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Asteroseismology of white dwarf stars with medium size telescopes

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Abstract. Pulsations of white dwarf stars provide a means of mapping the interiors of these objects. The Whole Earth Telescope (WET), consisting of a network of photometric telescopes, many of which have apertures of about one metre or even less and are located at different longitudes around the globe, has been exploiting the wealth of information contained in these pulsations. The motivation for the establishment of WET and a sample of exciting results on asteroseismology of white dwarf stars are presented in this paper.

1. Introduction

White dwarf stars are the end stages in the evolution of low mass stars. Stars with initial masses < 8 $M_\odot$ are believed to end up as white dwarfs, once the nuclear fuel in their interiors is exhausted. After evolution along the asymptotic giant branch in the HR diagram and planetary nebula formation, the central stars of planetary nebulae evolve as white dwarfs. A freshly minted white dwarf has an effective surface temperature of around 180,000K. As the white dwarf cools (due to the absence of nuclear energy sources at the centre of the star) gravitational settling of the elements takes place; the heavier elements slowly sink towards the centre of the star. A typical white dwarf has a C-O degenerate core, with a mass of about 0.6 $M_\odot$, surrounded by a thin shell of helium ($\sim 10^{-2}$ M_*) and a sprinkling of hydrogen ($\sim 10^{-10} M_*$) on the outside. The upper parts of the helium and hydrogen shells are only partially ionized, and changes in the degree of ionization in these zones, as the white dwarf cools, provide the driving mechanism that excites pulsations in the star. Observations show that there exist atleast three pulsational instability strips along the cooling track of white dwarfs. (see table 1).

Table 1.

Variable type	Temperature range	Surface composition
DOV	80000-180000 K	C, He, O
DBV	24000-29000 K	He
DAV	11000-13000 K	H

The nuclei (or central stars) of several planetary nebulae have also been observed as pulsators; they are called planetary nebular nuclei variables or PNNVs for short. Their surface composition is similar to that of DO variables. The catalogue of DA, DB, DO and PNN variables contain at present 24, 8, 4, and 10 objects respectively. Study of these pulsatifig white dwarfs provides a window to their interiors. The luminosity variations of these objects arise from temperature changes caused by nonradial g mode pulsations at their surfaces. Since the pulsating white dwarfs are similar in every other way to field white dwarfs, the properties that they reveal can be extended to all white dwarfs as a class.

Assuming spherical symmetry, white dwarf pulsations can be described in terms of spherical harmonic functions, with indices k, l and m, where k, the radial quantum number gives the number of zeroes in the radial direction and l and m describe the surface properties. l is called the degree of the mode and m the azimuthal order. l gives the total number of nodal planes slicing the surface of the star parallel to the equator and m gives the no. of nodal planes in the azimuthal direction that includes the center of the star. For a spherically symmetric star, the pulsation modes with the same value of l, but differing m, have the same frequency (i.e., they are degenerate). However, the rotation of the star or the presence of a magnetic field or both can lift the degeneracy and then one can have (2l+1) frequencies corresponding to m taking integer values from $-l$ to $+l$ through 0.

The pulsations of the variables mentioned above have periods in the range of 100s to 3000s. These periods are too long to be considered as p mode oscillations since p mode periods of white dwarfs are predicted to lie in the range of a few seconds. Moreover, in the case of many multiperiodic pulsators, for which specific pulsation modes have been identified (as we shall discuss later in this paper), the successive multiplets of a given l are equally spaced in period, as predicted by the theory of g mode pulsations (In the case of p modes, the successive multiplets will be equally spaced in frequency). Hence the theory of g mode pulsations can be exploited to derive several important seismological parameters, such as the stellar mass, rotation rate, composition and layer structure; they are all important information for the study of stellar evolution of low mass stars.

Seismological investigations of white dwarf pulsators have become possible because of (a) the simplicity of the structure of white dwarfs, (b) large amplitudes of the pulsations, as high as 0.3 magnitude in some cases and relatively large brightness (~ 13-14th magnitude) of some of the objects, allowing telescopes with small apertures to participate in the investigations and (c) the multiperiodic nature of the pulsations; each pulsation mode allowing one to map a different region of the interior of the star. Moreover, since the pulsational periods range from about 100s to 3000s, one can observe many stellar oscillations during a single night of observation and this helps motivate even the less patient observers!

2. The Whole Earth Telescope

The major aim in the study of white dwarf pulsations is to resolve the closely spaced frequencies that are present in the luminosity variations of the star, pulsating with several (may be, in hundreds of) frequencies simultaneously. Since the spacing between these frequencies can be as small as a fraction of a microhertz, it is necessary to collect continuous, uninterrupted time series data of duration not less than two weeks in order to resolve them. In principle the Fourier transform of a time series of noise-free data with infinite length can be employed to determine the frequencies and their amplitudes accurately. In reality, however, the photometric data from a single site will have interruptions due to the unavoidable day breaks and possible weather disturbances. And any real instrumental data will in addition have some noise in them as well. The data gaps will beat with the genuine frequencies and produce 'aliases' (or side lobes) in the frequency spectrum in such a way as to make it impossible to ferret out the genuine frequencies from the aliases. In order to circumvent this problem, the Whole Earth Telescope has been conceived (Nather et al. 1990). It consists of a network in which the collaborating astronomers use telescopes distributed at different longitudes around the globe and observe the same pulsating target star continuously for as long as nearly two weeks with minimum breaks in data coverage. The objective of getting continuous data is achieved by assuring that atleast one observatory is on the night side of the earth and is observing the program star. When two observers can observe the star and if the sky conditions are optimum at both places, the control centre (usually at the University of Texas at Austin) may advise one of the observers to switch over to the secondary target. Similar hardware for data collection and software for data analysis are employed by all observers participating in the WET runs. The apertures of telescopes that have so far been employed in WET runs range from 0.6m to 3.6m and every effort is made to collect data with two star photometers in which the program star and a nearby comparison (reference) star are monitored simultaneously with maximum possible signal to noise ratio (see Nather et al. 1990). From the wealth of asteroseismological information accumulated so far on a few pulsating DA, DB and DO variables (see for a sample, Winget et al. 1991, Winget et al. 1994, Kawaler et al. 1995, Kepler et al. 1995), it has become evident that even moderate size telescopes can contribute significantly to this newly emerging field of astrophysical investigation. Larger aperture telescopes do give data with better signal to noise ratio. They will in addition enable us to reach fainter magnitudes, but we wish to emphasize the fact that the breakthrough in seismological investigations of white dwarfs did come from the use of a network of telescopes with moderate apertures and there exist still many more objects and unsolved problems (like, for example, study of the stability/secular change in amplitude and frequency of the different pulsational modes exhibited by a single object) that can be tackled by means of WET observations employing medium size telescopes. In order to give a flavour of the richness of these investigations, we present below some highlights of results of WET observations on two objects, namely, GD 358 and PG 1159.

3. Some results

3.1 GD 358

Among the known DB variables, GD 358 (R.A.=$16^h47^m18^s$, Dec=$+32^\circ28'24''$ (2000)) with V = 13.7, is the brightest star among the known DB variables. It was observed as the primary WET target in May 1990 and again in May 1994. Figure 1 shows the reduced light curve of the star, using data collected continuously for about 6 hours with the UPSO 104cm Sampurnanand telescope on May 10, 1994. ISRO two star photometer with the University of Texas interface card and Q9 software were used for data collection. The complex light curve

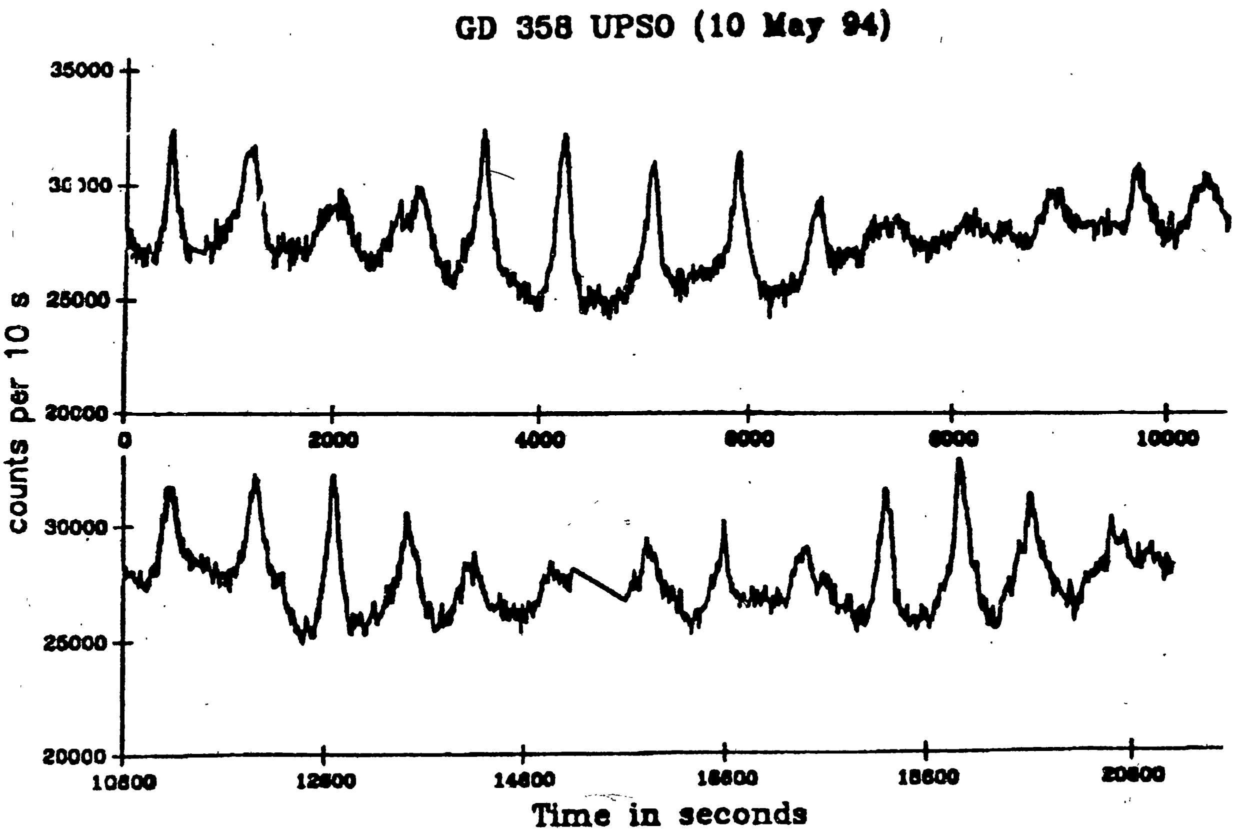

Figure 1. GD 358: Sky-subtracted reduced light curve of one night from UPSO (WET campaign May 1994).

shows the dominant oscillations with a period around 770s. We hasten to add that the star pulsates with many periods simultaneously and the beating between different periods is clearly evident in the amplitude modulations seen in the light curve. The high signal to noise ratio observable in this run bears testimony to the quality of the site, and the good performance of the UPSO telescope and the focal plane instrument. Figure 2 shows the lightcurve for a

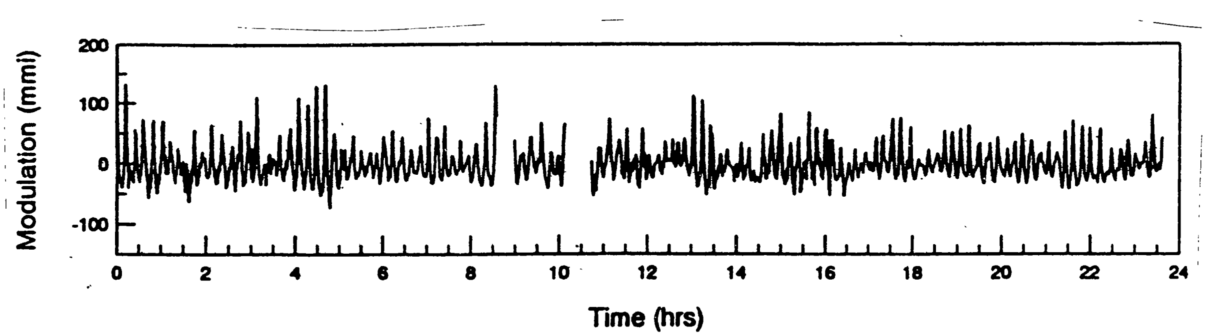

Figure 2. Reduced light curve of GD 538 for one day (24h) after combining data from individual telescopes (WET campaign May 1990) from Winget et al. 1994).

complete day (24 hours!) on the object during the WET campaign in May 1990. Here the runs from individual telescopes have been combined, after sky subtraction and removal of extinction effects. The figure shows the light modulations in units of millimodulation intensity (mmi) as defined in Winget et al. (1994). Fourier power spectrum of the WET run which had logged 154 hours of nearly continuous photometric data is shown in Figure 3. It may be noted that the ordinate scale is different for different panels to accommodate the large dynamic range

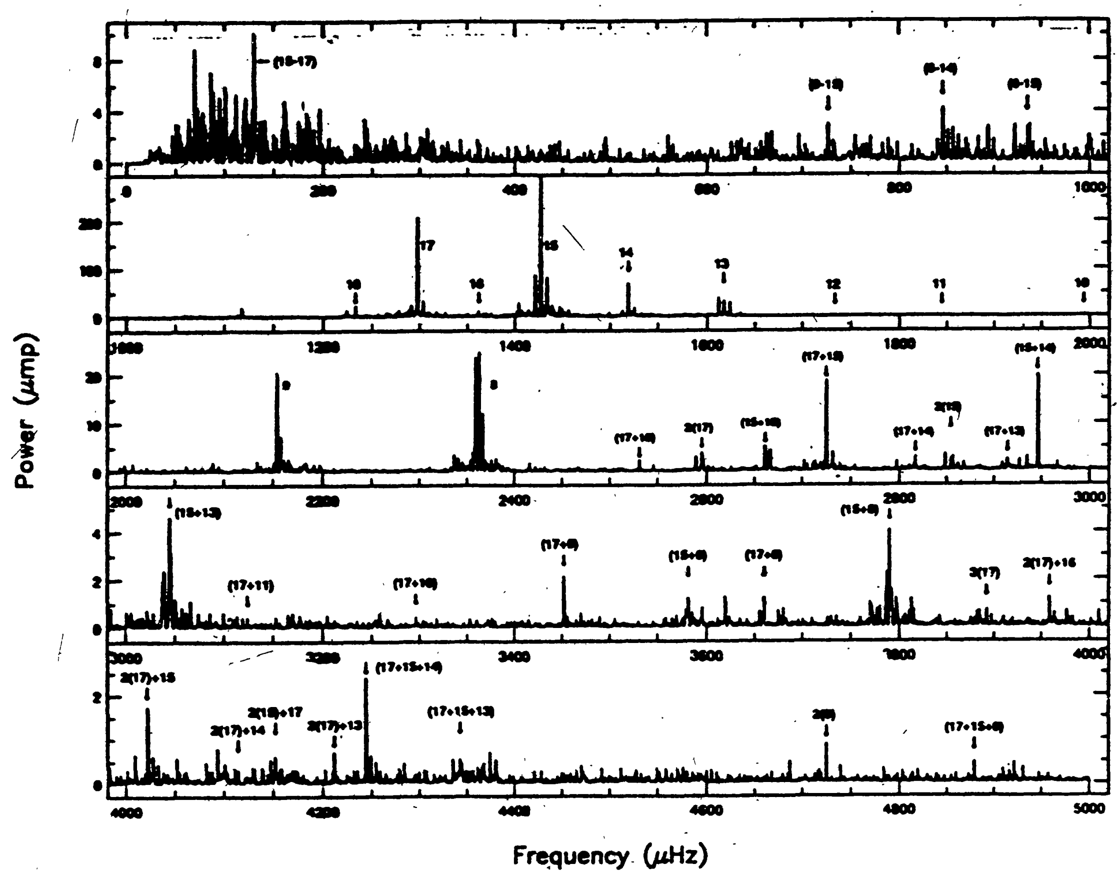

Figure 3. Fourier power spectrum of total data of GD 358 from WET campaign May 1990 (from Winget et al. 1994).

in power. Over 180 significant peaks can be identified in this spectrum. One notices several triplets in the frequency range 1000-2400 microhertz. The triplets are interpreted as l=1 modes with differing k values. The adjacent k values should be equally spaced in period for 'g' modes. We therefore determine this spacing by converting the X-axis of Fig. 3 to period and taking a FT of the resulting period transform. The derived mean period spacing is 39.2s. Further details are in Winget et al. 1994. The deviations of successive individual period spacings between multiplets from the mean value are caused by structure differences within the star - the degeneracy boundary, composition changes, thicknesses of the different layers and the total mass of the star. Theoretical predictions from a series of seismological models (Bradley and Winget 1994, Bradley 1995) are then compared with the observed period spacings, to derive a seismological mass of 0.61 ± 0.03 $M_\odot$ for GD 358, which is consistent with spectroscopically determined mass of 0.60 ± 0.17 $M_\odot$. The values of the radial quantum number (ranging from 8 to 18) are also uniquely determined from the models. These are marked on the figure. One can also determine from the models the mass of helium layer as (2.0±1) × 10^{-6} M_* and the absolute luminosity as 0.05 ± 0.012 $L_\odot$. Knowing the surface temperature of GD 358 (24000 ± 1000 K), the distance to the object can then be derived as 42 ± 3 pc which is consistent with the stellar parallax value of 36±4 pc. (A slightly higher temperature of 27000K has been estimated more recently, which will imply an increase in distance, but then the parallax distance has also been revised to 45pc (Bradley 1995)).

If the star rotates uniformly, the frequency splitting within the multiplets should remain constant. However in the case of GD 358, one notices in Fig. 3, that the splittings within multiplets with larger k values (= 6.51 microhertz) (see text and Fig. 6 of Winget et al. 1994 for details) are larger than those of smaller k value modes (=3.68 microhertz). Since the larger k value modes preferentially sample the outer envelope of the star, the above result has been interpreted to mean that the star is differentially rotating and that the outer envelope rotates with a period of 0.89d which is about 1.8 times faster than the speed with which the core is rotating. This important result will have to be explained by any of the models that try to explain the origin of GD 358.

One also notices in the Fourier spectrum (Fig. 3) several combination frequencies below 1000 micro Hz and in the range of 2500-5000 microHz, which are sums and differences of the dominant frequencies that have been identified with specific pulsation modes in the range of 1000-2400 microHz. These indicate the presence of nonlinear processes at work in the regions through which the pulsations propagate (perhaps due to harmonic distortion, i.e., the inability of the propagating medium to respond linearly to the full amplitude of the modulation). While it is true that many issues related to the combination frequencies and even the relative amplitudes of the siblings in the l=1 modes as well as the secular variations of the different frequencies remain to be fully investigated and understood, it is evident from the above illustration the power of asteroseismological investigations using the WET network and the bright future for further work that it heralds.

3.2 PG 1159-035

A WET campaign in 1990 on PG 1150-035 (GW Vir) was the first breakthrough observation with the WET for the study of white dwarf pulsations that became the benchmark for future asteroseimological studies of white dwarfs (Winget et al. 1991). PG 1159 (GW Vir; R.A.=$12^h01^m46^s$, Dec= - 03°45′.6) is a relatively bright DO variable, with V=14.84. Its effective surface temperature is ~140,000K. Using 264 hours of nearly continuous time series photometric data on the object and after identification of 101 specific quantised g mode pulsation frequencies (with l=1 triplets and l=2 quintuplets) in its high resolution Fourier spectrum, PG 1159 was found to have a seismological mass of 0.59 ±0.01 $M_{\odot}$, rotation rate of 1.38± 0.01 day and a magnetic field less than 6000G with the rotation axis and pulsation axis being aligned. All the results are base on the different splittings of k,l and m using our data (for details see Winget et al. 1991). The stellar interior is also found to be compositionally stratified. The mass of the Helium-rich layer was estimated as ~0.004 M_{*} (Kawaler and Bradley 1994). A study of the secular evolution of the dominant 516s pulsation period showed that the period is decreasing, implying that gravitational contraction is more effective than cooling at present. This puzzling result is, however, under reinvestigation.

4. Conclusion

The power of asteroseismological investigations using the WET has been demonstrated very effectively during the past several years. Medium size telescopes with apertures in the range of 1-2 metres constitute the WET elements. As there exist many more pulsating white dwarfs waiting in the queue to be observed and since many objects will insist on (!) a second and even a third look at them, to ascertain the stability or otherwise of the amplitude and frequency of their many pulsational modes, one can rightfully expect a busy schedule for the utilisation of medium size telescopes in the WET network in the years ahead. Temporal spectroscopy of stars to study their interiors is at last here to take its rightful place along with wavelength spectroscopy for the study of stellar atmospheres.

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