The Astrophysical Journal, 678:L51–L54, 2008 May 1

SDSS J142625.71+575218.3: A PROTOTYPE FOR A NEW CLASS OF VARIABLE WHITE DWARF

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Received 2008 March 5; accepted 2008 March 17; published 2008 April 10

ABSTRACT

We present the results of a search for pulsations in six of the recently discovered carbon-atmosphere white dwarf ("hot DQ") stars. On the basis of our theoretical calculations, the star SDSS J142625.71+575218.3 is the only object expected to pulsate. We observe this star to be variable, with significant power at 417.7 s and 208.8 s (first harmonic), making it a strong candidate as the first member of a new class of pulsating white dwarf stars, the DQVs. Its folded pulse shape, however, is quite different from that of other white dwarf variables and shows similarities with that of the cataclysmic variable AM CVn, raising the possibility that this star may be a carbon-transferring analog of AM CVn stars. In either case, these observations represent the discovery of a new and exciting class of object.

Subject headings: stars: evolution — stars: oscillations — stars: variables: other — white dwarfs

1. THE ENIGMA OF HOT DQ WHITE DWARFS

White dwarfs (WDs) are the end stage of evolution for the vast majority of stars in the universe. As the cores of former stars, WDs provide crucial observational constraints on stellar evolutionary models. Traditionally, two classes of WD stars were known: those with hydrogen-rich atmospheres (spectral type DA) and those with helium-rich atmospheres (non-DA spectral types). Recently, Dufour et al. (2007) announced a new class of WD with carbon-dominated atmospheres, the "hot DQ" stars, several examples of which have been found in the Sloan Digital Sky Survey (Liebert et al. 2003).

The origin of single carbon-atmosphere WDs is very uncertain. One proposed scenario has hot DQ stars as the progeny of stars with masses of 9–11 $M_{\odot}$, massive enough to ignite carbon and form an oxygen-neon WD with a carbon-oxygen atmosphere (e.g., Garcia-Berro & Iben 1994; Garcia-Berro et al. 1997). Alternatively, the hot DQ WDs may arise from a particularly violent late thermal pulse that burns all the hydrogen and helium (e.g., Herwig et al. 1999).

White dwarf asteroseismology is a potential avenue for studying the parameters and interior structures of hot DQ stars, providing that *g*-mode pulsations can be detected. Such pulsations have been detected in DA, DB, and PG 1159 stars, and nonradial pulsations have led to detailed constraints on these stars (see the forthcoming review article of Winget & Kepler 2008).

In this Letter, we report on the discovery of pulsations in the carbon-atmosphere object SDSS J142625.71+575218.3 (hereafter SDSS J1426+5752) and give evidence showing that this object is either the first known "DQV" WD or the first known cataclysmic variable (CV) with a carbon-dominated spectrum. A bulletin announcing this discovery has been published (DeGennaro, Williams, & Montgomery 2008).

2. THE MOTIVATION FOR PULSATION

There are three known classes of WD pulsators, the DAV, the DBV, and the PG 1159 (DOV) stars. The DAVs have hydrogen-dominated spectra and pulsate at temperatures at which hydrogen is partially ionized ($T_{\rm eff} \sim 12{,}000$ K), while the DBVs have helium-dominated spectra and pulsate at temperatures at which helium is partially ionized ($T_{\rm eff} \sim 25{,}000$ K). Thus, it is natural to expect that the hot DQ stars, with carbon-dominated atmospheres, will also pulsate near a $T_{\rm eff}$ associated with a partial ionization state of carbon.

More precisely, WD pulsations are seen in instability strips, with a high-temperature boundary (the "blue edge") and a low-temperature boundary (the "red edge"). Theoretical calculations have traditionally been done for the blue but not the red edges of the two instability strips; the blue edge calculation is linear, whereas the cessation of pulsation at the red edge appears to be an intrinsically nonlinear effect. In this Letter we focus solely on the blue edge, since it is the most pertinent for our sample of stars.

Theory and observation have firmly established that surface partial ionization causes pulsations in WDs. A particular pulsation mode is driven locally when maximum pressure lags maximum density. In models this can happen in two qualitatively different ways: the operation of the κ-γ ("kappa-gamma") mechanism and "convective driving." The essential feature of both driving mechanisms is that the mode periods need to be of order the thermal timescale, $\tau_{\rm th}$, at the base of the partial ionization zone. In the κ-γ mechanism, driving occurs locally when the opacity varies so that a net amount of radiative flux is still flowing into a region at maximum compression. Early calculations of driving in WDs focused on this mechanism, mainly due to the difficulties associated with modeling time-dependent convection. These calculations yielded results in good agreement with the known pulsators and led to the prediction and subsequent discovery that DB stars pulsate (Winget et al. 1982). However, the κ-γ approach is not self-consistent, since it ignores the response of the convection zone to the pulsations, and the turnover times in the convection zones are of order seconds—short compared to the observed pulsation periods for nonradial *g*-modes.

Improving on this situation, Brickhill (1990) and later Goldreich & Wu (1999) developed an approach that self-consistently includes perturbations of the convective flux. The crucial insight is that the convection zone responds nearly instantaneously to the pulsations, so that it is always in hydrostatic equilibrium. While more physically sound, these calculations show that the relevant criterion for mode driving is similar to that

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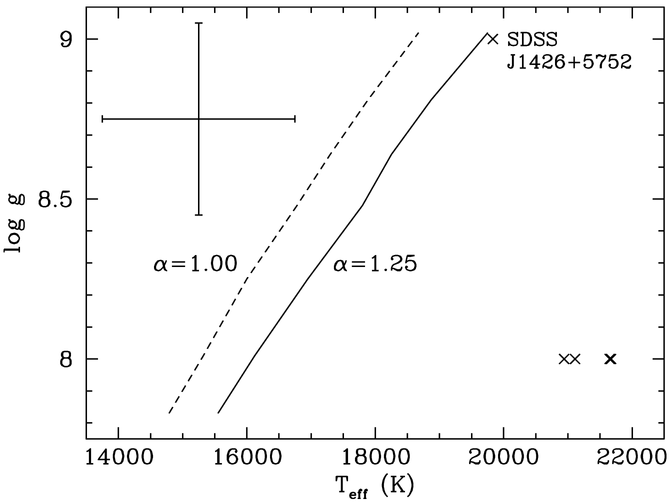

FIG. 1.—Plot of the theoretical blue edge of the carbon-rich instability strip in the $T_{\rm eff}$–log g plane, assuming ML2/α = 1.25 (*solid line*) and ML2/α = 1.00 (*dashed line*). The crosses give the current best estimates for the positions of the stars we observed based on the parameters in Dufour et al. (2008); in the upper left-hand corner we show a representative error bar for these stars.

of the κ-γ mechanism, namely, that the periods of driven modes be of order the convective response timescale τ_C, which itself is some multiple of $\tau_{\rm th}$. Thus, while predictions of the location of the blue edge of an instability strip move somewhat, generic features such as its mass dependence and the blue edge temperature boundaries are qualitatively unchanged. Furthermore, similar shifts in the position of the instability strip can be achieved through a different choice of α, the mixing length–to–scale height ratio, so there is not a clear predictive difference between the two mechanisms.

Since the two mechanisms make similar predictions, we defer further discussion of the detailed driving mechanism. We adopt the thermal timescale at the base of the convection zone as our diagnostic, and we assume that the blue edge corresponds to the point where $\tau_{\rm th} \sim 100$ s, since 100 s is at the lower end of the periods observed in pulsating white dwarfs.

In Figure 1 we show our calculation of the location of the blue edge of the instability strip for DQ WDs, as a function of $T_{\rm eff}$ and log g. The depth of a WD's convection zone also depends on the choice of the mixing length parameter α, and we show the results for two values of α: $\alpha = 1.25$ (*solid line*) is inferred from spectroscopic fits of DBs (Beauchamp et al. 1999), and $\alpha = 1.00$ (*dashed line*) is inferred from nonlinear light-curve fits to DBVs (Montgomery 2005, 2007). The range of log g chosen corresponds to models with masses from 0.5 to 1.2 $M_\odot$. The composition, from core to atmosphere, is assumed to be pure carbon. The stars in our sample are plotted as crosses in this figure; one star, SDSS J1426+5752, lies tantalizingly close to our theoretical blue edge.

3. OBSERVATIONS

Six hot DQ stars were well placed for observations during our observing run in early February of 2008. Time-series photometry of these stars were obtained on the nights of 2008 February 6–11 UT with the Argos high-speed photometer on the McDonald Observatory 2.1 m Otto Struve Telescope (Nather & Mukadam 2004). Other than SDSS J1426+5752, none of the WDs exhibited observable pulsations within the amplitude limits of our photometry (≈5 mma). These observations will be reported in a future paper.

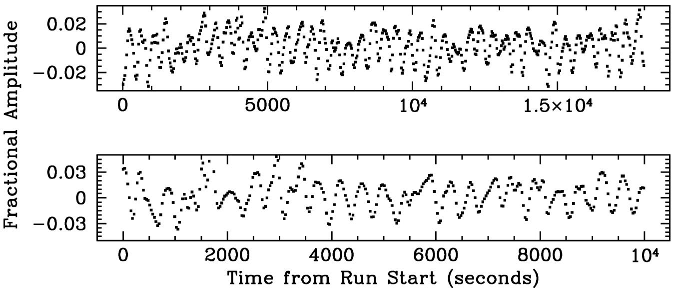

FIG. 2.—Time-series photometry for SDSS J1426+5752, from 2008 February 10 (*top panel*) and 2008 February 11 (*bottom panel*), Gaussian smoothed by 1.5 bins (45 s). The data between ~1200 and ~1800 s in the second night were affected by a passing cloud. Periodic pulsations are evident in the data from both nights.

Observations of SDSS J1426+5752 were obtained on the nights of 2008 February 10–11 UT. We obtained continuous time-series data for uninterrupted runs of 5.0 hr (February 10) and 2.8 hr (February 11). Exposure times were 30 s and taken through a Schott glass BG40 filter. The seeing ranged from 2″ to 3″, and transparency variations were minimal with the exception of a single passing cloud during the second night's run.

The photometric data were reduced with the methods and pipeline described in Mullaly et al. (2008). Light curves are shown in Figure 2. The pulsations are difficult to see in the raw data but readily observed when the data are smoothed with a Gaussian filter with $\sigma = 1.5$ bins (45 s).

4. ANALYSIS

In the upper panel of Figure 3 we present the discrete Fourier transform (FT) of the unsmoothed combined data set. It shows a single pulsational period of 417.66 s (2394.27 μHz) as well as the first harmonic of this peak (208.82 s). There is also a hint of power around 12000 μHz, which is near the fourth harmonic of the main frequency, though it may also be a signature of periodic drive or encoder errors. After prewhitening by the two main periodicities, no other pulsational frequencies are observed with an amplitude higher than 3.5 mma (lower

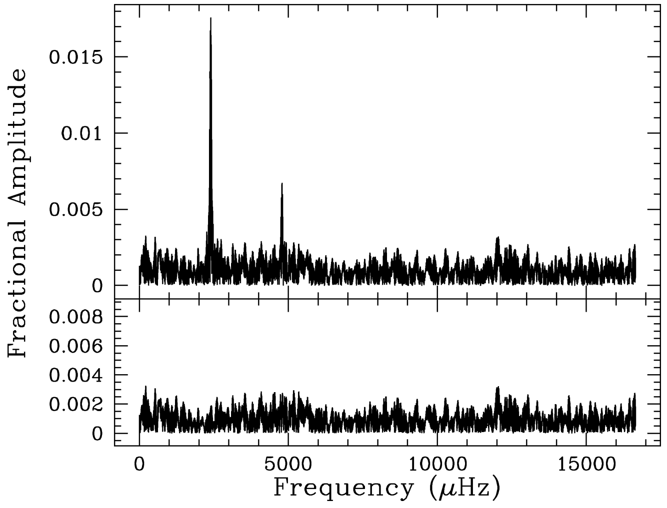

FIG. 3.—*Top panel:* Fourier transform of the two nights of data on SDSS 1426+5752. The dominant features in the FT are the main mode at 417.66 s and its first harmonic. *Lower panel:* Fourier transform after prewhitening by the main mode and its first harmonic.

TABLE 1
Frequency Solution for SDSS J1426+5752

Frequency (μHz)	Amplitude (mma)	Phase
Combined data set:		
2394.27 ± 0.19	17.54 ± 0.82	1.00 ± 0.01
4788.82 ± 0.49	6.67 ± 0.82	0.30 ± 0.02
12053.41 ± 1.02	3.20 ± 0.82	0.40 ± 0.04
First night:		
2393.25 ± 1.60	16.11 ± 0.84	0.97 ± 0.05
4787.63 ± 3.91	6.58 ± 0.84	0.26 ± 0.12
12056.99 ± 17.46	1.47 ± 0.84	0.52 ± 0.52
Second night:		
2393.06 ± 4.61	20.07 ± 1.68	0.06 ± 0.25
4766.32 ± 12.25	7.51 ± 1.68	0.48 ± 0.65
12044.79 ± 14.39	6.42 ± 1.68	0.85 ± 0.77

panel in Fig. 3). We note that these periods are consistent with those seen in other white dwarfs with *g*-mode pulsations.

In Table 1 we summarize frequency fits of this data, for both the combined data set and the individual nights. We have included the main periodicity and its harmonic in these fits, as well as one at 12053.41 μHz. This last frequency was chosen because it is the highest in this region of the FT, but due to aliasing another nearby peak in the FT may be the true frequency. More data are needed to determine the frequency more accurately.

Notice that the frequencies, amplitudes, and phases are broadly consistent within the errors; this, together with the successful prewhitening, shows that these modes were coherent across the 2 day baseline. We note that the amplitude of the ~12050 μHz mode changed significantly between the two nights, being much larger the second night, and that the frequency of the ~4790 μHZ mode was ~2 σ lower the second night than the first.

Since the light curve of this object is dominated by one frequency, we have computed a pulse shape by folding the data at a periodicity of 417.66 s (see Fig. 4). This unusual pulse shape is produced mainly by the presence of first and fourth harmonics. While the first harmonic could be due to "normal" nonlinear processes, such as a varying convective response (e.g., Montgomery 2005) or bolometric flux corrections (e.g., Montgomery 2008; Brassard et al. 1995), the lack of second and third harmonics is puzzling.

In the lower panels of Figure 4 we show the pulse shapes of the only known single-mode WD pulsators with stable oscillation spectra, the DAV GD 154 and the DBV PG 1351+489. Even without the fourth harmonic (e.g., see top panel in Fig. 4, when this harmonic had a small amplitude), the pulse shape of SDSS J1426+5752 looks different from those of other stars. This is because the *phase* of the first harmonic is such that it makes the peaks lower and the valleys deeper. In a typical WD pulsator, the phase of the first harmonic makes the peaks higher and the valleys shallower.

While unlike that of known WD pulsators, the pulse shape of SDSS J1426+5752 *is* similar to one observed in a different type of object. In the bottom panel of Figure 4, we show a folded light curve from the object AM CVn (=HZ 29), a cataclysmic variable with a low-mass, presumably degenerate, helium star transferring mass to a white dwarf. The similarity to SDSS J1426+5752 is striking and serves to muddy the interpretation of this object. However, it should be noted that the pulse shape of AM CVn varies significantly, and at other epochs the similarities are not nearly as pronounced (e.g., see Provencal et al. 1995).

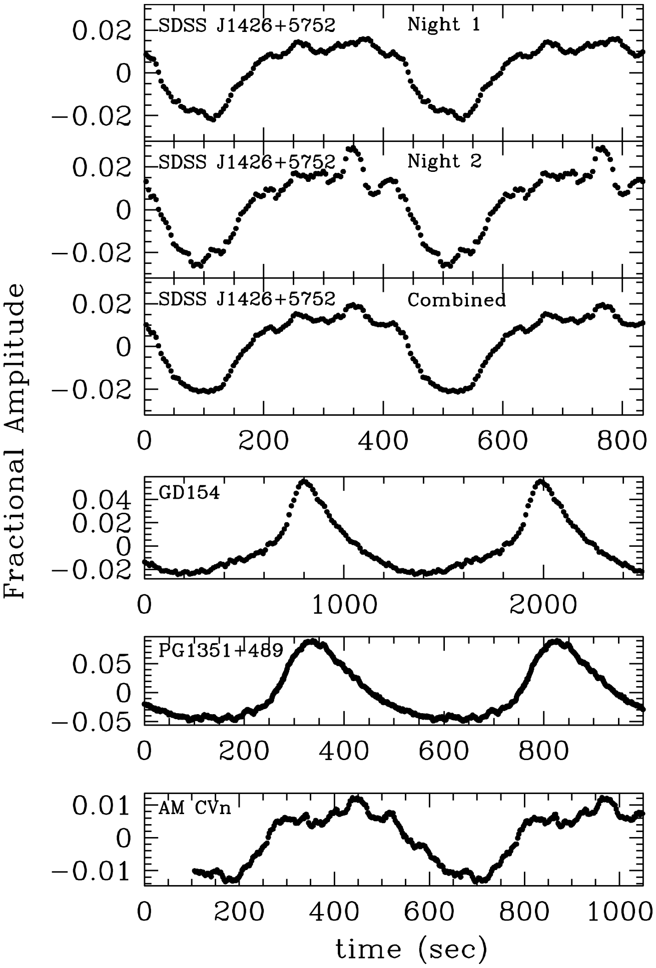

Fig. 4.—The top three panels are the light curve of SDSS J1426+5752 folded at a period of 417.66 s; the panels show the pulse shapes of the first night, second night, and both nights combined. For comparison, the bottom three panels show the pulse shapes of the DAV GD 154, the DBV PG 1351+489, and the CV AM CVn (HZ 29), respectively.

4.1. *A New Class of Pulsator?*

SDSS J1426+5752 may be the first of a new class of pulsating carbon-atmosphere WDs, the DQVs. These observations were motivated by theoretical calculations (see Fig. 1) that indicated that it was the only member of our sample of six hot DQ stars that should pulsate, and it *is* the only one found to vary. Its spectrum is consistent with that of a single, massive carbon-atmosphere white dwarf (Dufour et al. 2008). Given these facts, it seems natural to conclude that SDSS J1426+5752 is a member of a new class of WD pulsators.

At present, the *only* difficulty with the pulsator interpretation is the pulse shape, unique among the pulsating WD stars. If it really is a WD pulsator, then the modes with frequencies near the first and fourth harmonics must be independent pulsation modes and therefore free to have arbitrary phases. The reason these modes are excited would then be due to a parametric resonance with the main mode (e.g., see Goupil & Buchler 1994). The likelihood of resonances is increased by the high mass of this star (as preferred by the spectral models), since the density of modes increases with the mass of the star. Further, there is some evidence in the light curve of beating with a period of ~4000 s, though the noise level prevents meaningful conclusions about the reality of a mode with this frequency separation. We await further observations.

4.2. *An Interacting Double Degenerate?*

A few characteristics of SDSS J1426+5752 are similar to AM CVn stars. The light curves of several AM CVn systems show periodic variations consistent with a fundamental frequency and multiple harmonics. The folded light curve of AM CVn itself is qualitatively similar to that of SDSS J1426+5752 (see Fig. 4 and Provencal et al. 1995). This opens the possibility that SDSS J1426+5752 may be an AM CVn–like system, but with a carbon-dominated donor star. Such a system could make a compelling Type Ia supernova progenitor, depending on the total system mass.

In this scenario, SDSS J1426+5752 is a binary system consisting of two carbon-oxygen WDs, driven close together by gravitational radiation until mass transfer initiated, so the observed spectrum would be from an optically thick carbon-oxygen accretion disk around the more massive WD star. The spectra of high-state AM CVn systems show broad absorption features from an optically thick disk (e.g., Warner 1995), which would mimic high log *g* such as that claimed for SDSS J1426+5752.

However, models of mass transfer between two carbon-oxygen WDs suggest that the secondary star is disrupted in only a few dynamical times and would not evolve into an AM CVn–like system (e.g., Benz et al. 1990; Rasio & Shapiro 1995). And although a thick accretion disk may possibly remain around the primary WD for $\sim 10^6$ yr after the disruption of the secondary (Piersanti et al. 2003), the observed harmonics (explained in AM CVn systems as disk ellipticities, precession, and bright spots) would be hard to explain without a companion. Further, oxygen, which should be present in this scenario, has not yet been detected in the hot DQs, although the oxygen abundance limits are weak.

5. CONCLUSIONS

We have conducted a search for pulsations in six of the recently discovered DQ stars (Dufour et al. 2007). On the basis of our theoretical calculations, the star SDSS J1426+5752 was the only object predicted to pulsate, and it *is* the only target observed to be variable. This is a strong argument that SDSS J1426+5752 is the first member of a new class of pulsating white dwarf stars, the DQVs.

Another possibility, however, is that SDSS J1426+5752 is a carbon analog of an AM CVn system. Currently, the only evidence in favor of this model is the similarity of its pulse shape with AM CVn; we consider this possibility less likely.

How can we distinguish between these models? Signatures of disk activity, such as flickering on very short timescales, and radial velocity variations in the observed spectra were necessary to determine the nature of AM CVn. Additional observations, both time-series photometry and higher-quality spectra, are therefore necessary to determine if this system is an interacting binary.

Both of these possibilities imply that SDSS J1426+5752 is a prototype for a new class of white dwarf: either a pulsating carbon-atmosphere white dwarf or a carbon-dominated AM CVn–like system. The former would signal the discovery of a new class of pulsating WD, the first in over 25 years, while the latter could be a compelling candidate for a Type Ia supernova progenitor. We will continue the search for other objects of this exciting and enigmatic class.

M. H. M., K. A. W., and S. D. are grateful for the financial support of the National Science Foundation, under awards AST-0507639, AST-0602288, and AST-0607480, respectively; J. L. and P. D. are grateful for the support of NSF award AST-0307321. M. H. M. gratefully acknowledges the support of the Delaware Asteroseismic Research Center. D. E. W. is a fellow of CNPq, Brasil, and gratefully acknowledges their support. P. D. acknowledges the financial support of NSERC. The authors are grateful to R. E. Nather and A. Mukadam for the development and testing of the Argos instrument and to F. Mullally for developing the data analysis pipeline used here.

Facilities: Struve(Argos)

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