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A three-site photometric campaign on the ZZ Ceti star WD 1524-0030

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Abstract

We obtained 74 hours of time-resolved CCD photometry of the pulsating DA white dwarf star WD 1524-0030 from three different sites well separated in longitude. We found evidence for mild amplitude variability and detected a total of 15 independent and 10 combination frequencies in our light curves. The large number of excited modes, the high amplitudes and nonsinusoidal light curves, the apparent brightness and the equatorial location on the sky make WD 1524-0030 an attractive target for future campaigns with the goal of asteroseismology and nonlinear light curve fitting.

Individual Objects: WD 1524-0030

Introduction

Asteroseismology of pulsating DA white dwarf stars (the ZZ Ceti stars), in the sense of exploring their interior structures in very detail, has always been difficult. The sparse and temporally unstable mode spectra, combined with an interior structure more complicated than that of the DB and PG 1159 pulsators, have been a major obstacle to the study of cool white dwarf interiors.

The strategy that is generally applied to overcome these problems is to obtain observational mode identifications. Spectroscopy can lead to such identifications (e.g., see Thompson, van Kerkwijk, & Clemens 2008 and references therein), but requires very large telescopes to reach the necessary signal to noise ratio because pulsating white dwarf stars are intrinsically and apparently faint ($V > 12.2$) and oscillate rapidly (100 s $\lesssim P \lesssim$ 1000 s).

However, another method for mode identification may have come to the rescue. Brickhill (1992) showed how the surface convection zone of pulsating white dwarfs modifies their light curve shapes, causing harmonic and combination signals in frequency spectra. Following up on this work, Wu (1998) pointed out that the amplitudes and phases of these combination terms depend on the types of pulsation modes that cause them. Consequently, Montgomery (2005) derived a method to constrain pulsational mode identifications from the light curve shapes of pulsating white dwarfs, and to recover the thermal response time scale of the convection zone, which depends on effective temperature.

This is excellent news for asteroseismology of the cooler DB and DA white dwarf stars: if several pulsation modes are observed in some of these pulsators, and if their light curve shapes are nonsinusoidal and of reasonably large amplitude, mode identifications can be derived and compared with those from other methods, like pattern recognition or spectroscopy.

The Delaware Asteroseismic Research Center (DARC, Provencal & Shipman 2006), home of the Whole Earth Telescope (WET, Nather et al. 1990), has recently concentrated on exploiting this method. In May 2006, the prototype DB pulsator GD 358 was observed (Provencal et al. 2008), and the ZZ Ceti star EC 14012-1446 was the subject of a recent WET run in March/April 2008. Furthermore, additional targets for simultaneous nonlinear light-curve fitting and asteroseismology are searched for via smaller campaigns. Ideally, such an object is bright, has high pulsation amplitudes, nonsinusoidal light curves, and many modes. One of these candidates is the ZZ Ceti star WD 1524-0030, discovered by Mukadam et al. (2004). The present paper reports the results of an exploratory campaign devoted to WD 1524-0030.

Observations and reductions

In March/April 2007, we obtained time-resolved CCD photometry of WD 1524-0030 with three telescopes at different sites: the 0.9-m telescope at the Cerro Tololo Interamerican Observatory (CTIO) in Chile, the 0.8-m telescope at Vienna University Observatory in Austria, and the 2.1-m telescope at McDonald Observatory in Texas, USA. All measurements were acquired through a BG40 or S8612 filter, serving three purposes: first, to have similar wavelength response, close to that of a blue photomultiplier tube; second, to reduce effects of differential colour extinction; third, to suppress the contribution of the visual companion star of WD 1524-0030, a very red object, to the light curves. Table 1 contains the journal of the observations.

Table 1: Journal of the observations

Observatory	Run start date/time dd/mm hh:mm (UT)	Length hr	#data points
CTIO	30/03 04:27	5.32	646
CTIO	01/04 04:01	6.26	685
CTIO	03/04 03:49	6.31	762
CTIO	06/04 05:06	4.79	493
CTIO	08/04 03:42	5.86	568
CTIO	10/04 06:20	3.67	391
Vienna	11/04 22:18	4.96	843
Vienna	12/04 22:28	4.74	800
Vienna	13/04 22:23	4.42	722
Vienna	14/04 22:21	4.65	791
Vienna	15/04 22:24	4.56	713
McDonald	22/04 10:39	1.32	923
McDonald	24/04 06:19	5.73	2065
McDonald	25/04 05:46	6.06	2169
McDonald	26/04 06:18	5.56	1092
Total		74.21	13663

The data were reduced with standard IRAF procedures to correct the images for overscan, bias level (if needed), dark counts (if needed) and flat field. Photometry of the Vienna data was carried out using the MOMF (Multi–Object Multi–Frame, Kjeldsen & Frandsen 1992) package, whereas the other measurements were subjected to a series of IRAF scripts employing aperture photometry optimized for high-speed CCD data (Kanaan, Kepler, & Winget 2002). Both photometry packages give results of comparable quality, in the form of a differential light curve of the target star.

Given the difference in the size of the telescopes used, and given the fact that observatories at mountain sites, but also in an urban area were involved, one might wonder how the quality of the light curves compares. Some examples are shown in Fig. 1. Whereas the data from McDonald Observatory are clearly best, the oscillations of this $15^{\rm th}$ magnitude star are still conspicuously present in the light curves from Vienna. We note that we plotted the fractional intensity variation of the star, in units of modulation intensity, and that we will use the modulation amplitude as our unit of choice for expressing amplitudes (see WET 1993 for definitions) to avoid the logarithmic scale of magnitudes, and the consequent unphysical light curve distortions.

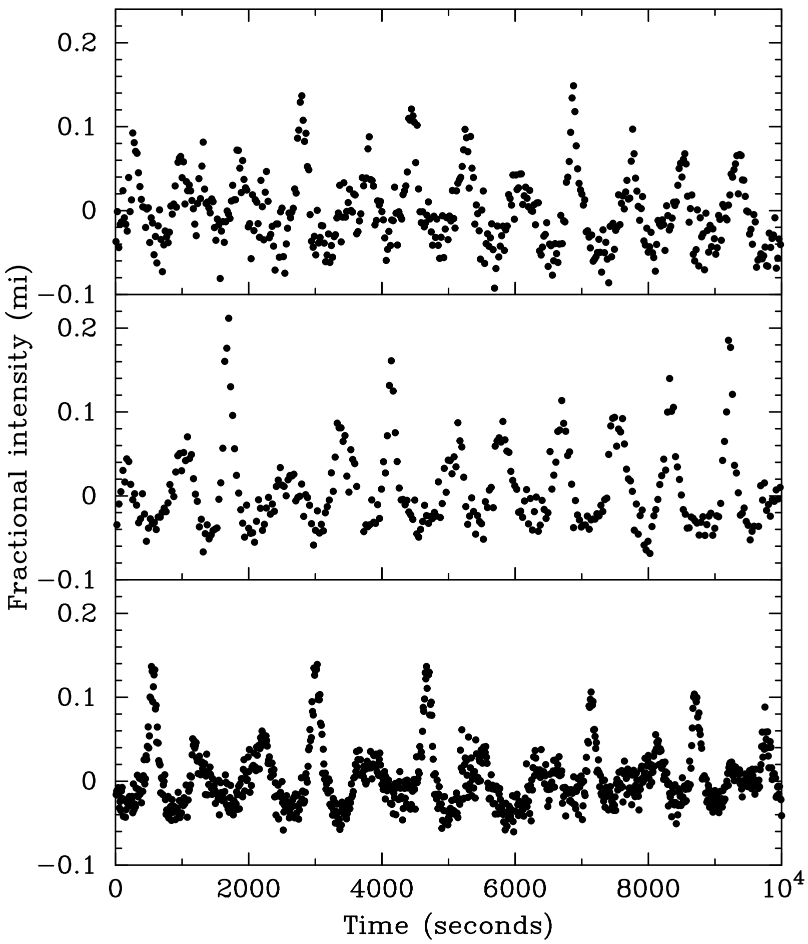

Figure 1: Some example light curves of WD 1524-0030. Upper panel: data from Vienna (April 12), from a 0.8-m telescope at an urban site. Middle panel: a light curve from CTIO (April 6), from a 0.9-m telescope at a mountain site. Lower panel data from McDonald Observatory (April 25), taken with a 2.1-m telescope at a mountain site. Note that the latter data have twice the sampling rate compared to the remainder.

As the last reduction step, the light curves were combined. To give all data equal weight in the frequency analysis to follow, the measurements from McDonald Observatory were binned to the same cadence as the CTIO and Vienna data (20 s). Finally, all timings were converted to Barycentric Julian Ephemeris Date (BJED) to ensure a common and consistent time base.

Frequency analysis

We searched the data for periodicities using the program `Period04` (Lenz & Breger 2005). This package applies single-frequency power spectrum analysis and simultaneous multi-frequency sine-wave fitting. It also includes advanced options such as the calculation of optimal light-curve fits for multi-periodic signals including harmonic and combination frequencies, which will be required in our analysis.

The amplitude spectrum of our combined light curves is presented in Fig. 2. There are several regions that contain significant power, and the spectral window function is in most cases simpler than the structure in the regions of power, indicating the presence of more than one signal.

Because high-amplitude pulsating white dwarf stars often show amplitude and frequency variations on short time scales, we first computed the Fourier amplitude spectrum of the data from the different sites, which are also separated in time (cf. Table 1). We noticed that the periodogram from the measurements at McDonald Observatory showed a maximum amplitude about 20 per cent higher than the periodograms from the other two sites, indicating possible amplitude variability.

We therefore used the following approach to frequency search: we examined three subsets of the data separately, and only accepted signals that were convincingly present in all three. The subsets were: a) all data (best time resolution and spectral window), b) the Vienna data plus the last night from CTIO (highest duty cycle), c) all CTIO and Vienna data (good spectral window and duty cycle). With this strategy we detected fourteen independent frequencies and the harmonic of the strongest signal.

With these frequencies a rough examination of the presence of amplitude and/or frequency variations during our observations is possible. We assumed constant frequencies over the whole data set and fitted them individually to the data from the three sites, leaving only the amplitudes and phases as free parameters. Whereas we found little evidence for temporal changes in the phases (and thus frequencies), some amplitude changes were detected. Because the amplitudes did not change systematically from site to site, we can rule out that they are affected by possible residual differences between the photometric passbands, and thus different contributions from the visual companion, within the accuracy of our measurements. The low duty cycle of our measurements precludes a deeper investigation of amplitude/frequency variability, but we can safely state that they must be intrinsic to the star, and are in most cases not due to beating between signals unresolved in frequency.

We continued the analysis by examining amplitude spectra prewhitened by the previously detected signals, keeping the frequencies and phases constant,

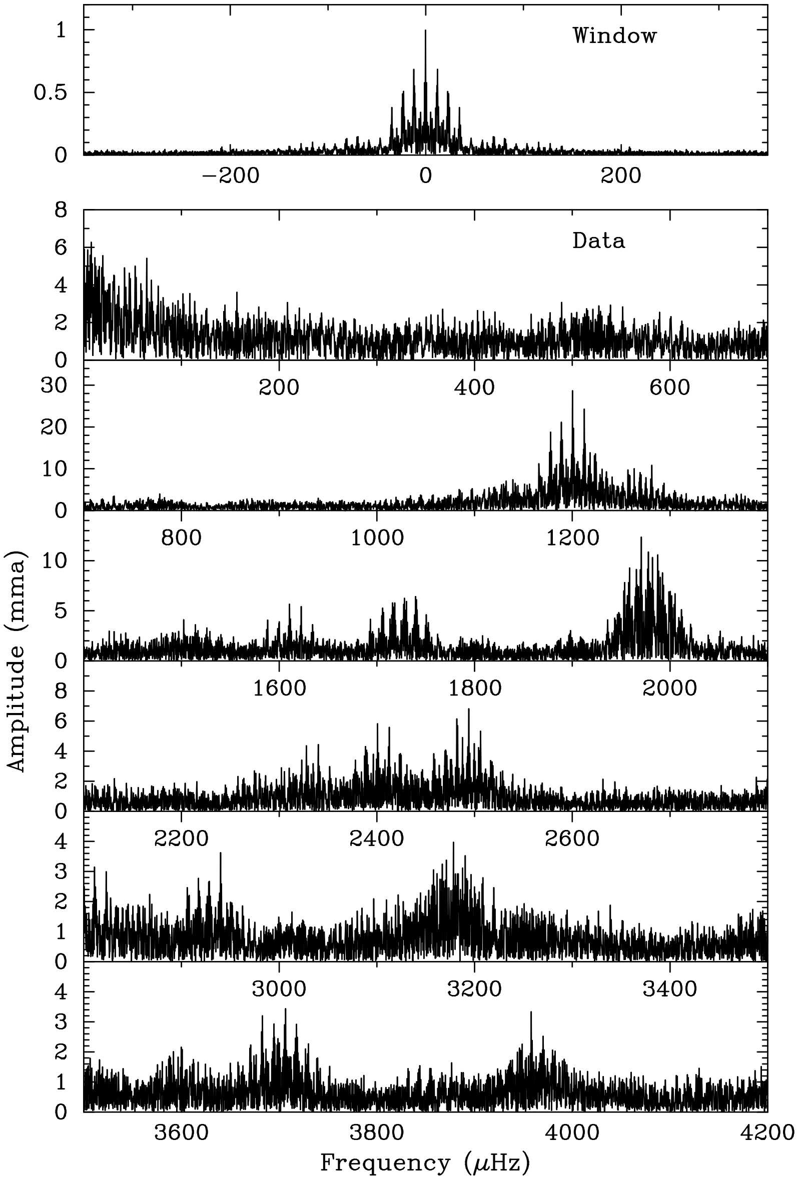

Figure 2: Amplitude spectrum of our multisite data of WD 1524-0030. The uppermost panel is the spectral window function of the data.

Table 2: Frequencies and mean amplitudes of the signals in our light curves of WD 1524-0030, not corrected for the influence of the close companion star.

ID	Freq. (μHz)	Ampl. (mma)	Period (s)	ID	Freq. (μHz)	Ampl. (mma)
Independent frequencies				Combination signals		
f_1	1139.31	6.8	877.7	$f_{10} - f_3$	777.80	4.0
f_2	1189.81	9.4	840.5	$2f_3$	2400.72	5.4
f_3	1200.36	25.7	833.1	$f_3 + f_4$	2481.83	4.2
f_4	1281.47	9.4	780.3	$f_3 + f_6$	2811.10	3.1
f_5	1502.54	4.2	665.5	$f_3 + f_9$	3171.07	3.0
f_6	1610.75	5.8	620.8	$f_3 + f_{10}$	3178.51	3.9
f_7	1718.35	5.1	582.0	$f_3 + f_{12}$	3187.73	2.9
f_8	1728.21	5.9	578.6	$2f_3 + f_4$	3682.19	2.1
f_9	1970.71	10.9	507.4	$f_7 + f_{12}$	3705.72	2.5
f_{10}	1978.15	10.1	505.5	$f_9 + f_{12}$	3958.09	3.3
f_{11}	1979.91	5.2	505.1			
f_{12}	1987.38	8.4	503.2			
f_{13}	2340.06	4.4	427.3			
f_{14}	2494.25	5.4	400.9			
f_{15}	2940.09	3.5	340.1			

but letting the amplitude vary for each site. However, keeping in mind the limitations of our data set, we concentrated on finding combination frequencies rather than independent signals. A single convincing independent frequency was added to our result, and nine more combination signals were found. The final list of frequencies obtained in this way is given in Table 2, and the residual amplitude spectrum after their prewhitening is the subject of Fig. 3.

Our frequency solution has succeeded in explaining most of the variability measured, with the notable exception of the frequency region around 1200 μHz, in which the periodogram is quite complicated. The broad envelope of this residual structure suggests the presence of several additional pulsational signals. However, we did not dare to push the frequency analysis further in this domain because we feared running into aliasing problems. In addition, amplitude variations of pulsating white dwarf stars are generally more pronounced at higher radial overtones (see Handler et al. 2008 or Provencal et al. 2008 for discussions), therefore lower frequencies, and we cannot expect our crude method to take them reliably into account in this case. We also note the occurrence of two peaks (f_{10} and f_{11}) spaced by only 1.8 μHz, but our data set does not

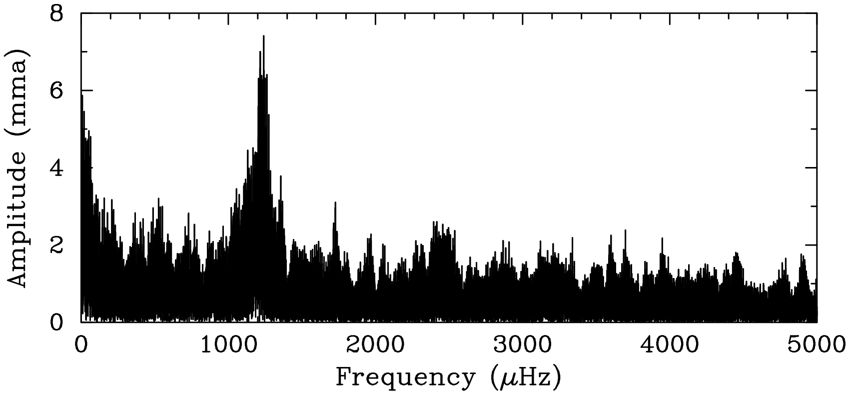

Figure 3: Residual amplitude spectrum of our data of WD 1524-0030 after prewhitening the 25 signals from Table 2.

allow us to investigate whether these are two independent signals or this might be an artefact caused by amplitude variability.

Discussion and conclusions

We have acquired over 70 hr of time-resolved CCD photometry of the pulsating white dwarf star WD 1524-0030 from three sites. We detected a fairly large number of independent signals in its light curves that should be caused by independent pulsation modes. Sometimes we found multiple peaks, notably in the 1980 μHz region, that could be an indication of rotational splitting. One might also speculate about the presence of an ≈ 40 s period spacing among the independent signals.

Our three-site campaign has succeeded to show that WD 1524-0030 is a good target for applying asteroseismic methods to this ZZ Ceti star. In addition, its high amplitudes and nonsinusoidal light curves make it an interesting target to apply Montgomery's (2005) nonlinear light curve fitting method. Such an effort has however to be based on a considerably more extensive data set, which could ideally be provided by the Whole Earth Telescope.

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