Pulsations in carbon-atmosphere white dwarfs: A new chapter in white dwarf asteroseismology

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Abstract. We present some of the results of a survey aimed at exploring the asteroseismological potential of the newly-discovered carbon-atmosphere white dwarfs. We show that, in certain regions of parameter space, carbon-atmosphere white dwarfs may drive low-order gravity modes. We demonstrate that our theoretical results are consistent with the recent exciting discovery of luminosity variations in SDSS J1426+5752 and some null results obtained by a team of scientists at McDonald Observatory. We also present follow-up photometric observations carried out by ourselves at the Mount Bigelow 1.6-m telescope using the new Mont4K camera. The results of follow-up spectroscopic observations at the MMT are also briefly reported, including the surprising discovery that SDSS J1426+5752 is not only a pulsating star but that it is also a magnetic white dwarf with a surface field near 1.2 MG. The discovery of g-mode pulsations in SDSS J1426+5752 is quite significant in itself as it opens a fourth asteroseismological “window”, after the GW Vir, V777 Her, and ZZ Ceti families, through which one may study white dwarfs.

1. Introduction
Dufour et al. (2007) reported recently on the unexpected discovery of a new type of white dwarfs, those with carbon-dominated atmospheres, also known as Hot DQ stars. These are very rare, and Dufour et al. (2007) wrote on the discovery of nine of those, out of a total of several thousands white dwarfs already identified spectroscopically. The Hot DQ stars were, in fact, uncovered within the framework of the SDSS project, which has led to many other surprises. Among other characteristics, the C-atmosphere white dwarfs bunch together in a narrow range of effective temperature, between about 18,000 K and 23,000 K (Dufour et al. 2008a).

It has been known for quite some time (see, e.g., Fontaine & Van Horn 1976) that models of C-atmosphere white dwarfs in this temperature range possess superficial convection zones that bear strong similarities with those found in H- and He-atmosphere stars. Given that the newly-found C-atmosphere white dwarfs are sandwiched between the V777 Her and ZZ Ceti instability strips, and given that convection plays a key role in the excitation of pulsation modes in these pulsators, it follows that the prospects of finding unstable models of Hot DQ stars looked good at the outset.
2. Stability survey of models of Hot DQ white dwarfs

In an initial effort, three of us carried out an exploratory stability survey of models of carbon-atmosphere white dwarfs using a full nonadiabatic approach, and this was reported in Fontaine, Brassard & Dufour (2008). Our theoretical survey has revealed that \( g \)-modes can indeed be driven in models of Hot DQ stars. However, we found that only those stars with a sufficiently large amount of He \( (\chi(\text{He}) > 0.25) \) in their C-rich envelope mixture could pulsate \textit{in the range of effective temperature where the real C-atmosphere white dwarfs are found.}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Predicted spectra of excited dipole \( g \)-modes computed from four distinct evolutionary sequences, each characterized by a total mass of 0.6 \( M_{\odot} \), but with a different envelope composition: pure C, pure He, \( (\chi(\text{He}) = \chi(\text{C}) = 0.5) \), and pure H, from left to right. The so-called ML2/\( \alpha=0.6 \) version of the mixing-length theory was used in these calculations. Each dot gives the period of an unstable mode, and its size represents a logarithmic measure of the modulus of the imaginary part \( \sigma_I \) of the complex eigenfrequency. The bigger the dot, the more unstable the mode.}
\end{figure}

In this connection, Figure 1 displays some revealing results. It depicts the locations of theoretical instability strips for evolving 0.6 \( M_{\odot} \) white dwarf models with different envelope compositions. Along with the usual V777 Her (pure He) and ZZ Ceti (pure H) instability strips, one can recognize the red edge of the pulsating pure C envelope white dwarf models. In fact, the pure C instability strip extends all the way up to the GW Vir regime as described at length in
Quirion et al. (2007). Given that the true red edge is hotter than the \( \sim 28,000 \) K value found in our survey (and see Fontaine & Brassard 2008), it follows that pure C-atmosphere white dwarfs cannot pulsate in the range of effective temperature where the Hot DQ stars congregate. This is contrary to the arguments put forward by Montgomery et al. (2008).

On the other hand, models with a mixed He and C envelope composition can also pulsate, but in different temperature intervals. For instance, Figure 1 illustrates a new instability strip between the V777 Her and the ZZ Ceti domains associated with white dwarf models with a mixed envelope composition specified by \( X(\text{He}) = X(\text{C}) = 0.5 \). Naively, one could have expected to find such a strip in between the pure C and pure He strips, but structural differences in the mixed envelope composition models explain why this is not so (see Fontaine et al. 2008 for more detailed explanations on this). In brief, the survey of Fontaine et al. (2008) revealed that some Hot DQ white dwarfs can indeed undergo low-order, low-degree \( g \)-mode pulsational instabilities, provided that the surface gravity is larger than average and a substantial amount of He is present in the C-rich envelope mixture.

Figure 2 illustrates the details of the driving/damping region in a Hot DQ model defined by \( \log g = 8.0, T_{\text{eff}} = 17,000 \) K, and with an envelope composition specified by \( X(\text{He}) = X(\text{C}) = 0.5 \). While this is cooler than the coolest C-atmosphere white dwarf known, there is a compensation effect related with the gravity such that a similar behavior is observed in a hotter but higher-gravity model as described in Fontaine et al. (2008). Out of the many \( g \)-modes found excited in the retained model, we have singled out a representative one with indices \( k = 8 \) and \( \ell = 1 \). It has a period of 489.1 s. The figure illustrates a driving/damping situation comparable to the cases of the V777 Her and ZZ Ceti pulsators, but is more complicated because of the presence of two maxima in the opacity distribution instead of a single peak in these other pulsators. In the present case, both opacity maxima (caused by two distinct partial ionization zones in the envelope mixture) are “active” in the sense that they both contribute to the driving/damping process. What we can observe from the plot is that the regions on the descending side (going in from the surface) of an opacity bump contribute locally to driving, while the deeper adjacent zones, where the opacity plummets to relatively low values, contribute instead to damping. In the model, the two opacity bumps are relatively close to each other and are part of a single convection zone. The damping region between the two bumps is then relatively narrow and the overall work integral comes out positive, meaning that the mode is globally excited.

In parallel with our theoretical investigations, but totally independently, Montgomery et al. (2008) carried out an observational search for luminosity variations in six Hot DQ stars accessible to observations in the winter of 2008. They were able to report the very exciting discovery that SDSS J1426+5752, one of the Hot DQ’s found by Dufour et al. (2007), pulsates in, at least, one mode with a period of 417 s, thus establishing the existence of a fourth type of pulsating white dwarf. Full credit should be given to Montgomery et al. (2008) for this important breakthrough. In addition, they reported that no luminosity variations were found, to the limit of detection, in the five other stars in their sample.

Concerning their work, we have to point out, however, that the theoretical arguments put forward by Montgomery et al. (2008) to “predict” pulsational instabilities in Hot DQ stars are fallacious. In particular, the thermal timescale argument that they used is a necessary but not a sufficient condition for instability. Only full nonadiabatic calculations such as those carried out by Fontaine et al. (2008), for example, can lead to the final verdict as whether or not a pulsation mode is unstable in a given stellar model. Montgomery et al. (2008) did not carry out nonadiabatic calculations and could not, therefore, conclude about the stability of Hot DQ models. Fortunately, this did not prevent them from going to the telescope and discovering the first pulsating C-atmosphere white dwarf. In the end, this is really what matters.
Figure 2. Details of the driving/damping process for a typical \( g \)-mode excited in a 17,000 K, ML2 model of a Hot DQ white dwarf with an envelope composition \( X(C) = X(\text{He}) = 0.5 \) and a gravity \( \log g = 8.0 \). The solid curve shows the integrand of the work integral of the mode as a function of fractional mass depth. The dashed curve shows the running work integral, from left to right, toward the surface of the model. The dotted curve shows the ratio of the convective to total flux. The long-dashed curve gives the run of the Rosseland opacity, to be read on the RHS ordinate axis. The maximum in the opacity profile, located at \( \log q \simeq -12.41 \) and corresponding to a temperature \( T \simeq 1.045 \times 10^5 \) K, is caused by the partial ionization of \( \text{He II}, \text{C III}, \) and \( \text{C IV} \) in the envelope mixture. The secondary maximum, located at \( \log q \simeq -8.98 \) and corresponding to a temperature \( T \simeq 1.177 \times 10^6 \) K, is caused by the partial ionization of \( \text{C V}, \) and \( \text{C VI} \). The vertical dotted line on the left (right) gives the location of the base of the atmosphere at optical depth \( \tau_R = 100 \) (of the photosphere at \( \tau_R = 2/3 \)).

3. Follow-up photometric observations of SDSS J1426+5752

Following this discovery, Green, Dufour & Fontaine (2008, in preparation) undertook follow-up wide band photometric observations of SDSS J1426+5752 at the Steward Observatory 1.6-m telescope on Mount Bigelow with the help of the new Montréal 4K×4K CCD camera (Mont4K), a joint venture between the University of Arizona and the Université de Montréal. Some 106 h of observations were obtained on this rather faint star \( (\mathcal{g} = 19.2) \). Figure 3 illustrates one of the nightly light curves obtained by Green et al., leaving no doubt as to the variability of
SDSS J1426+5752. The Fourier amplitude spectrum for the full data set confirms the presence of a dominant pulsation with a period of 417 s and of its first harmonic as first reported by Montgomery et al. (2008). In addition, it also reveals the likely presence of an additional pulsation with a period of 319 s at the 4.9 sigma level. Hence, with at least two independent periodicities uncovered, SDSS J1426+5752 can be considered as a multiperiodic pulsator like the other types of pulsating white dwarfs.

4. Follow-up spectroscopic observations of SDSS J1426+5752
In view of the rather poor SDSS spectrum available for SDSS J1426+5752, follow-up spectroscopic observations were pursued by Dufour et al. (2008b) using both the MMT and one of the Keck telescopes. The objective was, firstly, to obtain a sufficiently good spectrum for detailed atmospheric modeling and, secondly, to search for the presence of He 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 by mass fraction. This is in line with the expectations of nonadiabatic pulsation theory which require an important He “pollution” in the atmosphere/envelope of SDSS J1426+5752 for it to pulsate at its current effective temperature. In this context, Dufour et al. (2008a) also showed that the five other objects found not to vary by Montgomery et al. (2008) are, contrary to SDSS J1426+5752, not expected to vary.

To add to this small success, an unexpected surprise came out of the follow-up spectroscopic
The strong carbon lines are obviously affected by Zeeman splitting due to the presence of a strong magnetic field. The same is true of the faint HeI 4471 line. Although relatively weak, that line implies an atmospheric helium abundance comparable to that of carbon in that star.

Observations of Dufour et al. (2008b). It was found that the strong carbon lines seen in the spectrum of SDSS J1426+5752 feature Zeeman splitting, a structure that could not be seen in the original noisy SDSS spectrum. Figure 4 illustrates our MMT spectrum. The observed splitting between the $\pi$ and $\sigma$ components implies a large scale magnetic field of about 1.2 MG. Hence, SDSS J1426+5752 is both a pulsating and a magnetic white dwarf. As there is no sign of binarity in either the light curve or the optical spectrum (although the phase coverage has been quite limited), SDSS J1426+5752 is most likely the first example of an isolated pulsating white dwarf with a large detectable magnetic field. As such, it is the white dwarf equivalent of an roAp star. Interestingly, SDSS J1426+5752 could have been itself an roAp star in its distant past.

5. Conclusion
It remains to be seen if other stars similar to SDSS J1426+5752 will be found or if it will remain an isolated “freak”. If we adopt a conservative point of view, it takes at least two members to define a “class”, so we should perhaps refrain from referring to it as the prototype of a class for the time being. Note, however, that at the time of writing, rumors have it that two more Hot DQ stars may also be pulsating objects. Be it as it may, SDSS J1426+5752 is certainly different from the other kinds of pulsating white dwarfs that we know of (GW Vir, V777 Her, and ZZ Ceti). It is hoped that further data releases from the SDSS project might reveal siblings of this fascinating star. A fourth asteroseismological window has thus been opened through which one can further study the properties of white dwarf stars.
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