Whole Earth Telescope Observations of the DAVs R808 and G38-29

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\textbf{Abstract.} The Whole Earth Telescope, under operation by the Delaware Asteroseismic Research Center, have obtained multi-site observations of two pulsating white dwarf stars. The DAVs R808 and G29-38 both show an abundance of excited modes, mostly clustered around 1050\textmu Hz. We present the Fourier analysis of both multi-site campaigns, present the measured periods, discuss their combination modes, and show that amplitude modulation is present in these stars.

1. Introduction

The Delaware Asteroseismic Research Center (DARC) sponsored two multi-site campaigns of DAVs prior to the White Dwarf Workshop in Barcelona; a small campaign in November 2007 of G 38-29 and a full Whole Earth Telescope run in April 2008 of EC14012-1446, PG1159-035, and R808. The main purpose of these observations were to 1) accurately measure the light curve in order to map convective timescale across the DAV instability strip (Montgomery, 2005) 2) measure the frequencies for the purposes of asteroseismology and 3) for PG1159-0035 to measure the $\dot{P}$.

The convection zone distorts the pulsations, creating pulse shapes with sharp peaks and shallow troughs. By measuring the shapes of these pulses we can ultimately determine the depth of the convection zone and how it changes with temperature. This technique is most effective on stars with large amplitudes where the nonlinear effects introduced by the convection zone are largest. Though the technique is most easily applied to pulsators with only a couple modes, analysis of GD 358 (Montgomery, 2008; Proven\textsuperscript{\textsuperscript{c}}al, 2008), with its large, complicated set of frequencies, has shown that the convective fitting technique may be applied to a much larger sample of stars.

The first step for both convective fitting and asteroseismological analysis is to measure the pulsation modes on the star. Here we present the preliminary analysis of R808 and G38-29. We present the abundance of modes found for each, discuss how combination modes may help determine $\ell$ for some modes, and demonstrate that amplitude modulation plays an important role in the light curves of these stars. The large set of frequencies on each star may be ideal for asteroseismological studies and may complicate the measuring of their convection zones.
2. Light curves of R808 and G38-29
We analyzed time series photometry on R808 between April 4 and April 17, 2008 collected by 13 different telescopes. Similarly time series photometry of G38-29 was collected by 9 telescopes between November 5 and November 16, 2007 (Table 1). For both runs the reductions of the CCD images include, bias/dark subtraction and flat-fielding. We used IRAF routines to perform the aperture photometry, \texttt{wed} (Thompson & Mullally, 2008) to clean the light curve and apply the barycentric correction and Period04 (Lenz & Breger, 2005) for Fourier analysis.

Both were chosen for their large, nonlinear pulse shapes, in the hopes they may be ideal targets for measuring convection via light curve fitting. Figure 1 shows an example of both light curves. Each shows the nonlinear pulse shapes and beating between the various modes.

![Figure 1](image)

\section*{Figure 1.} A portion of the light curves of R808 (taken by Kitt Peak's 2.1 m) and G38-29 (taken by McDonald's 2.1 m). Each shows evidence of the nonlinear pulse shapes, with peaky tops and shallow troughs typical of large amplitude DAV light curves.

3. FTs and Periods
The Fourier transform for G38-29 and R808 are presented in Figure 2. By sequentially selecting the largest peak in the Fourier transform, we do a nonlinear fit at the selected frequencies and remove the fit from the light curve. With this process we found 24 frequencies in G38-29 and 29 in R808. Each mode is 4 times the average power of the surrounding residual peaks. However, be cautious when considering the low amplitude modes near 1000 \( \mu \)Hz in both stars. The one day alias peak is 57\% and 38\% of the amplitude of the mode for G38-29 and R808 respectively. Thus, with closely spaced, low amplitude modes (as around 1000 \( \mu \)Hz), the highest peak is not always the real signal. When presented with several peaks of similar amplitude we selected those modes that, once removed, left the residual FT with the least signal. Modes identified in each star are shown in Table 2 and 3.

\subsection*{3.1. Combination Modes}
Combination modes and harmonics are common to DAVs as a result of the nonlinear pulse shape. These are not physical standing waves of the white dwarf that could help reveal the internal structure of the star. The convection zone changes depth and it strongly attenuates the modes as the temperature changes on the star. As a result, it causes the pronounced nonlinearities and combination modes. Both G38-29 and R808 show peak-to-peak variations of 10\%, however only G38-29 shows obvious combination modes. R808 instead shows an abundance of low amplitude
pulsations that constructively interfere to create large amplitude pulsations. The combination modes on R808 are presumably present, but simply with too low amplitude to be detected when compared to the 1 mma noise level in the FT.

The ratio of the amplitudes between the combination mode and its parents, $R_c$ (van Kerkwijk et al., 2000; Wu, 2001) has been used as a diagnostic of $\ell$ in the low amplitude DAVs (Yeates et al., 2005). This method is complicated by the fact that $R_c$ also depends on the inclination and the azimuthal order ($m$) of the mode. We do not have space here to do a full combination mode analysis. However we note that for G38-29, the harmonic of F15 is much lower than the harmonic of F07, as one would expect if F15 is an $\ell=1$, $m=0$ and F07 is an $\ell=2$, $m=0$. Notice also that F10+F15 and F12+F15 have $R_c$ values similar to 2F15, as one would expect for the combination of two $\ell=1$ modes. The $R_c$ values for R808 are very large, implying large $\ell$, or more likely, mis-identification as combination modes.

![Figure 2.](image)

**Figure 2.** The Fourier transform of G38-29 and R808 and their windows (upper right plots). Both show an abundance of power near 1000 $\mu$Hz. Many of the shorter period modes in G38-29 are combination modes, while few of the significant peaks in R808 are combinations. See Tables 2 and 3 for the measured periods.

4. Amplitude Modulation
Both R808 and G38-29 show significant variations in the amplitude of the modes during the run. See Figures 3 and 4 for plots of amplitude versus time for a sampling of modes. In each
case the amplitudes were measured by fitting the modes listed in this paper to 5.5 day long segments of each light curve, long enough to resolve modes as close as 2.1$\mu$Hz. For R808, the larger amplitude variations occur for the longer period modes where an abundance of modes have been excited. For G38-29 there is no basic trend with period; one of the shortest periods, 546 s, shows a rise in amplitude from 4-10 mmag over the course of 10 days.

Either Figures 3 and 4 represent true variations in the amplitudes on time scales of days, or nearby modes exist that are not resolved in the 2-3 week time span of each data set. If these amplitude modulations were due to beating, we would expect sinusoidal variations in amplitude. As that is not what we observe, these are likely intrinsic amplitude modulations. However, amplitude modulation exemplifies the limitations of Fourier analysis; prewhitening by a constant amplitude when the mode’s amplitude is actually varying will leave significant signal that can easily be interpreted as a true stellar pulsation.

Figure 3. Mode amplitude vs. time for select modes of G38-29. Some modes show significant variations (980.14 s and 546.96 s) in amplitude while others show almost none (705.97 s). The first two points represent data taken prior to the November campaign, not included in the Fourier analysis of this paper.

5. Conclusions
We have observed two DAVs with large pulses and a plethora of modes. As each mode probes different layers of the star, these are good candidates for asteroseismology if we can be confident
Figure 4. Mode amplitude vs. time for select modes of R808. Shorter period modes clearly show less modulation than longer periods.

that the modes we identify are due to the star’s inherent structure, and are not due to changes in long term variations in mode amplitudes, or nonlinear effects on the star (combination modes). These data emphasize the need to explore different observing and/or analysis techniques to positively identify the physical pulsations from the nonlinear effects. We plan to apply the convection zone fitting technique on both of these stars if asteroseismological models can provide sufficient constraints on the $\ell$ and $m$ values of the observed modes present in G38-29 and R808.

References
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Table 1. Telescopes that observed R808, April 2008 and G38-29, November 2007.

| Observatory  | Longitude (° East) | Length (Hours) |
|--------------|--------------------|----------------|
| **R808**     |                    |                |
| OHP          | 5.7                | 1.7            |
| Loiano       | 11.3               | 6.48           |
| Vienna       | 16.3               | 13.72          |
| Konkoly      | 19.9               | 11.59          |
| Suhora       | 20.1               | 32.90          |
| Moletai      | 25.5               | 1.25           |
| Terskol      | 42.5               | 4.00           |
| BAO          | 116.3              | 5.09           |
| BOAO         | 128.9              | 9.09           |
| Kitt Peak    | 248.4              | 9.32           |
| SARA         | 248.4              | 20.39          |
| PJ Meyer     | 262.3              | 49.25          |
| Mount Cuba   | 284.4              | 5.50           |
| **G38-29**   |                    |                |
| Konkoly      | 19.9               | 11.50          |
| Suhora       | 20.1               | 22.82          |
| MIRO         | 72.4               | 27.2           |
| BOAO         | 128.9              | 34.54          |
| Faulkes North| 203.7              | 55.70          |
| U. Hawaii    | 204.5              | 68.05          |
| Apache Point | 247.5              | 11.15          |
| McDonald     | 257.0              | 42.71          |
| Mount Cuba   | 284.4              | 6.67           |
Table 2. Properties of the pulsation modes of G38-29 as measured with the function $A \sin(2\pi f(t + t_0))$. Error in frequency is $\sim 0.02 \mu$Hz, error in amplitude is $\sim 0.2$ mma. The initial barycentric Julian ephemeris day for this data set is 2454410.47025381.

| ID     | $f$ (µHz) | Period (sec) | $A$ (mma) | $t_0$ (sec) | $R_e$ |
|--------|-----------|--------------|-----------|-------------|-------|
| F01    | 917.948   | 1089.39      | 5.20      | 126.95      | –     |
| F02    | 920.169   | 1086.76      | 3.92      | 129.55      | –     |
| F03    | 924.369   | 1081.82      | 5.04      | 886.08      | –     |
| F04    | 984.107   | 1016.15      | 7.20      | 643.03      | –     |
| F05    | 997.841   | 1002.16      | 7.14      | 562.24      | –     |
| F06    | 1010.39   | 989.719      | 10.04     | 649.00      | –     |
| F07    | 1020.26   | 980.141      | 11.43     | 173.88      | –     |
| F08    | 1037.78   | 963.593      | 4.58      | 800.31      | –     |
| F09    | 1039.42   | 962.077      | 8.09      | 560.91      | –     |
| F10    | 1057.70   | 945.448      | 12.34     | 788.88      | –     |
| F11    | 1083.83   | 922.657      | 5.94      | 863.09      | –     |
| F12    | 1111.15   | 899.971      | 10.59     | 438.43      | –     |
| F13    | 1189.92   | 840.390      | 5.19      | 50.605      | –     |
| F14    | 1409.98   | 709.232      | 6.03      | 558.67      | –     |
| F15    | 1416.49   | 705.970      | 18.44     | 343.07      | –     |
| F16    | 1821.69   | 548.939      | 4.83      | 425.65      | –     |
| F17    | 1828.29   | 546.960      | 6.97      | 208.18      | –     |
| F18    | 1835.10   | 544.928      | 6.12      | 331.45      | –     |
| F19    | 2312.92   | 432.354      | 3.57      | 235.77      | –     |
| F20    | 2419.51   | 413.307      | 3.07      | 297.05      | –     |
| F18-F15| 418.185   | 2391.28      | 4.11      | 1131.97     | 18.2 |
| F17-F14|      "    |      "       |      "    |      "      | 48.9 |
| F17-F06| 818.380   | 1221.93      | 3.70      | 937.64      | 26.4 |
| 2F07   | 2040.54   | 490.067      | 3.72      | 19.88       | 28.5 |
| F07+F15| 2436.80   | 410.375      | 2.80      | 203.40      | 6.6  |
| F10+F15| 2474.26   | 404.162      | 3.46      | 1.457       | 7.6  |
| F12+F15| 2527.72   | 395.614      | 3.63      | 266.67      | 9.3  |
| 2F15   | 2832.61   | 353.031      | 2.55      | 352.51      | 7.5  |
| F15+F16| 3238.14   | 308.819      | 2.07      | 22.86       | 11.6 |
| F14+F17|      "    |      "       |      "    |      "      | 24.6 |

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Table 3. Properties of the pulsation modes of R808 as measured with the function $A \sin(2\pi f(t + t_0))$. Error in frequency is $\sim 0.02 \, \mu$Hz, error in amplitude is $\sim 0.2$ mma. The initial barycentric Julian ephemeris day for this data set is 2454555.53472367.

| ID  | $f$ ($\mu$Hz) | Period (sec) | $A$ (mma) | $t_0$ (sec) | $R_e$ |
|-----|---------------|--------------|-----------|-------------|-------|
| F01 | 406.652       | 2459.1       | 2.22      | 670.43      | –     |
| F02 | 874.16        | 1143.96      | 2.50      | 502.95      | –     |
| F03 | 916.516       | 1091.09      | 2.36      | 403.53      | –     |
| F04 | 937.444       | 1066.73      | 2.21      | 604.71      | –     |
| F05 | 959.649       | 1042.05      | 2.89      | 908.71      | –     |
| F06 | 961.476       | 1040.07      | 3.34      | 899.31      | –     |
| F07 | 988.736       | 1011.39      | 2.54      | 623.36      | –     |
| F08 | 1041.1        | 960.527      | 3.68      | 704.48      | –     |
| F09 | 1049.98       | 952.398      | 3.36      | 658.35      | –     |
| F10 | 1084.01       | 922.504      | 3.40      | 727.11      | –     |
| F11 | 1091.94       | 915.803      | 5.54      | 742.81      | –     |
| F12 | 1093.27       | 914.683      | 3.94      | 847.06      | –     |
| F13 | 1097.05       | 911.534      | 3.16      | 702.63      | –     |
| F14 | 1100.81       | 908.422      | 7.59      | 819.87      | –     |
| F15 | 1112.71       | 898.707      | 3.57      | 785.50      | –     |
| F16 | 1138.33       | 878.479      | 3.62      | 352.26      | –     |
| F17 | 1142.67       | 875.146      | 3.73      | 620.38      | –     |
| F18 | 1162.48       | 860.227      | 3.48      | 664.51      | –     |
| F19 | 1186.65       | 842.707      | 2.81      | 409.19      | –     |
| F20 | 1255.88       | 796.253      | 3.97      | 369.707     | –     |
| F21 | 1342.07       | 745.12       | 3.97      | 69.106      | –     |
| F22 | 1581.83       | 632.179      | 3.41      | 473.715     | –     |
| F23 | 1580.25       | 629.228      | 1.88      | 8.246       | –     |
| F24 | 1955.93       | 511.266      | 4.49      | 35.256      | –     |
| F25 | 2472.45       | 404.457      | 1.99      | 225.66      | –     |

F17-F08 101.555 9846.84 2.38 3881.2 86.7
2F16 2276 439.368 1.71 133.53 130.7
F14+F22 2682.77 372.749 1.5 131.561 29.0