s) with an amplitude of 3.72 ± 0.85 mmag, a 4.4σ result. This is slightly above our conservative identification criterion of 4σ, hence we suggest that this is a real detection of pulsation. The period of 159 s is within the known range of pulsation periods for g modes in white dwarf stars, hence is plausible. Clearly, however, the result needs confirmation.

The highest peaks in the amplitude spectrum of the r' light curve are above 6 mmag, thus the r' data are too noisy to improve significantly the S/N by combining them with the g' data. We therefore performed the same significance test as for the apparent detection of

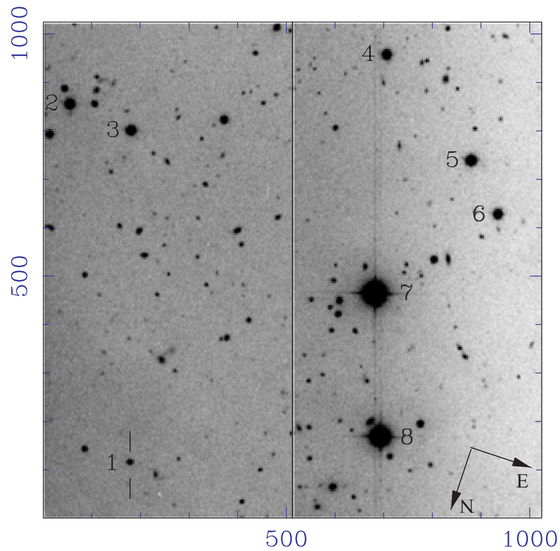

Figure 3. A finding chart for J010415. Star 1 is the target star itself. The other eight numbered stars were tested as comparisons stars. All are constant with respect to each other. The axes are in pixels; each pixel is 0.3 arcsec and there are 1024 of them, giving a field of view of ∼5 arcmin.

pulsation for J023520.02−093456.3 in Section 3.5: we divided the light curve into two independent halves and generated amplitude spectra for each, as can be seen in Fig. A7. The result is encouraging. Both halves of the light curve show a highest peak in the amplitude spectrum at the same frequency, within the errors, and it is the same frequency as found for the entire light curve. A least-squares fit of $\nu = 6.304$ mHz to each half of the light curve gives amplitudes of 2.7 ± 1.0 mmag for the first half, and 4.8 ± 1.3 mmag for the second half. Importantly, the phases are the same to $\Delta\phi = 0.3 \pm 0.5$ rad. While none of these results is strong individually, the fact that the two halves of the light curve give the same highest peak with the same amplitudes and phases (within large errors) is supportive. If the signal is not real, then there is no reason to expect similarity is the independent halves of the data. Unless, of course, the signal were really in the data, but caused by an instrumental artefact. The top panel of Fig. 4 showing the amplitude spectrum for the differential light curve of two comparison stars shows that there is no such artefact in the data.

We therefore claim J010415 as a new pulsator of the type for which we are searching, albeit one that needs confirmation. Observations are planned to do that.

5 CONCLUSIONS

We tested seven DA white dwarf stars in the DB gap for pulsational variability in low-degree g modes, as predicted by an instability analysis of models by Shibahashi (2007). Five of the stars have relatively low S/N using the SAAO 1.9-m telescope; two of the stars have higher S/N using the larger aperture 4.2-m WHT. We find two stars – one with each telescope – that have significant signals in the frequency range of known pulsating white dwarfs. We suggest, and justify our suggestion, that these two stars are the first members of a new class of predicted pulsating white dwarfs. Our claims do need confirmation with better S/N data, and we plan observations to do so. We also plan to continue our survey for this type of

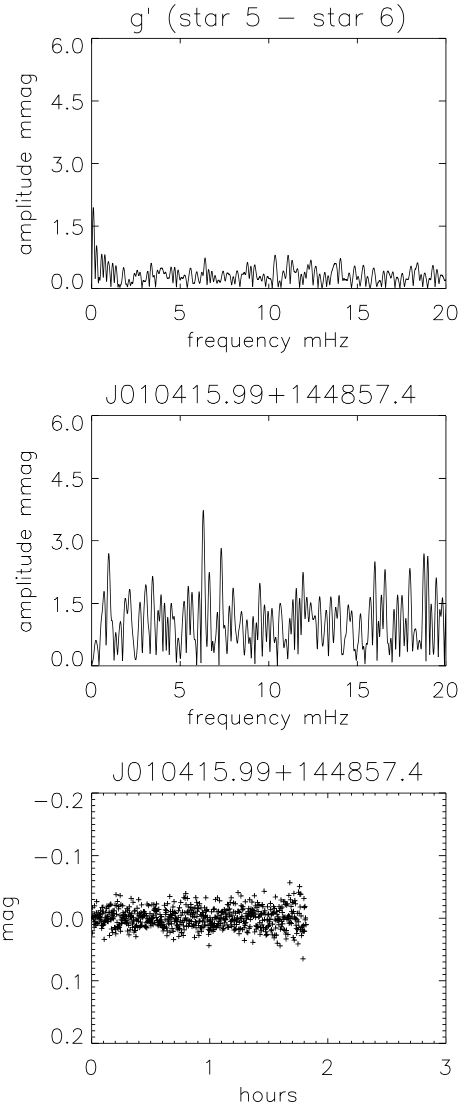

Figure 4. Top panel: amplitude spectrum for the differential light curve between comparison star 5 and comparison star 6 in the g' filter. The noise level has a highest peak of 1.9 mmag at low frequency, but otherwise the noise level has highest peaks of 0.8 mmag; we presume the low-frequency peak to be caused by differential extinction between two stars of probably different temperature. Star 5 is 0.63 mag brighter in g' than star 6. Middle and bottom panels: amplitude spectrum and differential light curve for J010415 in g' using star 5 as the comparison star. Star 5 is 2.80 mag brighter in g' than J010415, so contributes little to the noise in the amplitude spectrum. The highest peak is at $\nu = 6.304$ mHz with an amplitude of 3.72 ± 0.85 mmag, a 4.4σ result.

pulsating white dwarf by searching many more DA stars in the DB gap.

It is interesting that Nitta et al. (in preparation) find only a small fraction of the stars they are testing in the DBV range to be new V777 Her stars. They have more null results than detections. Some of this is a function of S/N, but it currently seems that the DBV instability strip is not exclusive, whereas the ZZ Cet instability strip is. There are both pulsators and non-pulsators among the DB stars with temperatures in the DBV range. Nitta et al. also find four DB stars hot enough to be in the DB gap to be constant within the errors of their search; those stars have $37\,600 \geq T_{\rm eff} \geq 30\,300$ K, thus overlap a few of our hotter DA stars, at least in the approximation of ignoring errors in $T_{\rm eff}$. Should these preliminary results – that DB stars and DA stars at the same temperature around the red edge of the DB gap have different pulsation characteristics – be confirmed, a significant new window into the structural differences in such star will be opened. Should our detection of two new pulsating white dwarfs be confirmed, and others like them be discovered, a new class of pulsating stars will become available for asteroseismic investigation.

ACKNOWLEDGMENTS

We thank Dr Atsuko Nitta for helpful correspondence and discussion. DWK thanks the Japan Society for the Promotion of Science (JSPS) for a fellowship during which the data presented in this paper were analysed and this paper was written at the University of Tokyo. ULTRACAM and SPL are supported by PPARC grants PP/D002370/1 and PP/E001777/1, respectively. This research has made use of NASA's Astrophysics Data System Bibliographic Services. Based on observations made with the WHT operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrosica de Canarias and the SAAO 1.9-m telescope at Sutherland.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Figure A1. An amplitude spectrum and 2.9-h light curve for SDSS J034428.27–003814.0. The bottom panel shows the amplitude spectrum for the first 1.6 h of data for which there is lower scintillation noise and no low-frequency drift.
Figure A2. An amplitude spectrum and 3.5-h light curve for SDSS J031405.83–081725.2. The bottom panel shows the amplitude spectrum for the first 2.7-h of data for which the noise level is lower.
Figure A3. An amplitude spectrum and 3.1-h light curve for SDSS J033032.32+000250.1. The bottom panel shows the amplitude spectrum for the first 1.3 h of data for which the noise level is lower, demonstrating that the peak in the top amplitude spectrum at 1.88mHz is not significant.
Figure A4. Amplitude spectrum for the first and second halves of the SDSS J023520.02–093456.3 data. The same peak is not found for both halves of the light curve, but both show significant highest peaks in a plausible frequency range for a white dwarf pulsator.
Figure A5. A finding chart for J020848. Star 1 is the target star itself. The other eight numbered stars were tested as comparisons stars. All are constant with respect to each other. The axes are in pixels; each pixel is 0.3 arcmin and there are 1024 of them, giving a field of view of ∼5 arcmin.
Figure A6. Top panel: amplitude spectrum for the differential light curve between comparison star 8 and comparison star 5 in the g filter. The noise level has highest peaks of 1.3 mmag, other than the low-frequency peak that we take to be caused by differential extinction between two stars of probably different temperature. Star 8 is 0.38 mag brighter in g than star 5. Middle and bottom panels: amplitude spectrum and differential light curve for J020848 in g' using star 8 as the comparison star. Star 8 is 3.95 mag brighter in g' than J020848, so contributes little to the noise in the amplitude spectrum. There is no signal.
Figure A7. Amplitude spectra for the first and second halves of the light curve for J010415. The highest peak in both halves occurs at the same frequency with the same amplitude and same phase, within the errors. The signal is not significant by our criterion in either half, but the agreement between the two supports our suggestion that we have detected a 159-s pulsation in this star, a period within the known range for g modes in white dwarf star.

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