

1. INTRODUCTION

Much to everyone’s surprise considering the statistical odds, a helium atmosphere white dwarf pulsating white dwarf (WD; a DBV) was discovered in the 115.6 deg$^2$ part of the sky monitored by the Kepler satellite. The pulsational characteristics of the star and the asteroseismic analysis strongly suggest that the star is hotter (29,200 K) than the 24,900 K suggested by model fits to the low signal-to-noise survey spectrum of the object. This result has profound and exciting implications for tests of the standard model of particle physics. Hot DBVs are expected to lose over half of their energy through the emission of plasmon neutrinos. Continuous monitoring of the star with the Kepler satellite over the course of 3–5 years is not only very likely to yield more modes to help constrain the asteroseismic fits, but also to allow us to obtain a rate of change of any stable mode and therefore measure the emission of plasmon neutrinos.

Key words: dense matter – elementary particles – stars: oscillations – stars: variables: general – white dwarfs

Online-only material: color figures

ASTEROSEISMOLOGY OF THE KEPLER FIELD DBV WHITE DWARF. IT IS A HOT ONE

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ABSTRACT

We present an asteroseismic analysis of the helium atmosphere white dwarf (a DBV) recently found in the field of view of the Kepler satellite. We analyze the five-mode pulsation spectrum that was produced based on one month of short-cadence Kepler data. The pulsational characteristics of the star and the asteroseismic analysis strongly suggest that the star is hotter (29,200 K) than the 24,900 K suggested by model fits to the low signal-to-noise survey spectrum of the object. This result has profound and exciting implications for tests of the standard model of particle physics. Hot DBVs are expected to lose over half of their energy through the emission of plasmon neutrinos. Continuous monitoring of the star with the Kepler satellite over the course of 3–5 years is not only very likely to yield more modes to help constrain the asteroseismic fits, but also to allow us to obtain a rate of change of any stable mode and therefore measure the emission of plasmon neutrinos.

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3. ASTEROSEISMIC ANALYSIS

3.1. The Models

To compute all our models, we used the White Dwarf Evolution Code (WDEC). The WDEC evolves hot polytrope models from temperatures close to 100,000 K down to the temperature of our choice. Models in the temperature range of interest for the present study are thermally relaxed solutions to the stellar structure equations. Each model we compute for our grids is the result of such an evolutionary sequence.

The WDEC is described in detail in Lamb & van Horn (1975) and Wood (1990). We used smoother core composition profiles and experimented with the more complex profiles that result from stellar evolution calculations (Salaris et al. 1997). We updated the envelope equation-of-state tables from those calculated by Fontaine et al. (1977) to those given by Saumon et al. (1995). We use OPAL opacities (Iglesias & Rogers 1996) and Wood (1990). We used smoother core composition of our grids is the result of such an evolutionary sequence.

DBVs are younger than their cooler cousins the DAVs. Time dependent diffusion calculations (e.g., Dehner & Kawaler 1995) show that at 24,000 K, a typical temperature for a DBV, the carbon has not fully settled into the core of the star yet. We expect the helium layer to be separated into a mixed He/C layer with a pure He layer on top, as shown in Figure 1. Following Metcalfe (2005), we adopted and parameterized this structure in our models.

We calculated grids of models using the WDEC and then ran a fitting subroutine to match the periods of the models ($P_{\text{calc}}$) with the observed periods and calculated residuals using the usual formula

$$\sigma_{\text{RMS}} = \sqrt{\frac{\sum_{1}^{n_{\text{obs}}} (P_{\text{calc}} - P_{\text{obs}})^2}{n_{\text{obs}}}},$$

where $n_{\text{obs}}$ is the number of periods present in the pulsation spectrum.

3.2. Parameters and Grids

In our asteroseismic fits, we vary up to six parameters: the effective temperature, the mass, and four structure parameters. There are two parameters associated with the shapes of the oxygen (and carbon) core composition profiles: the central oxygen abundance ($X_o$), and the edge of the homogeneous carbon and oxygen core ($\eta_{\text{in}}$). For envelope structure, $M_{\text{env}}$ marks the location of the base of the helium layer and $M_{\text{He}}$ the location where the helium abundance rises to 1 (see Figure 1). $M_{\text{env}}$ and $M_{\text{He}}$ are mass coordinates, defined as, e.g., $M_{\text{env}} = -\log(1 - M(r)/M_*)$, where $M(r)$ is the mass enclosed in radius $r$ and $M_*$ is the stellar mass.

With only five periods, six parameter fits are underconstrained. While there is much to learn from attempting six parameter fits, we settled for four parameters (later relaxing a fifth one). There are three logical ways of fixing two of the six parameters: (1) fix the mass and effective temperature according to the spectroscopy, (2) fix the core structure parameters, and (3) fix the envelope parameters. In light of the basic pulsational properties of the object (see also Section 3.3), option (1) seems the least promising. Of the other two choices, we decided to first try fixing the envelope structure to that of Dehner & Kawaler (1995). This meant that $M_{\text{env}}$ was fixed to $-2.80$ for all models and $M_{\text{He}}$ was first fixed to $-5.50$ for models between 20,000 K and 22,000 K, $-5.90$ for models between 22,200 K and 26,000 K, and $-6.30$ for models between 26,200 K and 28,000 K to match the profiles resulting from the diffusive settling computed by Dehner & Kawaler (1995).

We calculated two grids of models—one covering a broad range of parameter space at lower resolution and one zooming in on the promising area of parameter space with higher resolution. The range of parameters and step sizes for each are summarized in Table 2. The broad grid contains 305,820 models that successfully converged (out of 315,700 total computed) and the higher resolution grid contains 403,065 converged models, with a similar success rate. Table 2 also shows the parameters for the best-fit models discussed in Section 3.4.

3.3. Average Period Spacing

The average period spacing provides a useful asteroseismic measure of the mass and temperature of the star independent of the details of internal chemical composition profiles. Higher $k$ modes are not trapped in the core and, according to asymptotic theory, they are evenly spaced in period. This spacing is given by (Unno et al. 1989)

$$\Delta P = \frac{\pi}{\ell(\ell + 1)^{1/2}} \left[ \int_{r_1}^{r_2} N \frac{d r}{r} \right]^{-1},$$

where $r_1$ and $r_2$ are turning points of the mode and $N$ is the Brunt–Väisälä frequency. The asymptotic period spacing is $\ell$ dependent, with higher $\ell$ modes having smaller spacing. The dependence on the Brunt–Väisälä frequency leads to higher mass and higher temperature models having a smaller period spacing.

In the case of WD J1929+4447, we must be careful when using average period spacing arguments. First, the modes are...
not higher \( k \) modes, so at least a subset of them may be strongly trapped in the core (we are not in the asymptotic limit). Second, we only have a few modes to give us an average period spacing. That being said, and somewhat ignoring this warning, we proceed.

From the first four modes in Table 1 we determine an average period spacing of 35.9 s. This is to compare to 36.5 s for EC 20058-5234 (~28,000 K) and 38.8 s for GD358 (~25,000 K; Provencal et al. 2009). The former marks the current observed asteroseismology, it is given by parameters relative to the number of data points. Applied to Laney 2000). It penalizes fits involving a greater number of differing numbers of data points and free parameters (Koen & Deller 2000). Measures an absolute quality of the fit by taking into account parameter (Bayes Information Criterion). The BIC parameter used varies. One way to compare them is to use the BIC number of observed periods to fit and the number of parameters

\[ \text{BIC} = n_{\text{par}} \ln(n_{\text{obs}}) + n_{\text{obs}} \ln \left( \frac{\sigma_{\text{rms}}^2}{n_{\text{obs}}} \right), \]

where \( n_{\text{par}} \) is the number of free parameters in the fit. A smaller BIC parameter indicates a better fit.

### Table 2

| Parameter | Grid 1 | Grid 2 | Best Fit |
|-----------|--------|--------|----------|
| \( T_{\text{eff}} \) (K) | 20000 | 28000 | 24000 |
| \( M_\odot \) (solar) | 0.500 | 0.690 | 0.555 |
| \( M_{\text{env}} \) | 0.00 | 0.10 | 0.02 |
| \( X_0 \) | 0.00 | 1.00 | 0.40 |
| \( q_{\text{ev}} (M_\odot) \) | 0.10 | 0.80 | 0.32 |

Note. \(^a\) Close tie.

For the present case, \( n_{\text{obs}} = 5 \) and \( n_{\text{par}} = 5 \). With \( \sigma_{\text{rms}} = 0.28 \), this translates to \( \text{BIC} = -0.41 \). Among the best recent asteroseismic fits (Bischoff-Kim et al. 2008; Castanheira & Kepler 2008), using the BIC, only one fit among six comes out superior, but that is a fit to a single mode star using four parameters. It is difficult to argue for the significance of such a fit.

It is illuminating to also look at the parameters (mass and effective temperature) of models that did not fit quite as well, but were still good fits. Figure 3 is a plot of where all the models...
that fit to better than \( \sigma_{\text{rms}} = 1.0 \) s lie in parameter space. The best-fit models follow a negatively sloping trend in the mass versus effective temperature plane. This is a direct consequence of Equation (2). To fit a fixed set of observed periods, higher temperature models must compensate with a lower mass in order to keep the appropriate average period spacing. This trend frequently shows up in WD asteroseismology (e.g., Bischoff-Kim & Østensen, 2008; Castanheira & Kepler, 2008). The band of acceptable model fits in that plane misses the 1\( \sigma \) spectroscopic error region around it.

(A color version of this figure is available in the online journal.)

Figure 3. Best-fit models in three different planes of parameter space. The filled circles are models that fit the observed period spectrum with \( \sigma_{\text{rms}} \leq 1.0 \) s. The best-fit models at 29,200 K is circled. In the top panel (mass vs. effective temperature), we also mark the spectroscopic value (diamond) and the formal 1\( \sigma \) fitting error region around it.

In this paper, we took three different approaches using the pulsations to determine an effective temperature for WD J1929+4447: (1) through a quick inspection of the pulsation spectrum, noting that low period modes were observed; (2) using average period spacing arguments; and (3) by performing asteroseismic fits of the period spectrum. All three point to an effective temperature of 24,900 \( \pm \) 750 K. A well-calibrated high-S/N spectrum is urgently needed to settle the temperature issue.

5. CONCLUSIONS AND FUTURE WORK

We performed an asteroseismic analysis of WD J1929+4447, a DBV discovered in the field of view of the Kepler satellite. We find strong evidence that the star is a hot DBV. Our models also support the time-dependent diffusion calculations of Dehner & Kawaler (1995), though more positive results from the study of other DBVs are needed to further support these results. Also, it would be worth approaching the problem from another angle. In Section 3.2, we made the somewhat arbitrary choice of fixing the envelope parameters and allowing the core parameters to vary. We would most likely learn a lot by trying to fix the core parameters to those expected from stellar evolution (e.g., Althaus et al., 2010; Salaris et al., 1997) and allow the envelope parameters to freely vary over the entire reasonable range. Continuous observations with the Kepler satellite may also reveal more modes, hidden in noise at the current S/N level, allowing six parameter fits.

The discovery of a hot DBV is significant, as it gives us another chance to study plasmon neutrino emission from WDs. At 29,200 K, WD J1929+4447 should be radiating as much energy through the emission of photons as through the emission of plasmon neutrinos (Winget et al., 2004). The extra cooling due to neutrinos is therefore easily detectable if one could measure the cooling rate for the star with any significance. An observed period change in any of the modes can be a reliable estimator for the cooling rate, and only requires that at least one of the observed modes is phase stable over a sufficient number of years to detect the variation. If Kepler is permitted to maintain
observations of WD J1929+4447 for a period of five years, the cooling rate should be determined to a sufficient precision to establish the respective contributions from thermal radiation and plasmon neutrinos.

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