FOLLOW-UP OBSERVATIONS OF THE SECOND AND THIRD KNOWN PULSATING HOT DQ WHITE DWARFS

P. Dufour1,2, E. M. Green1, G. Fontaine3, P. Brassard2, M. Francoeur2, and M. Latour2

1 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA; dufourpa@astro.umontreal.ca, bgreen@as.arizona.edu
2 Département de Physique, Université de Montréal, Montréal, QC H3C 3J7, Canada; fontaine@astro.umontreal.ca, brassard@astro.umontreal.ca,
myriam@astro.umontreal.ca, marilyo@astro.umontreal.ca

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ABSTRACT

We present follow-up time-series photometric observations that confirm and extend the results of the significant discovery made by Barlow et al. that the Hot DQ white dwarfs SDSS J220029.08−074121.5 and SDSS J234843.30−094245.3 are luminosity variable. These are the second and third known members of a new class of pulsating white dwarfs, after the prototype SDSS J142625.71+575218.3. We find that the light curve of SDSS J220029.08−074121.5 is dominated by an oscillation at 654.397 ± 0.056 s, and that the light pulse folded on that period is highly nonlinear due to the presence of the first and second harmonic of the main pulsation. We also present evidence for the possible detection of two additional pulsation modes with low amplitudes and periods of 577.576 ± 0.226 s and 254.732 ± 0.048 s in that star. Likewise, we find that the light curve of SDSS J234843.30−094245.3 is dominated by a pulsation with a period of 1044.168 ± 0.012 s, but with no sign of harmonic components. A new oscillation, with a low amplitude and a period of 416.919 ± 0.004 s, is also probably detected in that second star. We argue, on the basis of the very different folded pulse shapes, that SDSS J220029.08−074121.5 is likely magnetic, while SDSS J234843.30−094245.3 is probably not.

Key words: stars: atmospheres – stars: evolution – stars: individual (SDSS J2200−0741, SDSS J2348−0943) – stars: oscillations – white dwarfs

1. INTRODUCTION

The existence of a new class of luminosity-variable white dwarfs was confirmed recently by the very important contribution of Barlow et al. (2008) who reported on their discovery of periodic variations in the light curves of two carbon-atmosphere (Hot DQ) stars from the Sloan Digital Sky Survey. This followed the initial discovery of Montgomery et al. (2008) that the Hot DQ white dwarf SDSS J142625.71+575218.3 (hereafter SDSS J1426+5752) shows luminosity variations dominated by a periodicity at 417.7 s along with its first harmonic. That harmonic proved remarkable in that it reached the unusually high amplitude of some 40% of that of the main oscillation. During an engineering run, Barlow et al. (2008) used the Goodman Spectrograph in imaging mode at the 4.1 m SOAR Telescope to monitor in broadband the light curves of two Hot DQ stars not previously investigated by Montgomery et al. (2008). The latter had found one variable star out of a sample of six objects of this kind. On the basis of 5.80 hr of observations, Barlow et al. (2008) found that SDSS J220029.08−074121.5 (hereafter SDSS J2200−0741) shows similar properties with SDSS J1426+5752 in that it displays a light curve dominated by a main oscillation plus its first harmonic. The main oscillation in SDSS J2200−0741 was determined to have a period of about 656 s, and the amplitude of its first harmonic, even more unusually, is nearly comparable to that of the dominant periodicity. Barlow et al. (2008) also found, on the basis of a further 4.71 hr of observations, a significant variation with a period of about 1052 s in the light curve of SDSS J234843.30−094245.3 (hereafter SDSS J2348−0943), but with no sign of a strong harmonic or other periodicities within their detection limit.

The results of Barlow et al. (2008), combined with that of Montgomery et al. (2008), indicate that three Hot DQ white dwarfs, out of a total of eight investigated so far, show periodic luminosity variations. These targets all come from the very small family of nine Hot DQ stars found previously by Dufour et al. (2007, 2008c) in a sample of nearly 10,000 spectroscopically identified white dwarfs. The Hot DQ stars form a newly discovered and exceedingly rare type of white dwarfs. The preliminary atmospheric analysis carried out by Dufour et al. (2008a) indicates that all the Hot DQ white dwarfs fall in a narrow range of effective temperature, between about 18,000 K and 24,000 K, and that they have atmospheric carbon-to-helium number ratios ranging from 1 to upward of 100. Depending on the exact values of the effective temperature, surface gravity, and envelope/atmosphere chemical composition, Fontaine et al. (2008) demonstrated that low-order and low-degree gravity-mode oscillations could be excited in models of Hot DQ stars in a way very similar to what is encountered in pulsating white dwarfs of the V777 Her and ZZ Ceti types. Pulsational instabilities thus provide a most natural explanation for the luminosity variations seen in some of the Hot DQ stars (and see Fontaine et al. 2009 for more details).

Montgomery et al. (2008) also proposed pulsational instabilities as their preferred explanation for the luminosity variations observed in SDSS J1426+5752, but they alternatively suggested that these variations could be associated with photometric activity in a carbon analog of AM CVn, the prototype of the helium-transferring cataclysmic variables (see, e.g., Warner 1995 on the properties of AM CVn systems). This was based on the observation that the light curve of SDSS J1426+5752 folded on the dominant periodicity of 417.7 s resembles that of AM CVn itself, exhibiting a flatter maximum than minimum, which is the opposite of what is seen in large amplitude pulsating white dwarfs. The first harmonic in a large amplitude pulsating white dwarf is quite generally nearly in phase with the main mode at light maximum, while it tends to be in antiphase in SDSS J1426+5752 and in AM CVn systems, thus producing the different pulse shapes. We note that Barlow et al. (2008) invoked this pulse shape argument again in their paper, arguing that pulsational instabilities are not necessarily to be preferred over the
interacting binary hypothesis as an explanation for the luminosity variations seen in the variable Hot DQ stars. However, in the meantime, Green et al. (2009) have presented a detailed analysis based on follow-up photometric and spectroscopic observations of SDSS J1426+5752. At the end of their exercise, they unequivocally ruled out the interacting binary hypothesis and concluded instead that, indeed, the luminosity variations seen in SDSS J1426+5752 are caused by g-mode pulsations as in other pulsating white dwarfs. Since their results can readily be generalized to other variable Hot DQ stars, from now on we consider variability in these stars to be caused by pulsational instabilities.

In this paper, we present the results of follow-up CCD photometry in integrated light gathered at the Steward Observatory 1.55 m Kuiper Telescope for both SDSS J2200−0741 and SDSS J2348−0943. Given the importance of the findings of Barlow et al. (2008) in the establishment of a new class of pulsating stars, we felt that rapid confirmation of their results should be given high priority. We thus carried out our observations as soon as we could after learning of the Barlow et al. (2008) results through collaborators. Despite the relative faintness of the target stars, $g = 17.70$ for SDSS J2200−0741 and $g = 19.00$ for SDSS J2348−0943, we were able to collect quite useful data. We present our analysis of these data in what follows.

2. SDSS J2200−0741

2.1. Observations

We followed the same procedure as that described in Green et al. (2009) for their follow-up photometric observations of SDSS J1426+5752. Hence, we used the Kuiper/Mont4K combination\(^3\) to gather some 13.29 hr of time-series observations over a baseline of 52.37 hr (three consecutive nights). The observations were taken on dark nights through a broadband Schott 8612 filter, and an effective exposure time of 65 s (on average) was used as a compromise between the signal-to-noise ratio ($S/N$) and the need to adequately sample the luminosity variations reported by Barlow et al. (2008). The data set we obtained for SDSS J2200−0741 is characterized by a formal temporal resolution of 5.30 $\mu$Hz and a duty cycle of 25.4%. Details of the observations are provided in Table 1.

Figure 1 shows the three nightly light curves that were obtained. The original images were reduced using standard IRAF photometric reduction tasks. We set the photometric aperture size individually for each frame to two times the FWHM in that image, and computed differential light curves of SDSS J2200−0741 relative to the average of three suitable comparison stars well distributed around the target. Final detrending of the effects of differential extinction was made through spline fitting. A zoomed-in view of the light curve gathered on 2008 September 4 is provided in Figure 2. Given the magnitude of the target ($g = 17.70$) and the small aperture of the Kuiper Telescope, the overall quality of the light curves is gratifying. We attribute this to the excellent sensitivity of the CCD, the relatively symmetrical distribution of the reference stars on the sky, and our optimized data pipeline. Without even the benefit of folding, Figures 1 and 2 clearly reveal that the light curve of SDSS J2200−0741 has flatter maxima than minima. This is similar to the behavior of SDSS J1426+5752, as already pointed out by Barlow et al. (2008).

2.2. Frequency Analysis

The time-series photometry gathered for SDSS J2200−0741 was analyzed in a standard way using a combination of Fourier analysis, least-squares fits to the light curve, and prewhitening techniques (see, e.g., Billeres et al. 2000 for more details). Figure 3 shows the Fourier amplitude spectrum of the full data set in the 0−7.5 mHz bandpass (upper curve) and the resulting transforms after prewhitening of two (middle curve) and four frequency peaks (lower curve). Our results reveal that the light curve of SDSS J2200−0741 is dominated by an oscillation with a period of around 654.4 s along with its first harmonic at 327.2 s. The harmonic has an amplitude of nearly 82% of that of the main oscillation, which readily explains the highly nonlinear shape of the light pulses seen in Figures 1 and 2. This is in excellent agreement with, and thus provides a confirmation of, the findings of Barlow et al. (2008). In addition, our higher S/N data also suggest the possible presence of two additional oscillations with low amplitudes and periods of around 577.6 s and 254.7 s, as can be seen in Figure 3. These are not harmonically related to the main pulsation. It is also quite likely that there are additional frequency components in the light curve of SDSS J2200−0741, but we could not detect them due to the finite sensitivity of our observations.

The results of our frequency analysis are summarized in Table 2, where we list the basic characteristics of the four oscillations that we isolated. In addition, Table 2 gives the derived parameters of the second harmonic (218.1 s) of the main periodicity, an oscillation that we uncovered after the fact (see below). Note that the phase given in the table is relative

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\(^3\) Please consult the following Web site: http://james.as.arizona.edu/~psmith/61inch/instruments.html for more details, if interested.

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### Table 1

| Date (UT) | Start of Run (HJD2454710+) | Number of Frames | Length (s) |
|-----------|---------------------------|------------------|------------|
| 2008 Sep 3 | 2.7018786                 | 249              | 16,089     |
| 2008 Sep 4 | 3.7084887                 | 240              | 15,433     |
| 2008 Sep 5 | 4.6947030                 | 254              | 16,337     |

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![Figure 1](image-url) All light curves obtained for SDSS J2200−0741 using the Mont4K CCD camera mounted on the Steward Observatory 1.55 m Kuiper telescope. The data have been shifted arbitrarily along the x- and y-axes for visualization purposes. They are expressed in units of fractional brightness intensity and seconds. From top to bottom, the curves refer to the nights of UT 2008 September 3, September 4, and September 5. For details, see Table 1.

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Figure 2. Expanded view of the light curve of SDSS J2200−0741 obtained on 2008 September 4. The units are the same as those used in Figure 1. One can clearly see that the minima are generally sharper than the maxima.

Figure 3. Fourier transform of the entire data set in the 0–7.5 mHz range (upper curve). The lower transforms show the successive steps of prewhitening by the two strongest frequencies (the 654.397 s peak and its first harmonic), and finally by all four frequencies that we isolated. The dotted vertical line segment associated with the lower curve indicates the location of the second harmonic of the main periodicity.

Table 2
Harmonic Oscillations Detected in the Light Curve of SDSS J2200−0741

| Period (s)  | Frequency (mHz) | Amplitude (%) | Phase (s)  |
|------------|-----------------|---------------|------------|
| 654.397 ± 0.056 | 1.5281 ± 0.0001 | 0.800 ± 0.036 | 418.7 ± 4.8 |
| 327.218 ± 0.017 | 3.0560 ± 0.0002 | 0.655 ± 0.036 | 254.3 ± 2.9 |
| 218.097 ± 0.052 | 4.5851 ± 0.0011 | 0.096 ± 0.036 | 201.0 ± 13.2 |
| 577.576 ± 0.226 | 1.7314 ± 0.0007 | 0.155 ± 0.036 | 134.7 ± 21.7 |
| 254.732 ± 0.048 | 3.9257 ± 0.0007 | 0.145 ± 0.036 | 135.9 ± 10.2 |

When we computed this mean value from the residual Fourier transform (the lower curve in Figure 3), the mean noise level in the 0–7.5 mHz interval turned out to be 0.045% of the mean brightness of the star.

Given this noise value, and following standard procedure, our possible detection of the low amplitude 577.6 s periodicity can be seen as a 3.4σ (0.155/0.045) result. An evaluation of the false alarm probability following the method of Kepler (1993) indicates that there is a ~9.9% chance that this frequency peak is due to noise, a nonnegligible value. Likewise, our possible detection of the 254.7 s periodicity is a 3.2σ (0.145/0.045) result. In that case, the false alarm probability rises to ~27.1%, making the detection even more insecure. However, we note that, outside the very low frequency regime, only these two peaks have amplitudes larger than three times the mean noise level in the Fourier spectrum given by the middle curve in Figure 3. We also point out that there is a low amplitude peak at ~3.85 mHz in the Fourier spectrum shown by Barlow et al. (2008) in their Figure 2 that could be identified with our 254.7 s periodicity, although is not possible to infer the same for the 577.6 s oscillation because it is embedded in the sidelobe structure of the dominant mode in their transform (assuming that it is also present in their data).

2.3. Amplitude and Phase Variations

We investigated the stability of the amplitude and phase of the dominant oscillation (654.4 s) and of its first harmonic.
(327.2 s) by performing nightly measurements. A clue about possible amplitude variations on a daily timescale is first provided by Figure 4, in which we show a montage of the nightly Fourier amplitude spectra. Although the amplitude of the first harmonic (3.0560 mHz; 327.218 s) does not change significantly as can be judged by the eye, that of the main mode (1.5281 mHz; 654.397 s) clearly varies in relation to the harmonic. For instance, on September 5, the amplitude of the main mode and that of its first harmonic are about equal, while the main mode dominates for the two other nights. Interestingly, similar variations in the amplitude of the main mode are also suggested in the results of Barlow et al. (2008, see their Table 2). In Figure 4, we further indicate the locations of the two other potential periodicities at 577.6 s and 254.7 s, but their amplitudes are so low that possible variations are lost in the noise.

A more quantitative and standard way of measuring the nightly amplitudes and phases is to fix the periods at their values given in Table 2 and simultaneously perform least-squares sine fits with these periods for each nightly run. The outputs are nightly amplitudes and phases with formal estimates of their uncertainties. It is interesting to point out that the formal estimates of the uncertainties on the amplitudes and phases that came out of our least-squares exercise were, again, essentially the same as those obtained through the method of Montgomery & O’Donoghue (1999), which we explicitly used after the fact as a verification.

Figure 5 summarizes our results in the case of the main periodicity found in the light curve of SDSS J2200−0741. The upper panel in the figure displays the amplitudes of the 654.397 s peak along with their formal 1σ uncertainties for the three nightly runs. The central dotted horizontal line represents the weighted average of the nightly amplitudes and the horizontal lines above and below the average value give the 1σ uncertainty on that value. Likewise, the lower panel illustrates the behavior of the phase. In the latter case, the average value was shifted to zero (since the phase is arbitrary) and ultimately expressed in units of cycle. The equivalent results for the 327.218 s peak are displayed using the same format in Figure 6. As expected, the uncertainties on the amplitudes for a given night are essentially independent of the amplitudes themselves, while the uncertainties on the phases increase with decreasing amplitudes. This is clearly demonstrated by comparing the two figures.

Quite unfortunately, no firm conclusions can be drawn from Figures 5 and 6 about possible amplitude and phase modulations in the light curve of SDSS J2200−0741 on timescales of days, if we take the quantitative results at face value. There is, however, a strong suggestion of, at least, amplitude variation of the main mode, in accordance with the qualitative picture that can be obtained from the nightly Fourier transforms as depicted in Figure 4. These variations in amplitude are probably real, but they need to be confirmed with higher sensitivity measurements. Comparing Figure 5 with Figure 6, there is also the weaker (but interesting) suggestion that the amplitude and phase behaviors of the dominant periodicity may be anticorrelated with those of its first harmonic. Clearly, however, a longer observational campaign on SDSS J2200−0741 is badly needed to progress on that front.

2.4. Pulse Shape

Following the remarks of Montgomery et al. (2008) on the pulse shape in the light curve of SDSS J1426+5752 and similar observations made by Barlow et al. (2008) about SDSS J2200−0741 and SDSS J2348−0943, we found it instructive to further investigate the question with the help of our data set. Hence, we show in the top panel of Figure 7 our 13.29 hr long light curve of SDSS J2200−0741 folded on the main period of 654.397 s. To reach a decent S/N, we distributed the folded amplitudes in 10 different phase bins, each containing 74 points on average. The error bars about each point in the folded light
curve correspond to the errors of the mean in each bin. Given that the first harmonic of the 654.397 s mode in the light curve has a very high amplitude, about 82% of that of the main peak (see Table 2), it is not surprising that the pulse shape illustrated in the top panel of Figure 7 is highly nonlinear. This behavior is very similar to that observed in SDSS J1426+5752, as can be seen in Figure 7 of Green et al. (2009), but is even more extreme here due to the higher relative value of the amplitude of the first harmonic. In neither case does the folded light pulse resemble those of typical large amplitude pulsating white dwarfs (and see Montgomery et al. (2008) and Green et al. (2009) for specific examples).

In the middle panel of Figure 7, we again display our folded light curve of SDSS J2200−0741, but only after having prewhitened the data of the first harmonic component (327.218 s) of the main periodicity. If higher order harmonics have negligible amplitudes, and if other modes do not interfere in the folding process, the pulse shape in the middle panel should be that of a perfect sinusoid with an amplitude equal to that of the 654.397 s oscillation described in Table 2. Contrary to what Green et al. (2009) found for SDSS J1426+5752 (see their Figure 7), the match between the observed points and the 654.397 s sinusoid (dotted curve) is less than perfect here. The simplest interpretation is that higher order terms have nonnegligible effects on the folded pulse shape, and thus we actively sought for evidence of the presence of the second harmonic of the main mode as described below.

In the lower panel, we plotted the same template (dashed curve) corresponding to the 654.397 s sinusoid. Properly taking into account the phase difference, we also plotted a sinusoid (dotted curve) with the defining characteristics of the 327.218 s periodicity as given in Table 2. The sum of these two sine waves gives the solid curve, the overall nonlinear pulse shape associated with the 654.397 s oscillation. We replotted this model pulse shape in the upper panel of Figure 7 (now as a dotted curve) so that a direct comparison can be made with the observations. Again, the agreement is less than perfect and could be improved as some of the points fall off the template.

To follow up on this idea of improving the model pulse shape, we went back to the Fourier transform and searched for the possible presence of the second harmonic of the main pulsation. This oscillation would necessarily have a lower amplitude than three times the mean noise level since we did not pick it up in our initial frequency analysis. In this context, Figure 8 shows the Fourier amplitude spectrum of our light curve of SDSS J2200−0741 in the immediate vicinity of where the second harmonic of the 654.397 s periodicity should be, if present with some amplitude. The two vertical lines define the ±3σ frequency range in which the second harmonic should occur. Specifically, this range is defined by 3 × 1.52813 ± 3 × (3 × 0.00013) mHz (see Table 2). As can be seen in the figure, there is a peak with an amplitude slightly less than 0.1% that falls in this narrow frequency interval. (See also the dotted vertical line segment in Figure 3 which indicates the position of this peak on another scale.) It has a measured frequency (period) of 4.5851 mHz (218.097 s). As before, we least-squares fitted a sine wave with that frequency to our observational data and

![Figure 6](image1.png)

**Figure 6.** Similar to Figure 5, but for the 327.218 s periodicity.

![Figure 7](image2.png)

**Figure 7.** Top panel: light curve of SDSS J2200−0741 folded on the period of 654.397 s and distributed in 10 phase bins (points with error bars), each of which contains 74 points, on average. The dotted curve is a model pulse shape obtained by summing two sinusoids with the periods, amplitudes, and phases of the 654.397 s periodicity and of its first harmonic (327.218 s) as listed in Table 2. Middle panel: light curve of SDSS J2200−0741 folded on the period of 654.397 s and distributed in 10 phase bins after prewhitening of the first harmonic component. The dotted curve is a pure sine wave computed using the period, amplitude, and phase of the dominant 654.396 s periodicity. Bottom panel: the dotted curve is a pure sinusoid computed with the period, amplitude, and phase of the 327.218 s harmonic; the dashed curve is a pure sine wave computed using the period, amplitude, and phase of the dominant 654.397 s periodicity (this is the same as the dotted curve in the middle panel); the solid curve is the sum of these two sinusoids and corresponds to the model pulse shape represented by the dotted curve in the top panel.
obtained the parameters given in Table 2. A statistical analysis would no doubt reveal that the chance occurrence of a peak with an amplitude of ~0.1% (2.1 times the mean noise level) falling within 2.3 μHz (the formal resolution is 5.3 μHz) of its expected position is quite small. However, in view of the results that we obtained, we felt that such an analysis would be redundant.

Indeed, Figure 9 is a remake of Figure 7, except that, this time, the effects of the newly found 2.1σ peak—interpreted as the true second harmonic—are taken into account. In the middle panel, the data points correspond to the folded light curve after prewhitening the contributions of the first (327.218 s) and second (218.097 s) harmonic of the main mode. This time, the data points fall much closer to the 654.397 s sinusoid template. Likewise, our new model pulse shape (dotted curve in the upper panel of Figure 9) is significantly improved at the qualitative level compared to our initial attempt displayed in the upper panel of Figure 7. In addition, it is revealing to point out, from the lower panel of Figure 9, that at phase 1.0, the first harmonic is in antiphase with the main 654.397 s periodicity, while the second harmonic is in phase. This argues strongly against the notion that the 218.097 s peak seen in Figure 8 could be there by chance since its phase would presumably be a random value in that case. Together with the improvements in the model pulse shape, we take this phase correlation as convincing proofs that the second harmonic of the main periodicity has indeed been detected in our data set. It remains to be seen how the pulse shape of the main periodicity detected in the light curve of SDSS J2200−0741 can be explained and modeled in details. Along with the phase/antiphase behavior of its harmonic components, the amplitude hierarchy of 1.00:0.82:0.12 poses an interesting challenge to modelers.

3. SDSS J2348−0943

3.1. Observations and Frequency Analysis

We also carried out follow-up photometric observations of SDSS J2348−0943, the second variable star reported by Barlow et al. (2008), and the third known pulsating Hot DQ white dwarf. SDSS J2348−0943 is significantly fainter than SDSS J2200−0741 (g = 19.00 versus g = 17.70), and is not well located in the sky for observations taken at Mount Bigelow, since it transits in the bright Tucson sky to the south. Anticipating the need to build up sufficiently the S/N, we requested and were allocated 17 nights of observing time in the fall trimester of 2008. We were able to gather useful data during 10 of those nights. Table 3 gives the details. Altogether, we accumulated some 50.19 hr of observations over a moderately long timebase (1222 hr, from October 1 through November 21). This corresponds to a low duty cycle of 4.1%, but to a relatively high temporal resolution of 0.23 μHz. As before, all images were taken through a broadband Schott 8612 filter. An effective exposure time of about 69 s (on average) was chosen, and the large field of view of the Mont4K allowed us to use nine comparison stars for reduction purposes. This proved important for such a faint target embedded in a relatively bright background.

Figure 10 is a montage showing the 10 nightly light curves that were gathered. Naturally, the noise is substantially larger than what we obtained for the brighter SDSS J2200−0741 (see Figure 1), but the variability of SDSS J2348−0943 is nevertheless obvious in the plot. A zoomed-in view of the light curve gathered on 2008 October 28 is provided in Figure 11. In that case, the noise masks the pulse shape of any dominant periodicity. Following our standard approach, we were able to extract a significant pulsation and a probable one in the light curve of SDSS J2348−0943. Their characteristics are summarized in Table 4 where, this time, the phase refers to the beginning of the first run on UT 2008 October 1. The first
Figure 10. All light curves obtained for SDSS J2348−0943 using the Mont4K CCD camera mounted on the Steward Observatory 1.55 m Kuiper telescope. The data have been shifted arbitrarily along the x- and y-axes for visualization purposes. They are expressed in units of fractional brightness intensity and seconds. From top to bottom, the curves refer to the nights of UT 2008 October 1, October 2, October 27, October 28, October 29, October 30, October 31, November 1, November 2, and November 21. For details, see Table 3.

of these pulsations, the dominant one in amplitude, has a period of 1044.168 ± 0.012 s, and clearly corresponds to the single ∼1052 s oscillation reported by Barlow et al. (2008) in their paper. Our derived amplitude for that mode, 0.81 ± 0.07%, is also compatible with theirs. In addition, due to the higher sensitivity of our data set, we likely uncovered a new mode with a low amplitude and with a period of 416.919 ± 0.004 s which is not harmonically related to the first one. Interestingly, we found no sign of a strong first harmonic component of the main periodicity, contrary to what is seen in SDSS J1426+5752 and SDSS J2200−0741.

The upper curve in Figure 12 illustrates the Fourier amplitude spectrum of our entire data set in the 0–5 mHz bandpass. The other two transforms depict the prewhitening sequence. After removal of the two periodicities listed in Table 4, the mean noise level found in the residual transform (lower curve in Figure 12) corresponds to 0.088% of the mean brightness of the star. According to the standard criterion, this implies that the detection of the 416.919 s periodicity is a 0.362/0.088 = 4.1σ result. Taking into account the number of available frames, we estimate that the false alarm probability for that periodicity is ∼0.6%, sufficiently small in our view for claiming a probable detection. For its part, the 1044.168 s signal is a 9.2σ detection, its false alarm probability is virtually equal to zero, and there is no doubt at all about its reality. Finally, we wish to point out that the estimates of the uncertainties on the amplitudes and phases that we obtained from our least-squares exercise in the prewhitening process turned out to be about 10% smaller than the estimates based on the Montgomery & O’Donoghue (1999) method, contrary to what we found for the brighter SDSS J2200−0741, for which the two approaches gave identically the same results. We adopted the more conservative estimates based on the Montgomery & O’Donoghue (1999) method in the data reported in Table 4, but we also report in parentheses in that table the estimates based on the least-squares approach.

3.2. Amplitude and Phase Variations

In a similar manner as described above for SDSS J2200−0741, we investigated the possibility of detecting amplitude and phase modulations on timescales of days by making

| Date (UT) | Start of Run (HJD2454740+) | Number of Frames | Length (s) |
|-----------|--------------------------|------------------|------------|
| 2008 Oct 1 | 0.7893267               | 146              | 10,046     |
| 2008 Oct 2 | 1.6495160               | 322              | 22,157     |
| 2008 Oct 27 | 26.6075224             | 262              | 18,028     |
| 2008 Oct 28 | 27.5955684             | 294              | 20,230     |
| 2008 Oct 29 | 28.5830507             | 300              | 20,643     |
| 2008 Oct 30 | 29.5827912             | 296              | 20,368     |
| 2008 Oct 31 | 30.5891725             | 286              | 19,680     |
| 2008 Nov 1 | 31.5843403             | 288              | 19,817     |
| 2008 Nov 2 | 32.5902712             | 260              | 17,891     |
| 2008 Nov 21 | 51.5683732            | 172              | 11,835     |

Figure 11. Expanded view of the light curve of SDSS J2348−0943 obtained on 2008 October 28. The units are the same as those used in Figure 10.
Table 4
Harmonic Oscillations Detected in the Light Curve of SDSS J2348−0943

| Period (s) | Frequency (mHz) | Amplitude (%) | Phase (s) |
|-----------|----------------|--------------|-----------|
| 1044.168 ± 0.012 | 0.95770 ± 0.00001 | 0.812 ± 0.071 (0.065) | 879.3 ± 14.5 (13.0) |
| 416.919 ± 0.004 | 2.39855 ± 0.00002 | 0.362 ± 0.071 (0.065) | 250.6 ± 12.9 (11.9) |

Figure 12. Fourier transform of the entire data set in the 0–5.0 mHz range (upper curve). The lower transforms show the successive steps of prewhitening by the strongest frequency (the 1044.168 s peak), and by the two frequencies with statistically significant amplitudes.

Figure 13. Montage showing four of the nightly Fourier transforms. These are shifted arbitrarily along the y-axis for visualization purposes. The locations of the two detected frequencies are indicated by the vertical dotted lines. Amplitude variations are suggested.

nightly measurements. Before presenting the results of this exercise, we draw attention to Figure 13, which shows the Fourier transforms of four representative nights. This plot does suggest possible amplitude variations in the two modes that we have isolated. However, the level of noise in each nightly transform is rather high, which makes it difficult to be entirely convinced of the reality of these variations. We point out, however, that the light curve of SDSS J2348−0943 was completely flat as far as we could judge in real time at the telescope during the night of November 2. And indeed, the Fourier amplitude spectrum of that night (lower curve in Figure 13) is entirely consistent with noise. This was rather striking as we could always see some variations in real time during the other nights. And yet, there was nothing peculiar to report about the night of November 2 in terms of weather or equipment performance.

Figure 14 summarizes our results for the daily measurements of the amplitude and phase of the dominant 1044.168 s pulsation in the light curve of SDSS J2348−0943. The format is the same as that used in Figure 5 above. As before, we used the Montgomery & O’Donoghue (1999) method for estimating the uncertainties on the nightly values of the amplitude and phase. In the upper panel, there is a hint of amplitude variation, particularly over the seven consecutive nights from October 27 to November 2. As extreme cases, the amplitude of the 1044.168 s periodicity reached a maximum value of 0.939% ± 0.147% during the night of October 29, and it dropped to the smallest observed value of 0.343% ± 0.157% on November 2 when no obvious brightness variations could be seen at the telescope. In comparison, within the estimated uncertainties, the phase of the 1044.168 s oscillation appears fairly stable. We suspect that amplitude modulations on timescales of days probably occur for the 1044.168 s mode. Quite possibly, phase modulations also occur, but the accuracy with which the phase can be measured is insufficient to be certain.

In the case of the 416.919 s oscillation, as depicted in Figure 15, the amplitude appears not to vary significantly, but we note that the relative errors are huge. The results for the phase are more puzzling, but we suspect in this case that the formal uncertainties may have been underestimated. Certainly no firm conclusions can be drawn here. As discussed briefly below, there is interest in determining if, indeed, the pulsations in both SDSS J2200−0741 and SDSS J2348−0943 really display amplitude and phase variations. To reach that goal, higher sensitivity observations will need to be gathered. In the specific case of SDSS J2348−0943, a week of 4 m telescope time would probably be needed to derive nightly measurements with sufficient accuracy.

3.3. Pulse Shape

The question of the folded pulse shape in SDSS J2348−0943 has been raised by Barlow et al. (2008), and we return to it with the help of our higher sensitivity data set. Figure 16 shows our 50.19 hr long light curve of SDSS J2348−0943 folded on the main periodicity of 1044.168 s. In order to reach an adequate
Figure 14. Nightly measurements of the amplitude and phase of the 1044.168 s harmonic oscillation seen in SDSS J2348−0943.

Figure 15. Similar to Figure 14, but for the 416.919 s periodicity.

S/N, we distributed the folded amplitudes in 10 distinct phase bins, each containing 263 points on average. What Figure 16 reveals is that, within our measurement errors, the pulse shape of the 1044.168 s periodicity is perfectly linear, i.e., sinusoidal. This is in line with the fact that no harmonics of that oscillation have been detected in our data set. This is in marked contrast to what has been found in the light curves of both SDSS J1426+5752 (Montgomery et al. 2008; Green et al. 2009) and SDSS J2200−0741 (Barlow et al. 2008; this work) where the first harmonic boasts an amplitude that is a very large fraction of the amplitude of the main oscillation, thus producing a highly nonlinear pulse shape.

Given the fact that nonlinear pulse shapes have been found for the dominant mode in both SDSS J1426+5752 and SDSS J2200−0741, it becomes interesting to search for the possible presence of the first harmonic of the main oscillation, a harmonic that could perhaps be buried in the noise. This is similar in spirit to the procedure we followed above to uncover the second harmonic of the 654.397 s oscillation in SDSS J2200−0741. Our search is summarized in Figure 17 which shows the Fourier amplitude spectrum of our light curve of SDSS J2348−0943 in the immediate vicinity of where the first harmonic of the 1044.168 s periodicity should occur, if present with some amplitude. As in Figure 8, the two vertical lines define the ±3σ frequency range about the first harmonic. Specifically, this range is defined by 2 × 0.95770 ± 3 × (2 × 0.00001) mHz (see Table 4). Given that the resolution (0.23 μHz) in our SDSS J2348−0943 data set is much better than that (5.30 μHz) obtained in our shorter time series for SDSS J2200−0741, the accuracy achieved in frequency is noticeably higher, and this is reflected in the range of frequencies plotted in Figure 17 compared to the range illustrated in Figure 8. The frequency range ratio, 0.2:0.009, from Figure 8 to Figure 17, corresponds approximately to the resolution ratio, 5.30:0.23, between our two data sets. This was chosen in order to have approximately the same scale for the band of expected harmonic frequency in both figures.

Contrary to what was found in Figure 8, Figure 17 now reveals that there is no peak with any significant amplitude in the frequency interval where the first harmonic should be found. To be fair, there is a tiny peak with a formal least-squares amplitude of 0.043% ± 0.071%. This corresponds to a relative amplitude of about 5% of the amplitude of the 1044.168 s oscillation, but the uncertainties allow a “true” amplitude that could very well be close to zero. To reinforce this result, Figure 18 illustrates the outcome of another folding exercise in which our light curve of
SDSS J2348−0943, prewhitened of the two periodicities listed in Table 4, has been folded on the period (522.084 s) of the potential first harmonic. In sum, within the uncertainties, our data show no detectable sign of an oscillation at the frequency of the first harmonic of the main 1044.168 s mode, implying that the pulse shape of that mode must be sinusoidal. At most, the amplitude of such a harmonic could reach only a few percent of the amplitude of the main component, not nearly enough to distort the pulse shape to the extent seen in SDSS J1426+5752 and SDSS J2200−0741.

In view of this, we found the result of Barlow et al. (2008) on the pulse shape of SDSS J2348−0943 to be somewhat puzzling and worthy of further investigation. Indeed, in their Figure 5, these authors illustrate a nonlinear pulse shape for the 1044 s periodicity and use this, among other things, to argue against the pulsational instabilities interpretation. What is puzzling is how they could find a nonsinusoidal pulse shape in the absence of harmonics with significant amplitudes. In both our and their data sets, harmonics of the 1044 s oscillation have not been detected. In such circumstances, the folded light curve has to be an essentially perfect sinusoid, unless other modes interfere in the folding process. Such interference becomes possible, particularly for short runs, if the contributions of the other modes are not prewhitened before the folding process. Since Barlow et al. (2008) obtained only two rather short time series on SDSS J2348−0943 (7446 s on 2008 June 28 and 9520 s on 2008 July 31, according to their Table 1), this constitutes a clue on which to base a possible explanation for the small mystery posed by their Figure 5. We risk the suggestion that the nonsinusoidal pulse shape reported by Barlow et al. (2008) for the main oscillation seen in SDSS J2348−0943 is due to the combination of their short run and their neglect of the effects of the 416.919 s mode, and not to nonlinear effects.

4. DISCUSSION AND CONCLUSION

We have presented the results of follow-up photometric observations of SDSS J2200−0741 and SDSS J2348−0943 obtained in reaction to the discovery of Barlow et al. (2008) that those two Hot DQ stars display luminosity variations that are typical of g-mode oscillations in white dwarfs. Their discovery made these stars the second and third known specimens of a new class of pulsating white dwarfs after the GW Vir, V777 Her, and ZZ Ceti types (see, e.g., Fontaine & Brassard 2008), with SDSS J1426+5752 as the prototype (Montgomery et al. 2008). Our observations were gathered in integrated light using the Kuiper/Mont4K combination at the Steward Observatory Mount Bigelow Station. By gathering some 13.29 hr of photometry on SDSS J2200−0741 (g = 17.70) and some 50.19 hr on SDSS J2348−0943 (g = 19.00), we were able to reach a higher sensitivity than was possible in the discovery runs of Barlow et al. (2008).

Our results both reinforce and go beyond those of Barlow et al. (2008). We confirm that SDSS J2200−0741 has a light curve dominated by a periodicity at 654.397 ± 0.056 s along with its first harmonic (327.218 ± 0.017 s), in agreement with Barlow et al. (2008). The amplitude of the harmonic is unusually large—～82% of the amplitude of the main oscillation—for a pulsating white dwarf, and explains the highly nonlinear pulse shape of the light curve when folded on the main period of 654.397 s. In addition, we uncovered evidence for the presence of three new oscillations with low amplitudes, one being the second harmonic of the main oscillation, and two others not harmonically related to that same oscillation. Those two correspond, presumably, to two independent pulsation modes. The first one has a period of 577.576 ± 0.226 s and corresponds to a 3.4σ result, while the second one has a period of 254.732 ± 0.048 s and is a 3.2σ detection according to the standard criterion. Given that the false alarm probability is not negligible for these oscillations (～9.9% and ～27.1%, respectively), we consider these periodicities as possible detections only. Higher sensitivity observations are needed to confirm their reality. The characteristics of the five oscillations we isolated in SDSS J2200−0741 are summarized in Table 2.

We further confirm Barlow et al.’s (2008) result that the light curve of SDSS J2348−0943 is dominated by an oscillation with a period of 1044.168 ± 0.012 s (～1052 s in their data set). However, contrary to their findings, our light curve folded on the period of 1044.168 s shows no sign of nonlinearities. Within our measurement uncertainties, no oscillation is seen at that period.
the first harmonic of the main mode, but concluded that, if present at all, its amplitude could only reach a few percent of the amplitude of the 1044.168 s oscillation, quite insufficient to distort appreciably the folded light pulse. We also uncovered evidence for the presence of a new pulsation mode in SDSS J2348−0943, one with a period of 416.919 ± 0.004 s and a low amplitude corresponding to a 4.1σ detection according to the standard criterion. The false alarm probability in this case is estimated to be around 0.6%, sufficiently small for us to claim a probable detection. We suggest that the effects of that extra mode, not removed through prewhitening in the Barlow et al. (2008) data, combined with the short durations of their runs might be responsible for the nonsinusoidal 1052 s pulse shape that they discuss in their paper. The characteristics of the two oscillations we isolated in SDSS J2348−0943 are summarized in Table 4.

We investigated the stability of the amplitudes and phases of the largest amplitude frequency components that were found in the light curves of SDSS J2200−0741 and SDSS J2348−0943. Unfortunately, the measurements of the nightly amplitudes and phases suffer from rather large uncertainties because of the noise level in the light curves of these faint targets. We cannot therefore conclude with any certainty about the reality of possible amplitude and phase modulations over timescales of days. However, we note that for the dominant oscillation in both target stars, 654.397 s in SDSS J2200−0741 and 1044.168 s in SDSS J2348−0943, Figures 5 and 14 suggest, respectively, the strong possibility of amplitude modulation. This needs to be confirmed with higher sensitivity measurements.

It is instructive at this point to combine the results of Green et al. (2009) on the first known pulsating Hot DQ white dwarf, SDSS J1426+5752, with those of the present paper. Green et al. (2009) found that the light curve of SDSS J1426+5752 is dominated by a periodicity at 417.707 s along with its first harmonic, in agreement with the discovery paper of Montgomery et al. (2008). The amplitude of the harmonic component is some 30% of that of the dominant oscillation, leading to a highly nonlinear pulse shape for that periodicity. In addition, again in agreement with the findings of Montgomery et al. (2008), Green et al. (2009) found that the first harmonic is in antiphase with the main component at light maximum leading to a flat maximum and a sharp minimum in the pulse shape (and see their Figure 7). While this behavior is contrary to what is seen in large amplitude pulsating white dwarfs of well known types (whose pulse shape are quite generally characterized by flat minima and sharp maxima), Green et al. (2009) argued that the unusual pulse shape seen in SDSS J1426+5752 should not be taken as evidence against pulsations as the source of the luminosity variations. And indeed, these authors pointed out that there exist isolated pulsating stars, the large amplitude roAp stars, with pulse shapes reminiscent of those of SDSS J1426+5752. Green et al. (2009) further pointed out that there is one thing in common between roAp pulsators and the white dwarf SDSS J1426+5752 (and see Dufour et al. 2008b): a large-scale magnetic field sufficiently important in both cases to disrupt the atmospheric layers and influence the pulsations there. Hence, the suggestion was made that the magnetic field could be responsible for the unusual pulse shape (relative to known pulsating white dwarfs of the GW Vir, V777 Her, and ZZ Ceti types, all of which being nonmagnetic) observed in the light curve of SDSS J1426+5752.

The photometric properties of SDSS J2200−0741 are very similar to those of SDSS J1426+5752. In particular, its light curve is dominated by the contribution of a periodicity at 654.397 s along with that of its first harmonic which has an amplitude equal to 82% of that of the main component. This leads to an even more extreme case of a highly nonlinear pulse shape, compared to SDSS J1426+5752, when the light curve is folded on the period of 654.397 s. Moreover, we found that the first harmonic is in antiphase with the main oscillation at phase 1.0 (see Figures 7 and 9 above), and this leads to a pulse shape similar to that seen in SDSS J1426+5752, i.e., with a flat maximum and a sharp minimum. In contrast, the pulse shape of the dominant oscillation in the light curve of SDSS J2348−0943 appears perfectly sinusoidal, with no detectable sign of its first harmonic. In view of the suggestion of Green et al. (2009) about the magnetic field origin of the unusual pulse shape seen in SDSS J1426+5752, this implies that SDSS J2200−0741 is also probably magnetic, while SDSS J2348−0943 is not. This goes in the same direction as the prediction made by Dufour et al. (2008a) on the basis of purely spectroscopic arguments.

As it turns out, SDSS J2200−0741 and SDSS J2348−0943 are the only two known Hot DQ stars for which follow-up spectroscopy has not yet been carried out (see Dufour et al. 2009 for a report on the others). One of us (P.D.) has developed an ongoing program at the MMT to gather higher quality optical spectra than available in the SDSS archives, and it is through this program that a large-scale magnetic field of 1.2 MG was detected in SDSS J1426+5752 (Dufour et al. 2008b). The large-scale field produces a distinct signature on the spectrum through Zeeman splitting (see, e.g., Figure 12 of Green et al. 2009). Unfortunately, possibly through some small cosmic conspiracy, the night of MMT time allocated to observe SDSS J2200−0741 and SDSS J2348−0943 in 2008 September was lost to bad weather. These are obvious targets for the next season, but, in the meantime, we present Figure 19, which compares the available SDSS spectra of the three known pulsating Hot DQ white dwarfs. What Zeeman splitting produces at this level of accuracy is a significant broadening of the absorption lines (C II features here). Taking into account the different S/N of the spectra (due to the different magnitudes of the targets), it is clear that the spectrum of SDSS J2200−0741 resembles that of the known magnetic star SDSS J1426+5752. In contrast, the absorption lines in the spectrum of SDSS J2348−0943 have

![Figure 19. Archived SDSS optical spectra of the three known pulsating carbon-atmosphere white dwarfs. The absorption lines are noticeably sharper in SDSS J2348−0943 than in the other two stars. Note that, for better clarity, we applied a three-point average window smoothing in the display of these spectroscopic data.](image-url)
distinctly sharper cores than in the two other spectra. This comforts us in our prediction that SDSS J2200−0741 is likely to be magnetic like SDSS J1426+5752, and SDSS J2348−0943 is probably not. We are eager to return to the MMT to find out for sure.

If indeed SDSS J2200−0741 turns out to be a magnetic star, it will become, because of its relative brightness, the best test bed for the idea that some of these stars could be white dwarf analogs of roAp stars. In a roAp object, amplitude modulation is associated with the rotation of the star (see, e.g., Kurtz 1990). The pulsations align themselves along the magnetic field axis which is itself inclined with respect to the rotation axis of the star. The viewing aspect of the pulsations thus changes periodically with rotation, which produces amplitude modulation of a given mode. It will therefore be of utmost interest to verify whether rotationally induced amplitude modulation can be observed in SDSS J2200−0741, which would make it a true white dwarf equivalent of a roAp star.

Finally, we point out that the Hot DQ white dwarfs remain as puzzling as ever. According to Dufour et al. (2009), at least four (and perhaps six) of the 10 known Hot DQ’s are magnetic. This is much higher than the proportion of about 10% found in the normal population of white dwarfs according to Liebert et al. (2003). And if we are correct in the interpretation presented in this paper, there are three pulsating Hot DQ stars out of a sample of eight investigated so far, two of which are magnetic and the other not.

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