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Asteroseismology of GD358 with complex core carbon and oxygen profiles

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Abstract. GD 358 is the brightest ($m_{\rm v} = 13.7$) and best studied helium atmosphere white dwarf pulsator. We present an analysis based on over 1000 hours of observations spanning 2007-2014 as well as archival data going back to 1982. From the complete data set, we identify a total of 27 independent frequencies and fit 14 of them as m=0 modes in our asteroseismic analysis. We add GD358 to a set of helium atmosphere white dwarfs fitted with similar models. With this consistent set, we can see a trend in the thickness of the pure helium layer that are quantitatively consistent with time-dependent diffusion calculations.

Keywords. Convection, Dense Matter, Diffusion, stars: AGB and post-AGB, stars: evolution, stars: individual (GD358), stars: interiors, stars: oscillations, stars: variables: other, white dwarfs

1. Introduction

GD358 (V777 Her) is the brightest ($m_{\rm v} = 13.7$) and best studied helium atmosphere white dwarf pulsator. This star was discovered in 1982 (Winget *et al.* 1982) and has been the target of the Whole Earth Telescope (WET) in 1990, 1994, 2000, and 2006 (Provencal *et al.* 2009; Kepler *et al.* 2003; Winget *et al.* 1994). More observations (1105.1 hrs) were collected during WET runs spanning 2007-2014 (Bischoff-Kim *et al.*, in preparation).

Paradoxally, among the DBVs that have enough periods to be fitted asteroseismically, GD358 is the only one that has not been analyzed using the complex C/O profiles adapted and parameterized from stellar evolution calculations (e.g. Salaris *et al.* 1997; Althaus *et al.* 2005). In addition, we have identified more periods in GD358's pulsation spectrum, bringing the total of known modes to 15 (from 11).

2. Pulsation spectrum

Figure 1 summarizes all the modes found in GD 358 over the years. One can see clear clumps at frequencies where the modes are recurring. While there are variations in amplitude, frequencies are relatively stable. From the clumps, one can determine average frequencies, listed as periods in table 1. A formal determination of error bar based on the spread and number of peaks in each clump yet has to be done. The formal error on individual frequencies is less than 0.03μHz. The modes exhibit a nearly perfectly uniform pacing of 39.6 seconds, consistent with an $\ell = 1$ sequence. 13 of these modes belong to a consecutive sequence, the longest observed in a helium or hydrogen atmosphere white dwarf.

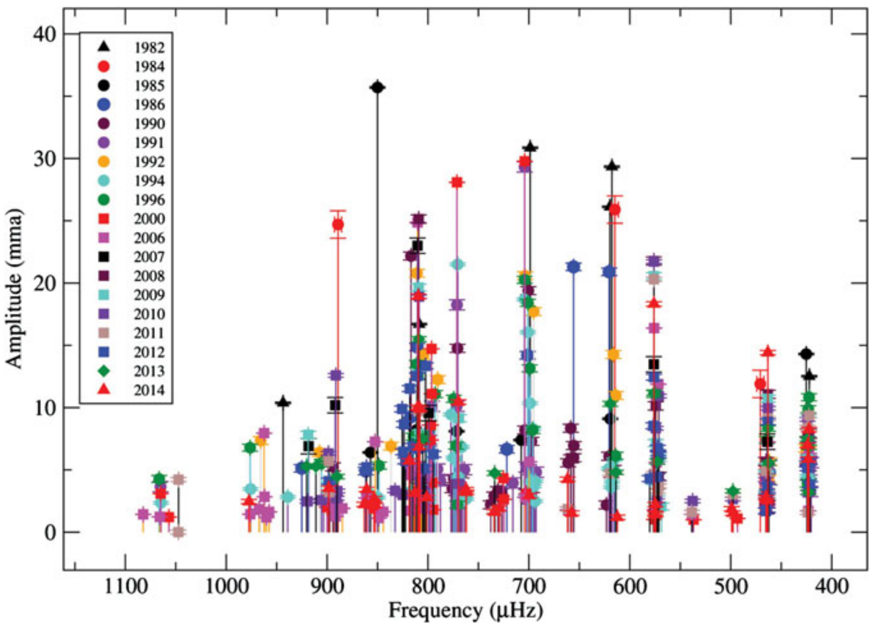

Figure 1. Modes found in GD358 in data collected since 1982.

Table 1. The 15 m = 0 modes found in GD358s period spectrum and the corresponding periods in the best fit model.

P_{obs} [s]	P_{model} [s]	k
423.13	421.92	8
463.92	461.92	9
498.08	496.40	10
538.30	538.70	11
574.22	573.18	12
617.41	617.61	13
658.68	659.08	14
699.80	698.42	15
730.25	731.77	16
769.72	771.74	17
807.92	807.27	18
854.52	853.29	19
902.52	894.53	20
968.03	962.65	22
1062.23	Not included	24

3. Modeling and fitting

We used the White Dwarf Evolution Code (WDEC), updated and adapted to helium atmosphere white dwarfs (Bischoff-Kim & Metcalfe 2011), to compute over ten million white dwarf models with their corresponding oscillation periods. Each model is characterized by 6 parameters: The effective temperature, the stellar mass, and 4 structure parameters, including the thickness of the helium layer. We look for the model whose periods most closely match the observed periods. The results are summarized in table 1. The RMS standard deviation between the observed and model periods is 1.58 seconds.

The quality of fit is the worst for the k = 22 mode. The highest k mode fits very poorly in our models and we rejected it in our final fits. Higher k modes have turning points close to the base of the convection zone, as shown in figure 2. It is not surprising that they are poorly fit by static models. Our goal with our fitting is to find the interior structure

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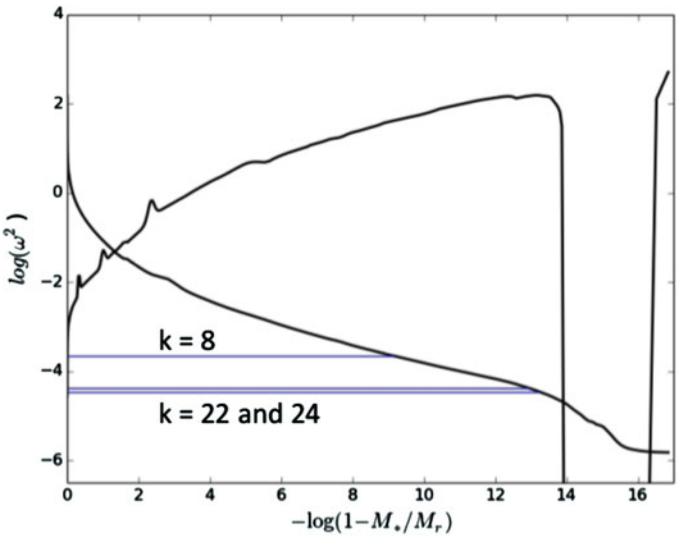

Figure 2. Propagation diagram for our best fit model of GD358. The center of the model is on the left. The monotonously decreasing curve is the Lamb frequency, while the other curve is the Brunt-Väisälä frequency. The convection zone lies between $\sim$ 14 and 16 in the mass coordinate defined below the horizontal axis. The $k = 8$ mode propagates between the center (or close) and an outer turning point that lies deep below the convection zone, while the $k = 22$ and 24 modes have their outer turning point close to the base of the convection zone.

of the star, so not being able to fit the surface modes or rejecting them is reasonable. A consecutive k = 8 to k = 20 sequence is more than enough to uniquely determine the parameters of the best fit model

The best fit model has an effective temperature of 23,600 K, a little over one sigma below the spectroscopic value (Bergeron *et al.* 2011). The mass we find, 0.605 $M_\odot$, is consistent with the spectroscopy. We find a central oxygen abundance of 0.99 (high) and the edge of the C/O homegeous core is located at 0.50 M_r/M_*. The base of the Carbon/Helium region is located at $q = -2.40$, and the base of the pure helium envelope at $q = -5.20$. q is a mass coordinate defined as $q = \log(1 - M_r/M_*)$.

4. Results placed in the context of diffusion theory

As a white dwarf cools, the heavier elements in its envelope sink down under gravity, pushing the lighter elements toward the surface. For helium atmosphere white dwarfs, this means that cooler stars should have thicker pure helium layers. We have now analyzed a total of four stars using grids of WDEC models. We indeed see a trend, with cooler models having the thicker helium layers (Fig. 3).

The star EC 20058 is strikingly off the trend. New analysis of its UV spectrum (Koester *et al.* 2015) indicates that the star may be cooler than we originally thought. It would be interesting to see if there is a good fit to the periods of the star that has a lower effective temperature, and what structure such a model would have.

5. Conclusion

Based on archival single and multi-site data going back to 1982, as well as over 1000 hours of observations spanning 2007-2014, we presented a new pulsation spectrum for GD 358. We used updated models that include core carbon and oxygen profiles scaled from

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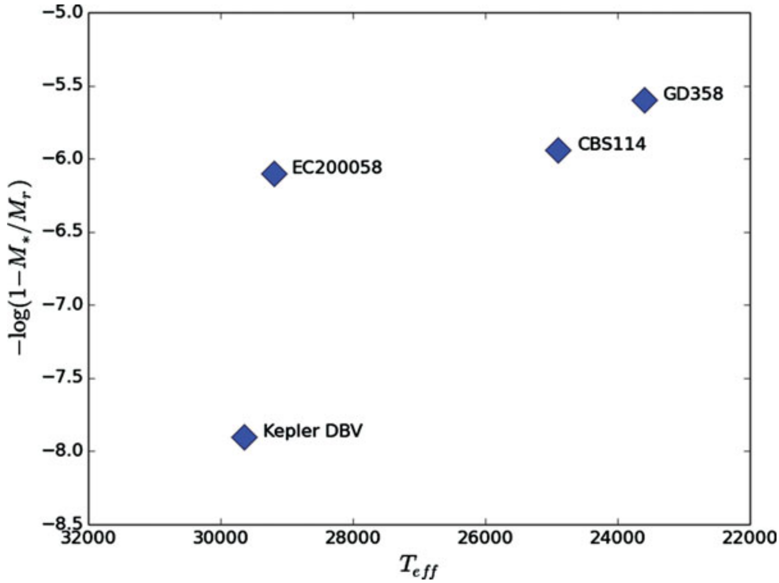

Figure 3. Correlation between the thickness of the pure helium layer of four helium atmosphere white dwarfs fitted using a consistent set of models: GD 358 (this work), CBS 114 (Metcalfe 2005), EC 20058 (Bischoff-Kim & Metcalfe 2011), and the Kepler DBV (Bischoff-Kim *et al.* 2014). The "Kepler DBV" is also known as WD J1929+4447 or KIC 8626021 in the *Kepler* input catalog. The temperatures used to make the plot are the ones derived from the asteroseismic fits. The vertical axis goes from thin to thick helium layer. All four stars are similar in stellar mass (0.605 $M_\odot$, 0.640 $M_\odot$, 0.550 $M_\odot$, and 0.550 $M_\odot$ respectively).

stellar evolution calculations to fit the period spectrum. We find a mass consistent with the spectroscopy and an effective temperature 1 sigma below the spectroscopic value.

More interestingly, we find a trend with best fit models of cooler stars having thicker helium layers. It would be worthwhile quantifying this trend and comparing it with time-dependent diffusion calculations. The mass dependence of the relation is worth exploring and the statement "GD358, CBS114, EC20058, and the Kepler DBV are similar in stellar mass" needs to be quantified in the framework of time-dependent diffusion.

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