FOLLOW-UP STUDIES OF THE PULSATING MAGNETIC WHITE DWARF SDSS J142625.71+575218.3

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ABSTRACT

We present a follow-up analysis of the unique magnetic luminosity-variable carbon-atmosphere white dwarf SDSS J142625.71+575218.3. This includes the results of some 106.4 h of integrated light photometry which have revealed, among other things, the presence of a new periodicity at 319.720 s which is not harmonically related to the dominant oscillation (417.707 s) previously known in that star. Using our photometry and available spectroscopy, we consider the suggestion made by Montgomery et al. (2008) that the luminosity variations in SDSS J142625.71+575218.3 may not be caused by pulsational instabilities, but rather by photometric activity in a carbon-transferring analog of AM CVn. This includes a detailed search for possible radial velocity variations due to rapid orbital motion on the basis of MMT spectroscopy. At the end of the exercise, we unequivocally rule out the interacting binary hypothesis and conclude instead that, indeed, the luminosity variations are caused by g-mode pulsations as in other pulsating white dwarfs. This is in line with the preferred possibility put forward by Montgomery et al. (2008).

Subject headings: stars: evolution — stars: oscillations — stars: atmospheres — stars: individual (SDSS J1426+5752) — white dwarfs

1. INTRODUCTION

The rather faint (g = 19.16) star SDSS J142625.71+575218.3 (referred to hereafter as SDSS J1426+5752) is a fascinating object in several aspects. First, it belongs to the newly-discovered type of carbon-atmosphere white dwarfs, also known as Hot DQ stars (Dufour et al. 2007, 2008a). These are exceedingly rare stars whose unexpected existence was revealed thanks to the availability of some of the data products that came out of the Sloan Digital Sky Survey (e.g., Liebert et al. 2003 and Eisenstein et al. 2006). Dufour et al. (2008b) found only nine such objects out of a total of about 10,000 white dwarfs identified spectroscopically. Their preliminary atmospheric analysis revealed that all the Hot DQ white dwarfs fall in a narrow range of effective temperature, between about 18,000 and 24,000 K, and that they have atmospheric carbon-to-helium number ratios ranging from 1 to upward of 100. Dufour et al. suggested that these stars could be the cooled-down versions of the, so far, unique and very hot (Teff $\approx$ 200,000 K) carbon-rich PG 1159 star H1504 (see, e.g., Werner & Herwig 2006) and form a new family of hydrogen- and helium-deficient objects following the post-AGB phase. In this scenario, residual helium would float rapidly to the surface after the PG 1159 phase of evolution, and the descendants of H1504-like stars would thus “disguise” themselves as helium-atmosphere white dwarfs (of the DO and DB spectral types). This would last until convective mixing dilutes the thin outermost layer of helium in the effective temperature range where substantial subphotospheric convection due to carbon recombination develops in models of these stars. Hence, a dramatic change in the atmospheres of such stars, from helium-dominated to carbon-dominated, would occur in the range of temperature where the Hot DQ’s are actually found. Further evolution would slowly restore the dominance of helium in the atmosphere of these objects as a result of diffusion. Although quite a bit of work needs to be done to establish quantitatively the foundations of this scenario, the preliminary investigations of Althaus et al. (2009) indicate that it is quite viable. An updated discussion of the properties of Hot DQ stars has been presented by Dufour et al. (2009).

The second interesting development concerning SDSS J1426+5752 was the important discovery by Montgomery et al. (2008) that it is a luminosity variable. On the basis of 7.8 h of integrated light photometry on the McDonald Observatory 2.1 m Otto Struve Telescope, these authors reported that SDSS J1426+5752 has a light curve dominated by a single periodicity at 417.7 s with an amplitude of about 1.7% of the mean brightness of the star, accompanied by its first harmonic (208.9 s) with a relatively large amplitude (0.7%). Quite interestingly, they also reported that no luminosity variations were detected in five other Hot DQ’s that they surveyed. Using some theoretical arguments, Montgomery et al. (2008) argued that the luminosity variations seen in SDSS J1426+5752 and not in their other targets could be accounted for naturally in terms of pulsational instabilities. If true, this means that SDSS J1426+5752 is the prototype of a new class of pulsating white dwarfs after the GW Vir, V777 Her, and ZZ Ceti types (and see, e.g., Fontaine & Brassard 2008 for a detailed review on these pulsators). The hypothesis that the luminosity variations seen in SDSS J1426+5752 are caused by pulsational instabilities associated with low-order and low-degree gravity-mode oscillations (as in the known types of pulsating white dwarfs) is backed by the exploratory nonadiabatic calculations carried out independently by Fontaine, Brassard, & Dufour (2008) in parallel to the efforts of Montgomery et al. (2008).
On the other hand, Montgomery et al. (2008) also noted that the folded light curve of SDSS J1426+5752 does not resemble those of pulsating white dwarfs showing nonlinearities in their light curves, but shows instead similarities with the folded pulse shape of AM CVn, the prototype of the family of helium-transferring cataclysmic variables. The AM CVn stars are close interacting binaries consisting of (probably) two helium white dwarfs with orbital periods in the range 1000–3000 s (and see the reviews of Warner 1995 or Nelemans 2005 for a lot more details on these challenging objects). In these systems, the main photometric period, almost always accompanied by several harmonics, corresponds to the beat period between the orbital period and the precession period of the slightly elliptical accretion disk around the more massive white dwarf. The dominant component of the light variability usually comes from the moving (precessing) optically thick accretion disk. Thus, on the basis of similarities in the folded light pulses between SDSS J1426+5752 and AM CVn, Montgomery et al. (2008) proposed an alternative to pulsational instabilities for explaining its luminosity variations: the possibility that it is, in fact, a new type of close interacting binary, a carbon-transferring analog of AM CVn. In this scenario, the observed spectrum of SDSS J1426+5752 would originate from an optically thick carbon-oxygen accretion disk around the more massive white dwarf component in the system. The pulse shape argument was again used recently by Barlow et al. (2008) to favor the close interacting binary model after those other authors discovered two more luminosity variable Hot DQ’s. However, counterarguments, favoring this time the pulsation model, have been put forward by Dufour et al. (2009) and Fontaine et al. (2009).

The third development concerning SDSS J1426+5752 resulted from follow-up spectroscopic observations carried out by Dufour et al. (2008c) at the 6.5 m Multiple Mirror Telescope (MMT) and at one of the 10 m Keck Telescopes. This was motivated by the sole availability of a rather poor SDSS spectrum, insufficient for quantitative analysis. Their objective was, firstly, to obtain a sufficiently good spectrum for detailed atmospheric modeling and, secondly, to search for the presence of helium as required to account for the observed pulsational instabilities according to the nonadiabatic calculations of Fontaine et al. (2008). The spectral analysis of the improved spectra readily revealed the presence of a substantial amount of helium in the atmosphere of SDSS J1426+5752, an abundance comparable to that of carbon. This is in line with the expectations of nonadiabatic pulsation theory which requires an important “helium pollution” in the atmosphere/envelope of SDSS J1426+5752 for it to pulsate at its current estimated effective temperature and surface gravity (Dufour et al. 2008b). In addition to this finding, an unexpected surprise came out of the follow-up spectroscopic observations of Dufour et al. (2008c). Indeed, it was found that the strong carbon lines seen in the optical spectrum of SDSS J1426+5752 feature Zeeman splitting, a structure that could not be seen in the original noisy SDSS spectrum. The observed splitting between the $\sigma$ and $\tau$ components implies a large scale magnetic field of about 1.2 MG. Hence, if SDSS J1426+5752 is really a pulsating star, it would be the first example of an isolated pulsating white dwarf with a large detectable magnetic field. As such, it would be the white dwarf equivalent of a rapidly oscillating Ap (roAp) star. The roAp stars are main sequence (or near main sequence) magnetic A stars (Ap) showing multiperiodic luminosity variations with periods in the range 5–15 minutes caused by low-degree, high-order pressure-mode pulsational instabilities (see, e.g., Kurtz 1990).

In view of the importance of SDSS J1426+5752, we carried out additional studies of that star. In particular, we present and discuss in this paper the results of some 106.4 h of integrated light photometry gathered at the Steward Observatory 1.55 m Kuiper Telescope. We also discuss the pros and the cons of the pulsational instabilities model versus those of the interacting binary model. This includes a detailed search for possible radial velocity variations due to rapid orbital motion using MMT spectroscopy. At the end of the exercise, we unequivocally conclude in favor of the pulsation model.

2. TIME-SERIES PHOTOMETRY

2.1. Observations

Our follow-up photometry was obtained with Mont4K (as in “Montréal 4K×4K camera”), a new CCD camera designed and built at the Steward Observatory. Mont4K is a partnership between Université de Montréal and the University of Arizona. The instrument was designed primarily with differential time-series photometry in mind (in the windowing mode), but the variety of filters available coupled with the excellent sensitivity of the chip and the large (9.7×9.7”) field of view make it ideal for many imaging projects. It is used at the Kuiper Telescope on Mount Bigelow near Tucson. Some details about the instrument can be found in Randall et al. (2007), but the interested reader will find more on the following web site: http://james.as.arizona.edu/~psmith/61inch/instrument.html.

At the outset, the relative faintness of SDSS J1426+5752 posed a challenge for a small instrument such as the Kuiper Telescope, but we were pleasantly surprised at the quality of the light curves that we could actually obtain. The time-series observations were taken on dark nights through a broadband Schott 8612 filter, and an effective exposure time of 67 s (on average) was used as a compromise between the S/N and the need to sample adequately the luminosity variations as reported by Montgomery et al. (2008). Altogether, we collected some 106.4 h of useful photometry over a 40 day span in the spring of 2008. This corresponds to a formal temporal resolution of 0.29 $\mu$Hz and a modest duty cycle of 11.8%. Details of the observations are provided in Table 1.

Figure 1 shows the 15 nightly light curves that were obtained. The original images were reduced using standard IRAF reduction aperture photometry routines, except that we set the photometric aperture size individually for each frame to 2.0 times the FWHM in that image. We computed differential light curves of SDSS J1426+5752 on the basis of three suitable comparison stars well distributed around the target. Final detrending of the effects of differential extinction was made through a spline strategy. A zoomed-in view of the light curve gathered on May 2 (2008) is provided in Figure 2. Again, in view of the magnitude of the target ($g = 19.16$), the overall
quality of the light curves is most gratifying. We attribute this to the excellent sensitivity of the CCD and our optimized data pipeline.

### Table 1: Journal of Observations for SDSS J1426+5752

| Date (UT)   | Start of Run (HJD2454550+) | Number of Frames | Length (h) |
|-------------|----------------------------|------------------|------------|
| 2008 Mar 31 | 6.6517743                  | 399              | 7.88       |
| 2008 Apr 01 | 7.6417324                  | 468              | 8.73       |
| 2008 Apr 03 | 9.6413232                  | 466              | 8.69       |
| 2008 Apr 04 | 10.6382536                 | 449              | 8.52       |
| 2008 Apr 05 | 11.6310329                 | 223              | 4.15       |
| 2008 Apr 06 | 12.6288716                 | 487              | 9.05       |
| 2008 Apr 09 | 15.6271095                 | 364              | 6.55       |
| 2008 Apr 10 | 16.6864942                 | 108              | 1.99       |
| 2008 Apr 11 | 17.7342303                 | 328              | 6.11       |
| 2008 May 01 | 37.6670997                 | 389              | 7.26       |
| 2008 May 02 | 38.6404921                 | 424              | 7.88       |
| 2008 May 03 | 39.6412906                 | 418              | 7.80       |
| 2008 May 04 | 40.6406385                 | 275              | 6.29       |
| 2008 May 08 | 44.6459373                 | 406              | 7.65       |
| 2008 May 10 | 46.6446166                 | 420              | 7.82       |

The two upper curves in Figure 4 provide a zoomed in view of the Fourier amplitude spectrum in the vicinity of the 417.707 s peak before and after prewhitening. Likewise, the two lower curves give a similar view for the 319.720 s peak. It is interesting to note that, within our measurement errors, the main peak at 417.707 s is a singlet. Given that SDSS J1426+5752 has a large scale magnetic field of some 1.2 MG, one could have expected instead the presence of l+1 components due to magnetic splitting according to Jones et al. (1989). Perhaps the multiplet components have much lower amplitudes than the main mode and are buried in the noise, or perhaps the field geometry is such that magnetic splitting cannot be observed. Either way, this remains an interesting curiosity.

We thus were able to extract three distinct harmonic oscillations in the light curve of SDSS J1426+5752. The basic characteristics of these oscillations are summarized in Table 2. Note that the phase is relative to an arbitrary point in time; in our case, the beginning of the first run on UT 31 March 2008. The uncertainties on the period, frequency, amplitude, and phase of each oscillation as listed in the table were estimated with the method put forward by Montgomery & O’Donoghue (1999). We point out, in this context, that the uncertainties on the
TABLE 2
HARMONIC OSCILLATIONS DETECTED IN THE LIGHT CURVE OF SDSS J1426+5752

| Period (s) | Frequency (mHz) | Amplitude (%) | Phase (s) |
|------------|-----------------|---------------|-----------|
| 417.70687±0.00082 | 2.394023±0.000005 | 1.630±0.048 | 127.90±1.97 |
| 319.72035±0.00271 | 4.788047±0.000015 | 0.487±0.048 | 21.06±3.30 |

Fig. 3.— Fourier transform of the entire data set in the 0−7.4 mHz range. The lower transforms show the successive steps of prewhitening by the two strongest frequencies (the 417.707 s peak and its first harmonic), and finally by all three frequencies with statistically significant amplitudes. The dotted horizontal lines indicate the 4 σ noise level.

amplitudes and phases obtained by our least-squares fits during the prewhitening stage were virtually the same as those derived with the Montgomery & O’Donoghue (1999) method. A basic quantity in that latter approach is the average noise level in the bandpass of interest, and we thus computed this mean value from the residual Fourier transform (the lower curve in Fig. 3) spanning the 0−7.4 mHz interval. The mean noise level in that range turned out to be 0.060% of the mean brightness of the star. In comparison, if we use the shuffling technique discussed by Kepler (1993) for estimating the noise level, we find an almost identical value of 0.061%.

In the context of being able to discriminate between the two possibilities put forward by Montgomery et al. (2008) to explain the luminosity variations of SDSS J1426+5752 – pulsations versus interacting binary – our detection of a periodicity (319.720 s) that is incommensurate with the periods of the main peak and its harmonics is potentially quite important (see below). Hence, it is essential that its presence be well established. Formally, according to the results of Table 2, our detection of the 319.720 s periodicity is a 6.0 σ (0.288/0.048) result. In the more standard way, the derived amplitude is rather compared to the average noise level, in which case our detection would be seen as a 4.8 σ (0.288/0.060) result. If we divide our runs into two “seasons”, i.e., from March 31 through April 11, and then from May 1 through May 10, we find that the 319.720 s period is present in both sets of observations (319.715±0.011 s and 319.738±0.013 s), at the level of 4.2 σ according to the standard criterion. We also verified explicitly that the 319.720 s periodicity is not present in the light curves of our comparison stars, thus ruling out a possible instrumental effect. We note finally that Montgomery et al. (2008) would not have been able to pick up the 319.720 s periodicity in their data – assuming that it was present in their light curve with an amplitude comparable to our detection – because their sensitivity was at least a factor of two lower than what we could achieve on a smaller telescope (1.55 m versus 2.1 m) at a brighter site but at the price of much longer observations (106.4 h versus 7.8 h).

2.3. Amplitude and Phase Variations

We investigated the stability of the amplitude and phase of each of the three frequencies we extracted from the light curve of SDSS J1426+5752 by performing nightly measurements. A clue about possible amplitude variations on a daily timescale is first provided by Fig-
Figure 5 in which we show a montage of the nightly Fourier amplitude spectra. Considering the main peak (2.3950 mHz, 417.707 s), the figure does suggest some possible amplitude variations. However, things are a lot less suggestive for the two other peaks given the level of noise and their relatively small amplitudes.

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 output 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 6 summarizes our results in the case of the main periodicity found in the light curve of SDSS J1426+5752. All nights were included, except those of April 5 and April 10 corresponding to rather short runs (see Table 1) and, consequently, to nightly estimates with uncertainties significantly larger than those typically illustrated here.

6 do suggest some variations in amplitude and in phase over timescales of days. For instance, on March 31, we find a “low” amplitude of $1.36 \pm 0.18\%$ for the dominant periodicity at 417.707 s, while we find a “high” amplitude of $1.95 \pm 0.14\%$ on May 2. In this context, it may be appropriate to recall that amplitude modulation associated with the rotation of the star is typically seen in roAp stars (see, e.g., Kurtz 1990). This phenomenon (and many others) observed in roAp stars has been explained within the framework of the very successful oblique pulsator model. In that model, 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. In the case of SDSS J1426+5752, we do not yet know if its large scale magnetic field is aligned with the rotation axis.

Although the material presented in this subsection is suggestive of possible amplitude and phase modulations with timescales of days for the dominant 417.707 s period, it is simply not possible at this stage to be certain about their reality. If, for example, we were to double the uncertainties on the derived nightly amplitudes and phases (assuming that our least-squares approach or the method of Montgomery & O'Donoghue 1999 underestimates the true errors by that factor), then we could only conclude that the nightly amplitudes and phases of the 417.707 s periodicity we extracted from the light curve of SDSS J1426+5752 do not vary within our measurement errors. Things are even worse for the lower amplitude 319.720 s and 208.853 s oscillations in that the uncertainties on their nightly amplitudes and phases prevent us from concluding with any certainty about possible modulations although there are hints of variations. Here then is a classic case of “more observations are needed”.

2.4. Pulse Shape
We have followed up on the remark made by Montgomery et al. (2008) that the folded pulse shape of SDSS J1426+5752 is different from that of pulsating white dwarfs and rather shows similarities with that of AM CVn, the prototype of helium-transferring double degenerate binaries. The top panel of Figure 7 shows our 106.4 h long light curve of SDSS J1426+5752 folded on the period of 417.707 s. To reach a decent S/N, we distributed the folded amplitudes in 10 different phase bins, each containing 572 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 417.707 s periodicity in the light curve has a very high amplitude, about 30% 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. Along with this, another striking characteristic with respect to known pulsating white dwarfs is the fact that it boosts a relatively flat maximum and a sharp minimum (see Montgomery et al. 2008 and the examples below).

In the middle panel of Figure 7, we again display our folded light curve of SDSS J1426+5752, but only after having prewhitened the data of the first harmonic (208.853 s) as listed in Table 2. The sum of these two sine waves gives the solid curve, the overall nonlinear pulse shape associated with the 417.707 s oscillation. We reported 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, within our measurement errors, the agreement is nearly perfect. One can see that the relatively flat maximum and sharp minimum in the pulse shape is due to the fact that the first harmonic of the main oscillation falls nearly in phase at the minimum and in antiphase near the maximum of the main sinusoid. This is particularly well illustrated in the lower panel of the figure.

For comparison purposes, we carried out similar folding exercises using representative light curves from the archives that one of us (G.F.) built up over the years using LAPOUNE at the 3.6 m Canada-France-Hawaii Telescope (CFHT). LAPOUNE is a portable three-channel photometer that uses photomultiplier tubes as detectors. The archived light curves are integrated “white light” data and were generally obtained with a sampling time of 10 s. They include a short (2.04 h) light curve of AM CVn itself, originally taken as a test as part of a multisite campaign carried out on that star (Provencal et al. 1995; Solheim et al. 1998). In a format identical to that of Figure 7, Figure 8 summarizes the results of our calculations after having folded that light curve of AM CVn on the period of 521.105 s, which is the dominant photometric periodicity in that star (see Provencal et al. 1995). Although the model pulse shape (dotted curve in upper panel and solid curve in lower panel) based on the superposition of two sinusoids (the 521.105 s oscillation and its first harmonic) is far from perfect, it is nevertheless sufficient for illustrating the fact that AM CVn does show a main pulse shape with a rounded top and a sharp bottom. The lower panel of Figure 8 explains why: the first harmonic (dotted curve) of the 521.105 s oscillation shows a relatively large amplitude compared to that of the main component, and it tends to be in phase and in antiphase at the minimum and maximum, respectively, of that component. There is a significant offset however, between the extrema of the 521.105 s sinusoid and those of its first harmonic, and this largely explains the asymmetric shape of the pulse in this particular light curve.

In contrast to this behavior, known pulsating white dwarfs with nonlinear light curves (the large amplitude

3 We explicitly verified that the results displayed in both the upper and middle panel of Fig. 7 are completely insensitive to whether or not the data is prewhitened of the low-amplitude 319.720 s oscillation. This should not be surprising given the large number of 319 s cycles in 106.4 h, but for very short runs, prewhitening of the other modes is required in this sort of exercise.
ones) quite generally display pulse shapes that have flatter minima and sharper maxima. An example of this is provided by Figure 9 which refers to the large amplitude ZZ Ceti star PG 2303+242, a pulsator with a light curve dominated by a periodicity at 712.250 s. In the present case, the model pulse shape based on only two components (the dominant mode and its first harmonic) does a very good job at explaining the folded light curve, as can be appreciated in the top panel of Figure 9.

A second example is provided by another large amplitude ZZ Ceti star, GD 154, as illustrated in Figure 10. In that case, we retained also the second harmonic along with the main oscillation (1186.085 s) and its first harmonic in the construction of the model pulse shape. Although the top panel of the figure clearly demonstrates that the model could be improved (GD 154 has a complicated multiperiodic light curve with higher-order harmonic terms; see, e.g., Fig. 23 of Fontaine & Brassard 2008), the results presented here are sufficient to make our point about the general shape of a light pulse in a large amplitude pulsating white dwarf.

Another interesting example is shown in Figure 11. It concerns Balloon 090100001, which is not a pulsating white dwarf at all, but instead belongs to the family of hot B subdwarf pulsators (and see Fontaine et al. 2006 for a brief review on these stars, if interested). The light curve of that star, the largest amplitude variable of that type currently known, is dominated by a main pulsation (the fundamental radial mode according to Van Grootel et al. 2008) with a period of 356.194 s. Our model pulse shape, based on the superposition of the main periodicity and of its first two harmonics, gives a perfect fit to the folded light curve.

What is common in these examples, and what is generally true for large amplitude pulsating white dwarfs and hot subdwarfs, is that the harmonic components tend to be in phase at light maximum. This produces relatively sharp maxima and flat minima. In contrast, the first harmonic tends to be in antiphase with the main periodicity at light maximum in the light curve of SDSS J1426+5752 and AM CVn, and this now produces pulse shapes with rounded tops and sharp minima. Mont-
that periodicity are also involved in the plot. The light curve comes was folded on the period of 356.194 s and both lowest harmonics of that periodicity are also involved in the plot. The light curve comes from four consecutive nights covering a length of 17.81 h and was gathered in white light using the CFHT/LAPOUNE combination.

The folded light curve has been distributed in 20 phase bins, each containing ~321 points.

Montgometry et al. (2008) interpreted this as evidence that the luminosity variations observed in SDSS J1426+5752 could be caused, not by pulsational instabilities (their preferred possibility), but by photometric activity in a carbon-transferring analog of AM CVn. We show below, however, that the pulsation hypothesis provides the better explanation.

2.5. Pulsations or Interacting Binary?

On the basis of our photometry, we can argue in favor of one or the other of the two possibilities put forward by Montgometry et al. (2008) to account for the luminosity variations seen in SDSS J1426+5752? To begin with, it is well known that flickering—incoherent light bursts arising on short timescales—is a telltale sign of mass transfer in an interacting binary system (Warner 1995). Flickering is actually observed in the CFHT/LAPOUNE light curve of AM CVn as can be readily seen in Figure 1 of Provencal et al. (1995) where the light curve has been displayed for the first time. The sampling time was 10 s, sufficiently short to pick up some flickering. However, when degraded to a sampling time of 60 s, flickering all but disappears in the light curve of AM CVn. We conclude from this that we could not have detected flickering in our photometric observations of SDSS J1426+5752 if present, because of the large sampling time we used. Hence, we cannot use this as a diagnostic.

On the other hand, the light curves of AM CVn systems are known to be unstable and irregular. Solheim et al. (1998) discuss this phenomenon in some detail in relation to their Figure 2, where the CFHT/LAPOUNE light curve (binned in 40 s data points) is again displayed. The authors comment that, in spite of the fact that the CFHT/LAPOUNE light curve is essentially noise-free, it is irregular compared to that of isolated pulsating white dwarfs. For instance, the troughs in the light curve are irregularly spaced in time. Random flickering is blamed for this state of affairs. In contrast to this, and not withstanding the noise, the light curves we have gathered (see Fig. 1) have kept the same appearance and regularity over a six week period. However, it is not clear if this is really significant since flickering is not coherent over long timebases.

The light curves of AM CVn systems are generally dominated by a principal periodicity along with a suite of several harmonics of that dominant oscillation (Warner 1995). Montgometry et al. (2008) reported the detection of the 417 s oscillation in SDSS J1426+5752 along with its first harmonic and possibly also the 4th harmonic, but not the 2nd or 3rd one. The detection of a period—ideally several periods—that would be incommensurate with such series of harmonically related oscillations would go against the interacting binary hypothesis and would favor the pulsations alternative. This would be the best evidence for pulsations according to Barlow et al. (2008). Our detection of the 319 s oscillation (see Subsection 2.2) therefore goes a long way in that direction.

What about the pulse shape argument? We do not know at this stage why the folded light curve of SDSS J1426+5752 features a maximum that is flatter than its minimum, contrary to what is observed in large amplitude pulsating white dwarfs and hot subdwarfs. However, the fact that the pulse shape is unusual does not rule out by any means the possibility that pulsations are involved. In fact, Nature provides us with explicit examples of isolated pulsating stars with pulse shapes that qualitatively resemble that seen in SDSS J1426+5752 in that they display rounded maxima and sharper minima. These are some of the roAp stars with the largest amplitudes that show harmonics of dominant modes in their light curves. An excellent case is that of HR 3831 which exhibits a pulse shape with a rounded top and a sharp bottom as can be seen in Figure 1 of Kurtz, Shibahashi, & Goode (1990). The fast rise, rounded maximum, slower decline, and pointed minimum are very reminiscent of what is observed in the light curve of the AM CVn system CR Boo in its high state as can be seen in Figure 6 of Warner (1995) for instance. Yet, HR 3831 is a genuinely pulsating star. Another example is provided by the roAp star HD 99563 studied by Handler et al. (2006). As can be seen in their Figure 1 (and see also the discussion in the text), the pulsations of that star show again flatter light maxima than minima. The authors comment on the phasing of the harmonics with respect to the main mode in their paper.

SDSS J1426+5752 has one thing in common with roAp stars, and that is a large scale magnetic field sufficiently important in both cases to disrupt the atmospheric layers and influence the pulsations there. It would therefore not surprise us if the magnetic field were responsible for the unusual pulse shape (relative to nonmagnetic pulsating stars) observed in the light curves of SDSS J1426+5752 and large amplitude roAp stars. Be that as it may, in view of the very existence of roAp stars such as HR 3831 and HD 99563, the argument that the pulse shape of SDSS J1426+5752 is different from those seen in (nonmagnetic) pulsating white dwarfs cannot be held against the pulsations interpretation.
3. SPECTROSCOPY

3.1. Search for Radial Velocity Variations

Dufour et al. (2008c) presented follow-up spectroscopy of SDSS J1426+5752 including, in particular, an optical spectrum obtained with the Blue Channel Spectrograph at the MMT using a 500 line mm$^{-1}$ grating with a 1" slit, resulting in a $\sim$3.6 Å FWHM spectral resolution over a wavelength range of 3200–6400 Å. A total of 17 individual spectra were obtained over a timebase of 3.37 h, resulting in an overall exposure time of 180 minutes. Part of the final combined spectrum, taken from Dufour et al. (2008c), is reproduced in Figure 12 (upper curve). It shows a S/N$\sim$75 per pixel at 4500 Å. The most prominent features are CII lines which clearly show Zeeman splitting in their cores. As a comparison, we also plotted the available SDSS spectrum for the star (lower curve).

![Optical spectra of SDSS J1426+5752 obtained 1) at the MMT (upper curve), and 2) in the SDSS archives (lower curve). Note that we have applied for clarity a three-point average window smoothing in the display of the SDSS spectroscopic data.](image)

If SDSS J1426+5752 is truly a double degenerate carbon analog of AM CVn systems, then one should be able to pick up radial velocity variations associated with orbital periods in the range 1000–3000 s as found in most such systems. This excludes, of course, the improbable configuration of having the orbital plane at nearly 90 degrees with respect to the line-of-sight. The sampling and the baseline of 3.37 h used during the MMT observations of Dufour et al. (2008c) are well suited to search for such radial velocity variations. In addition, the combination of the Blue Channel Spectrograph and the MMT is well known to provide a very stable platform for radial velocity measurements, and one of us (E.M.G.) has developed over the years a large MMT program dedicated to radial velocity measurements in hot subdwarf stars. We therefore went back to the MMT spectroscopic data and searched for possible radial velocity variations using the tools and expertise developed at Steward Observatory. We provide some details on the procedure followed.

We first interpolated the 17 individual spectra of SDSS J1426+5752 onto a logarithmic wavelength scale with identical starting and ending wavelengths (3215–6357 Å). After manually removing cosmic ray signatures from each spectrum, we fitted the continuum, divided by the fit, and subtracted 1.0 to get a flattened continuum with a mean level of zero. We median-filtered the 17 resulting spectra into a single spectrum to create a higher S/N radial velocity template. Radial velocity cross-correlations of the individual continuum-removed spectra relative to the template spectrum were performed using the double precision version of IRAF’s FXCOR task, fitting the cross-correlation peak with a gaussian. A ramp filter was used prior to the cross-correlation to select the optimal range in Fourier space, with adopted values of 125, 275, 1480, and 1490, respectively, for the cut-on, full-on, cut-off, and full-off points. The high frequency noise cut-off corresponds to 2.75 pixels, which is slightly better than the instrumental resolution of 3.0 pixels, as determined by the FWHM’s of the HeArNe comparison arc lines. The low-frequency cut-on, corresponding to 33 pixels, is slightly wider than the observed FWHM (30 pixels) of the strongest absorption lines in the spectrum.

The essential result that came out of this exercise is that the velocities are constant to within 7.1 km s$^{-1}$ (the standard deviation), which is about 1/32 of the velocity resolution, and there is no sign of any velocity trend over the 3.37 h of the observations. We point out that 1/32 of a resolution element represents quite a high level of accuracy for spectra at this S/N. In comparison, the typical radial velocity semi-amplitude expected in a AM CVn system is $K = 62 \sin i$ km s$^{-1}$. This estimate uses the following representative values: $M_1 = 0.7 M_\odot$ for the mass of the helium degenerate primary, $M_2 = 0.07 M_\odot$ for the mass of the helium degenerate or semi-degenerate donor, and $P = 2000$ s for the orbital period, as can be inferred in the reviews of Warner (1995) and Nelemans (2005) and references therein. Actually, if we assume that the dominant photometric period of 417 s is approximately equal to the orbital period in a putative SDSS J1426+5752 carbon system equivalent of AM CVn (this is the case for the known systems of the type, except for AM CVn itself), then the estimate of the velocity semi-amplitude goes up to $K = 105 \sin i$ km s$^{-1}$. If, as in AM CVn itself, the orbital period is rather approximately equal to twice the dominant photometric periodicity of 417 s (521 s in AM CVn), the velocity semi-amplitude takes on the value $K = 83 \sin i$ km s$^{-1}$. Hence, unless the inclination of the orbital plane is quite low, this argues strongly against the interacting binary hypothesis as the explanation for the luminosity variations observed in SDSS J1426+5752.

3.2. Pulsations or Interacting Binary?

Along with the fact that we do not detect radial velocity variations, the available spectroscopic data on SDSS J1426+5752 can further be used to build up the case against the interacting binary model. In a AM CVn-type system in its high state, most of the light does not come from the photosphere of the helium degenerate primary, but rather from an optically thick accretion disk orbiting around that star. According to Warner (1995), the HeI lines seen in absorption have quite different profiles from those observed in isolated helium-atmosphere (DB) white dwarfs. Their profiles are asymmetric, and they vary both in shape and depth, contrary to the symmetric and stable lines seen in DB white dwarfs.

In this context, we wish to point out that the available spectroscopy on SDSS J1426+5752 shows that the
broad (carbon) absorption lines are symmetric (see, e.g., Fig. 12). Furthermore, the spectrum appears quite stable, at least over a timescale of 20 h, which is the time lapse between the observations of SDSS J1426+5752 carried out at the MMT and those gathered at the Keck I Telescope (and see Dufour et al. 2008c). The spectrum does not show any sign of accretion disk activity. However, it does show clear Zeeman splitting in the line cores, a feature that would presumably be washed away if SDSS J1426+5752 were part of a interacting binary system because of the rapid orbital motion. Zeeman splitting is seen in both the MMT and Keck spectra, and the spacings between the $\pi$ and $\sigma$ components are the same within the measurement errors in both spectra. In contrast, Zeeman splitting has never been reported for AM CVn systems.

Finally, we beg to disagree with Montgomery et al. (2008) who suggested that the broad absorption lines seen in a hypothetical carbon analog of AM CVn could mimic those seen in the photosphere of an isolated white dwarf. And indeed, it has already been established (see, e.g., O’Donoghue & Kilkenny 1989 or Warner 1995), that the HeI absorption lines seen in AM CVn systems, although relatively broad by main sequence standards, have strengths that are more akin to those observed in dwarf primary where the physical conditions are similar to those encountered in $\log g = 6$ hot subdwarf stars than log $g = 8$ DB atmospheres. This reflects the fact that they are formed in the inner region of the accretion disk orbiting the white dwarf primary where the physical conditions are similar to those encountered in $\log g = 6$ atmospheres. In contrast, the spectral fits carried out by Dufour et al. (2008b) for Hot DQ stars totally rule out equivalent surface gravities of $\log g = 6$, as the line strengths observed in these stars bear the clear signature of $\log g = 8$ environments, even log $g = 9$ in the case of SDSS J1426+5752 (notwithstanding the presence of a magnetic field). In brief, the spectrum of SDSS J1426+5752 cannot be confused with that of the accretion disk in a hypothetical carbon analog of AM CVn.

4. CONCLUSION

We have presented an analysis based on follow-up photometric and spectroscopic observations of the faint but highly interesting star SDSS J1426+5752. On the photometric front, we carried out a campaign in integrated light over a baseline spanning some 40 days. We used the Kuiper/Mont4K combination at the Steward Observatory Mount Bigelow station near Tucson. Altogether, we acquired some 106.4 h of useful photometry during the campaign. Our analysis of this data set confirms that the light curve of SDSS J1426+5752 is dominated by a periodicity at 417.707 s along with its first harmonic (208.853 s) as found originally, but with less accuracy, by Montgomery et al. (2008) in their discovery paper. In addition, due to the higher sensitivity achieved in our campaign, we uncovered the presence of a new oscillation with a period of 319.720 s, a 4.8 $\sigma$ result using the standard detection criterion (a 6.0 $\sigma$ detection at the formal level). The characteristics of these three oscillations are summarized in Table 2.

We investigated the stability of the amplitude and phase of each of the three periodicities extracted from the light curve of SDSS J1426+5752. Our results suggest possible variations over timescales of days, and this is particularly true for the dominant 417.707 s periodicity. However, this needs to be confirmed with higher S/N data since observing a $g = 19.16$ star in integrated light photometry with a small telescope such as the Kuiper remains challenging. On the basis of our current data, we cannot be absolutely certain of the reality of the suggested amplitude and phase modulations in the light curve of SDSS J1426+5752.

We followed up on the suggestion made by Montgomery et al. (2008) that the luminosity variations in SDSS J1426+5752 may not be caused by pulsational instabilities, but rather be associated with photometric activity in a carbon-transferring analog of AM CVn. If true, SDSS J1426+5752 would represent the prototype of a new class of cataclysmic variable. Since their argument hinges on the shape of the light curve folded on the dominant periodicity of 417.707 s, we further exploited our 106.4 h data set in that direction. Using this and archived light curves of known pulsating stars, we found, in agreement with Montgomery et al. (2008), that the folded pulse shape of SDSS J1426+5752 is unusual compared to those of large amplitude pulsating white dwarfs and hot subdwarfs. However, in view of the existence of isolated pulsators such as the roAp stars HR 3831 and HD 99563 exhibiting pulse shapes with flatter light maxima than minima (the opposite of what is seen in large amplitude pulsating white dwarfs), we emphasize that the pulse shape argument cannot be used to discriminate against the pulsations interpretation. Since SDSS J1426+5752 and these roAp stars and others share the common property of having a magnetic field sufficiently strong to affect the pulsations in their atmospheric layers, we suggest instead that the magnetic field may be responsible for the different pulse shape as compared to those of (nonmagnetic) pulsating white dwarfs.

On the other hand, arguments against the interacting binary hypothesis can be put forward. For instance, the light curves we gathered have shown to be quite regular and stable over at least a six week period, a behavior that is not commonly observed in AM CVn systems. Our discovery of a periodicity (319.720 s) that is not harmonically related to the dominant oscillation of 417.707 s also goes against the interacting binary proposal. Likewise, on the spectroscopic front this time, our detailed radial velocity analysis of the available MMT spectroscopy has revealed that the velocities are constant to within 7.1 km s$^{-1}$ over a period of 3.37 h. This is to be compared with expected velocity semi-amplitudes in the range 80–100 sin $i$ km s$^{-1}$. Furthermore, the spectrum of SDSS J1426+5752, unlike those of AM CVn systems, exhibits well defined symmetric absorption lines and it has proven stable over at least a 20 h period. It shows sharp Zeeman splitting in the line cores, indicative of the presence of a large scale magnetic field of 1.2 MG, a property never observed in a AM CVn system. Finally, the line strengths indicate a physical environment appropriate for log $g = 8$ atmospheres, unlike that found in the inner region of an accretion disk around a white dwarf and more akin to what is found in a log $g = 6$ stellar atmosphere.

It should also be pointed out that the interacting binary hypothesis does not account well at all for the existence of the family of Hot DQ white dwarfs as a whole since, among other things, not all of them exhibit lu-
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In contrast, the single-star evolutionary scenario originally proposed by Dufour et al. (2007) appears quite viable as demonstrated recently by Althaus et al. (2009). Also, the nonadiabatic calculations of Fontaine et al. (2008; also Dufour et al. 2008b) do predict a mixture of pulsators and nonpulsators in the Hot DQ population. In addition, according to Montgomery et al. (2008) themselves, citing the work of Benz et al. (1990), Rasio & Shapiro (1995), and Piersanti et al. (2003), carbon-transferring AM CVn-type systems are not expected to exist. Putting all these arguments together, we conclude with high confidence that, of the two possibilities put forward by Montgomery et al. (2008) to account for the luminosity variations seen in SDSS J1426+5752, pulsational instabilities is the correct cause. This is also the preferred solution of Montgomery et al. (2008).

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REFERENCES

Althaus, L.G., Garcia-Berro, E., Córscio, A.H., Miller Bertolami, M.M., & Romero, A.D. 2009, ApJ, 693, L23
Barlow, B.N., Dunlap, B.H., Rosen, R., & Clemens, J.C. 2008, ApJ, 688, L95
Benz, W., Cameron, A.G.W., Press, W.H., & Bowers, R.L. 1990, ApJ, 348, 647
Billères, M., Fontaine, G., Brassard, P., Charpinet, S., Liebert, J., & Saffer, R.A. 2000, ApJ, 530, 441
Dufour, P., Fontaine, G., Liebert, J., Schmidt, G.D., & Behara, N. 2008b, ApJ, 683, 978
Dufour, P., Fontaine, G., Liebert, J., Williams, K.A., & Lai, D.K. 2008c, ApJ, 683, L167
Dufour, P., Liebert, J., Fontaine, G., & Behara, N. 2007, Nature, 450, 522
Dufour, P., Liebert, J., Fontaine, G., & Behara, N. 2008a, Astronomical Society of the Pacific Conference Series, 391, 241
Dufour, P., Liebert, J., Swift, B., Fontaine, G., & Sukhbold, T. 2009, ArXiv e-prints, 901, arXiv:0901.3487
Eisenstein, D.J. et al. 2006, ApJS, 167, 40
Fontaine, G., & Brassard, P. 2008, PASP, 120, 1043
Fontaine, G., Brassard, P., Charpinet, S., Green, E.M., Chayer, P., Randall, S.K., & Dorman, B. 2006, in Proc. SOHO18/GONG2006/HELASI, Beyond the Spherical Sun (ESA SP-624; Noorwijk: ESA), 32
Fontaine, G., Brassard, P., & Dufour, P. 2008, A&A, 483, L1
Fontaine, G., Brassard, P., Dufour, P., Green, E.M., & Liebert, J. 2009, ArXiv e-prints, 901, arXiv:0901.3489
Halter, G., et al. 2006, MNRAS, 366, 257
Jones, P.W., Pesnell, D.W., Hansen, C.J., & Kawaler, S.D. 1989, ApJ, 336, 403
Kepler, S.O. 1993, Bal. Astron., 2, 515
Kurtz, D.W. 1990, ARAA, 28, 607
Kurtz, D.W., Shibahashi, H., & Goode, P.R. 1990, MNRAS, 247, 558
Liebert, J. et al. 2003, AJ, 126, 2521
Montgomery, M.H., & O’Donoghue, D. 1999, Delta Scuti Newsletter, No. 13
Montgomery, M.H., Williams, K.A., Winget, D.E., Dufour, P., DeGennaro, S., & Liebert, J. 2008, ApJ, 678, L51
O’Donoghue, D., & Kilkenney, D. 1989, MNRAS, 236, 319
Piersanti, L., Gagliardi, S., Iben, I., & Tornambé, A. 2003, ApJ, 598, 1229
Provençal, J., et al. 1995, ApJ, 445, 927
Randall, S.K., Green, E.M., Van Grootel, V., Fontaine, G., Charpinet, S., Lesser, M., Brassard, P., Sugimoto, T., Chayer, P., Fay, A., Wroblewski, P., Daniel, M., Story, S., & Fitzgerald, T. 2007, A&A, 476, 1317
Rasio, F.A., & Shapiro, S.L. 1995, ApJ, 438, 887
Solheim, J.-E., et al. 1998, A&A, 332, 939
Van Grootel, V., Charpinet, S., Fontaine, G., Brassard, P., Green, E.M., Chayer, P., & Randall, S.K. 2008, A&A, 488, 685
Werner, K., & Herwig, F. 2006, PASP, 118,183