White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
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Variable white dwarfs

H. L. Shipman

University of Delaware, Dept. of Physics and Astronomy, Newark, DE 19716
email: harrys@udel.edu

Abstract. Asteroseismology of white dwarf stars has led to a number of interesting results pertaining to the long term evolution and present state of white dwarf interiors. I will review recent results and will give a not necessarily comprehensive view of the prospects for further progress in this area. Two – but only two white dwarf stars — have shown the expected cooling as they age. Careful observations of a few white dwarfs with rich pulsational properties reveal interior compositions as well as the thickness of their surface layers. A few very well observed stars have revealed changes in their pulsational spectra which we don't understand yet.

Keywords. white dwarfs, oscillations

1. Introduction

Variability in white dwarf stars was discovered roughly 50 years ago by Landolt (1968). Since then, pulsating white dwarf stars have made the transition from astronomical curiosities into one powerful tool for understanding the late stages of stellar evolution. I highlight some important transitions but admit I have not identified the people or papers whom I should credit. When the pulsation spectrum of PG 1159-035 was analyzed to give the star's mass and cooling (or shrinking) rate in the late 1970s, it began the use of variable white dwarf stars to determine stellar properties. Other milestones include the determination of the thickness of hydrogen layers in DA whites, the use of white dwarf variables to determine white dwarf rotation rates, and the observational testing of convection theories in white dwarf stars.

In this brief contribution I wish to make three main points. The use of a single mode to draw conclusions of broader astrophysical interest is fraught with difficulties and should be avoided. Variable white dwarf stars can provide much information about the composition of white dwarf stars, including their deep interiors all the way to their centers. As we look to the future, there are many more stars to be analyzed, and there is much that can be done even with small (1-2 meters) telescopes.

2. The Danger of Analyzing a Star with only one mode

One person who articulated the dangers of drawing too much insight from a single mode was Kepler *et al.* (2003), While this story is quite familiar to the small group of astronomers who analyze variable white dwarfs, I think it is worth retelling to a broader audience. Some years ago the Whole Earth Telescope project (hereafter WET) became involved in the analysis of the DB white dwarf EC 20058-053. Preliminary work with one easily observable mode indicated that there was a long term variation with an approximately 13 years period which would indicate the presence of a planet around this object. The data for this mode seemed convincing, When a second mode was added to the data set it seemed even more convincing.

Rather than the embarrassment of adding to the already large pile of discoveries of extra-solar planets whose discovery had to be retracted (for a popular history of this work see Bartusiak (2018)). James Dalessio and Judi Provencal were persistent, for a third independent mode was also present in the data and we needed to get more data to be sure. Fortunately, the more senior members of the team, including me, accepted their arguments. The period was there, but the variations were completely out of phase with the variations produced by the two dominant modes. If the variations were produced by a planetary companion, all the pulsations would have the same phase. The team knew that the variations were not produced by a planet. The cause is not yet firmly established, but we can exclude the presence of an extra-solar planet as the cause (Dalessio *et al.* 2013).

A talk I heard in the summer of 2019 at an astronomy teaching conference by Stephanie Slater gave me some support for the possible answer. Her talk was on the techniques of Polynesian wayfinders. In the talk she told stories of wayfinders who could feel the paths of ocean waves which were in several separate modes, sometimes in opposite directions. I tried this myself by observing ocean waves from aboard a ship. I could not observe the claimed seven different modes which could be detected by experienced navigators, but I could detect two different modes in some circumstances. This suggestion was also made in the paper on EC 20058 (Dalessio *et al.* 2013). (Disclosure statement: I was one of the "et al" authors on both this paper and the GD 358 paper, obtaining some of the observational data).

There was extensive discussion at the Hilo conference on the presence of debris disks around white dwarf stars as indicated by the presence of lines of heavy elements in the spectra of some white dwarf stars. After the conference yet before this article was written (Dec 3 2019), close analysis of these lines in the white dwarf star WD J0914+1914 by a group led by Boris Gaensicke has indicated the presence of a massive exoplanet around this object (Gaensicke *et al.* 2019; Garlick 2019). I am including this since I have confidence in Gaensicke's work based on previous papers. I hope this result will pass the test of time. (I am respecting the embargo on the news release with the timing of the present paper.)

3. Recent Results on the Deep Interior of Two White Dwarf Stars

Two recently published papers indicate the power of applying time-variable astrophysics to white dwarf stars (Giammichele 2018; Kim *et al.* 2019). Both papers illustrate the power of making extensive observations over long periods of time: one with Kepler spacecraft observations which provide continuous data over a period of two months, and one with 36 years of data including a few WET campaigns.

I believe it will not be necessary in the future to obtain several decades of data in order to obtain enough information to determine the detailed run of chemical composition of other white dwarf stars. In Giammichele's wonderful words, "the star must cooperate" by having enough observable modes to permit this sort of analysis (Smart 2018). What remains to be determined is whether future ground-based observations, which can only achieve millimagnitude accuracy but can, with effort, obtain adequate cadence over long periods of time, will suffice. Another possible route to obtaining data is to piggyback on spacecraft like TESS which may produce long-term light curves as they search for earth-sized exoplanets.

Both papers required a fair amount of effort in developing models to interpret the data. I am most familiar with the analysis in Kim *et al.* (2019) where she reports that over a million models were used to interpret the data. This amount of effort is in great contrast to the work several decades ago described by Van Horn (2015), where several hours of work with the computers available at the time were required to produce a single model. I can remember the later stages of this era, where months were required to develop a program to calculate single profiles of neutral helium lines in B stars.

4. Prospects for the Future

These two recent results indicate that the power of time-variable astrophysics will continue to produce interesting results which will impact many other areas of astronomy. The long series of observations of GD 358 have uncovered many changes in the pulsation behavior over periods of years which remain to be understood. The results described above for EC 20058 remain to be fully understood, though it is unclear to me that increased understanding in this particular case will lead to dramatic insights. My own choices for additional targets for observation are G 29-38, GD 514 (and other high mass white dwarf stars), PG 1351+48, and GD 358. These four stars are within reach of current telescopes in the 1-2 m class. Several telescopes of this type have survived their abandonment by national observatories. One of the cooperating observatories in WET has continued to operate in spite of being located in a rather unstable part of the world. We have been able to obtain good data from an amateur group in Texas.

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