ASTEROSEISMOLOGY OF O-TYPE HOT SUBDWARF STARS

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Abstract: An asteroseismological study of sdO stars is presented. The study comprises two aspects: observationally we look for oscillations and theoretically we explore the possibility of finding excited modes in sdO stars.

Out of 78 sdO stars that we have observed to search for oscillations, 2 show evidence for pulsations well above the 3σ level and need follow-up observations to confirm variability.

Only 1 of 20 sdO stellar evolution models analyzed with a non-adiabatic pulsation code was found to have unstable modes. The κ-mechanism associated with an iron opacity bump is responsible for driving the pulsations. This is the same mechanism as is believed responsible for driving oscillations in long and short period sdB variables.

1 Introduction

Hot subdwarfs were discovered by Humason and Zwicky in 1947 [1] in a survey to search for blue objects in the Hyades cluster and in the North Galactic Pole, and they were established as a separate spectroscopic class by Greenstein in 1960 [2]. In 1974 [3] published a pioneering paper in which they posed most of the open questions for hot sds that are being addressed today.

Hot subdwarfs dominate the population of faint blue stars in our Galaxy and are found both in the disk and in the halo as blue tails of the Horizontal Branch of globular clusters. The UV excess, known as the UV upturn, found in elliptical galaxies and galaxy bulges is also attributed to hot subdwarfs [4].

The hot subdwarfs are separated mainly into two spectroscopic classes: B and O type hot subdwarfs (hereafter sdBs and sdOs):

- sdB stars are burning helium in their cores and have a tiny hydrogen envelope. In the Hertzsprung-Russell diagram they are located in the bluest part of the Horizontal Branch, known as the Extended Horizontal Branch (EHB). They have mass ~ 0.5 M$\odot$, effective temperature (T$_{eff}$) between 20 000 and 40 000 K and log g between 5.0 and 6.2. sdBs are mostly hydrogen rich objects, although 5% are He-sdBs corresponding to the hottest sdBs. Binarity seems to play a major role in their origin, but a single star origin can not be discarded. During their progenitor evolution, most of the envelope is lost near the tip of the Red Giant Branch and due to the remaining low mass hydrogen envelope, they either only partially ascend the Asympthotic Giant Branch, or directly evolve to the white dwarf cooling sequence.
- sdOs are more evolved objects. They have C/O cores and a helium burning shell. They have a canonical mass of 0.5 M$\odot$, T$_{eff}$ is between 40 000 and 100 000 K and log g between 4 and 6.5. Spectroscopically sdOs are very inhomogenous, although they are defined as He-rich objects with the common characteristic of a strong HeIIλ4686 line. As they cover such a big part of the Hertzsprung-Russell diagram, they are thought to have many different origins: as born-again AGB descendants; as stars that failed to have thermal pulses on the AGB called post-early AGBs; or stars that failed to ascend the AGB at all, called AGB-manqué or post-EHB stars [5], this last possibility meaning that sdOs would be sdB descendants. The very recent spectroscopic analysis [6] of 180 post-EHB sdO stars with the aim of deriving constraints to their evolutionary state seems to demonstrate an evolutionary link between the sdOs which have H in different amounts in their atmospheres and the He-sdBs, while the He-sdOs (the coolest of the sdOs with no detectable H) seem to have a different origin. Further evolution of the sdOs seems to be clearer: they will evolve to the white dwarf cooling sequence, possibly first evolving into the so called PG 1159 stars

(pulsating members of this spectroscopic class are called GW Vir stars) before becoming low mass white dwarfs.

2 Pulsational instability

It is difficult to put constraints on the different evolutionary scenarios proposed for sdOs. Spectroscopic analyses could be used to do it, but they are difficult and scarce, which implies large uncertainties in what the canonical chemical composition for sdOs might be. Also there are no theoretical predictions of their chemical abundances.

If sdO stars pulsate, we could use the power of asteroseismology to shed some light on their evolutionary state. Pulsating stars are a gift of great value in astrophysics, as their pulsation modes are tightly linked to the inner structure of the star. So by means of asteroseismologic techniques, similar to the seismology techniques used to peer into the interior of our own planet, we can gain knowledge about the inner structure, mass, radius, and consequently also of the evolutionary stage.

Regarding pulsational instability, as early as 1957, [7] had suggested looking for oscillations in sdO stars, but to date, there are only a few studies claiming to have found microvariability in 4 sdOs, none of which have yet been confirmed [8, 9, 10].

2.1 The driving of oscillations

The opacity mechanism is responsible for driving oscillations in most types of stars. This mechanism is based on the increase of the opacity with increasing pressure.

Generally, if the material in a star layer is compressed, the temperature rises and the opacity decreases, as approximately given by the formula:

$$\kappa = \rho / T^{3.5} \tag{1}$$

An increase in temperature results in heat transferred to the surroundings and work done on the layer by them, which would dampen any perturbation.

For oscillations to be driven, heat has to enter a layer of the star during its maximum compression and leave it during expansion. In this way, work is done by the layer on its surroundings, driving the oscillations. That is, if a layer of the star becomes optically thicker upon compression, it can hold the heat flowing from the core of the star and push up the upper layers. As they then become more transparent, heat is released and the cycle starts again. Thus, if the work done by the driving regions in a cycle of pulsation is greater than the work done on the damping regions oscillations could be driven in the star.

But only in certain regions of the star, called the partial ionization zones , is the opacity more sensitive to density. Part of the work done on the gases when they are compressed in these zones goes into producing further ionization of the chemical species rather than increasing the temperature.

There are 4 main partial ionization zones responsible for driving the oscillations in stars:

- the hydrogen ionization zone, where HI and HeI turn into HII and HeII at 10 000 - 15 000 K
- the helium ionization zone, where HeII turns to HeIII at 40 000 K
- the ionization zone of heavier elements, mainly iron and nickel, at around 200 000K
- the C/O ionization zone, at around 1 000 000 K

But also for efficient driving of a pulsation mode, its period (or dynamical time scale τ_{dyn}) should be of the same order of magnitude as the thermal time scale in the driving region, defined locally as the thermal relaxation time τ_{th}. These time scales are given by the formulae:

$$\tau_{dyn} = (R^3/GM)^{1/2} \qquad \tau_{th} = \frac{4\pi r^3 \rho c_p T}{L_R} \tag{2}$$

Depending on the effective temperature of the star, the zones named above are located at different depths within the star (where the ratio of the thermal to dynamical time scale has different values), and it is this fact that ultimately determines if the star actually pulsates or not (see Figure 1).

2.2 Pulsating stars evolutionary linked to sdOs

The sdOs' domain in the log g –T$_{eff}$ diagram is sandwiched between the instability strips of the sdB variables (sdBV) and the pre-white dwarf GW Vir stars which are thought to be evolutionary linked to sdOs.

Within the sdB variables we have the EC 14026 stars, also known as V361 Hya stars, theoretically predicted by [11] and observationally discovered by [12]. They show low-degree, low-radial order p-modes caused by the opacity bump due to partial ionization of iron in the envelope.

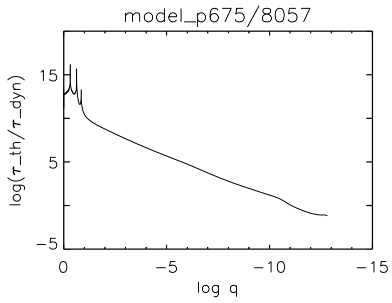

Figure 1: The ratio of thermal to dynamical time scales vs. the fractional mass depth parameter q=1-M_r/M_{star} for model 1 in Table 1.

Long period sdB variables, known as PG 1716 after the class prototype, with periods around 1h were discovered in 2003 [13], have the same excitation mechanism as short period sdBs, but show high-degree and high-radial order *g*-modes [14].

Just recently 2 hybrid sdB pulsators showing both long and short periods have been discovered [15, 16]. These stars pose challenges to pulsational theory, which does not predict the simultaneous existence of long and short period pulsations.

Long period pulsations have been detected for the first time in a He-sdB [17], which has high-radial order *g*-modes. As yet its pulsation mechanism has not been identified.

Finally, the pre-white dwarf GW Vir stars show high-radial order *g*-modes caused by an opacity bump due to partial ionization of carbon and oxygen [18].

In Figure 2 we show roughly the instability regions occupied by GW Vir stars and sdB variables, and the domain of the sdOs in the log g–T_{eff} plot. The highest gravity sdOs overlap in most of their effective temperature range with the GW Vir instability strip. Diamonds in the plot show the locations of the computed sdO models (see next section).

Having a powerful tool to learn more about sdOs if they were found to pulsate, we undertook an observational search for sdO pulsations by means of photoelectric and CCD photometry techniques and a theoretical stability analysis with the aid of stellar models and a nonadiabatic oscillations code that will be described in section 4.

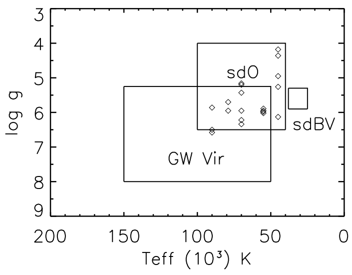

Figure 2: Rough sketch of the sdO domain and the sdBV and GW Vir theoretical instability strip in the log g–T$_{eff}$ plane.

3 Observations

Observations where accomplished both in the Northern and Southern hemispheres in the period 2003–2006. A total of 66 objects were observed at the observatories of Sierra Nevada (OSN), Teide (OT), Roque de los Muchachos (ORM) and Calar Alto (CAHA) and 12 objects were observed at the South African Astronomical Observatory (SAAO). We mainly performed CCD photometry with a Johnson B filter. Differential photometry was done as long as the comparison stars were bright enough and did not introduce further noise in the amplitude spectra.

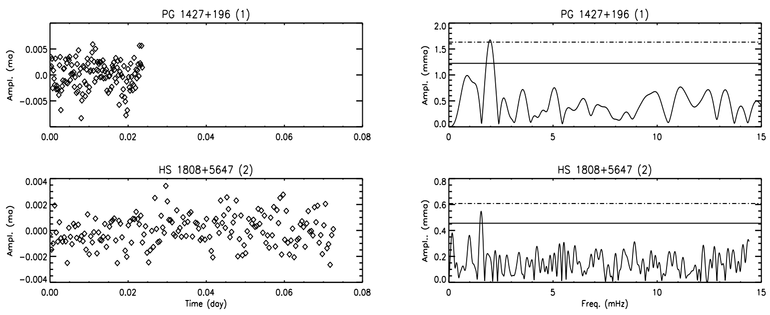

Figure 3: Light curves (left) and amplitude spectra (right) of promising pulsating sdOs. The horizontal lines are 3 and 4 times the mean amplitude noise.

Figure 3 (left) shows the light curves and (right) amplitude spectra of the 2 most promising sdOs. Object 1 was observed with the NOT 2.5 m telescope at ORM in a 0.6 hours run and object 2 with a 2.2 m telescope at CAHA in a 1.9 hours run. The solid line (dashed-dotted) is 3 (4) times the amplitude noise. A detection could be confidently claimed should the signal be above 4σ. One of the stars shows signal close to the 4σ level and the second is well above the 3σ level. Hence, unless there are systematic effects, it is highly likely that at least one of these 2 objects is pulsating.

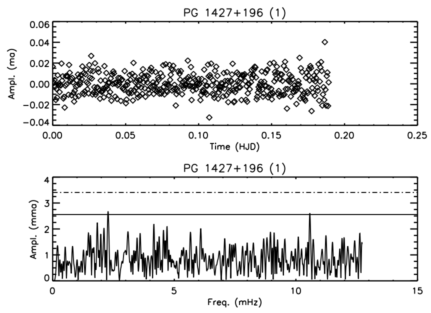

Figure 4: Light curve and amplitude spectra of the reobserved object 1.

Both objects were reobserved at OSN in runs of 4.5 and 4.9 hours respectively. Figure 4 shows the light curve amplitude spectra of object 1. Although the noise is higher than in the previous run, a signal is still present at $\sim$2 mHz, which is consistent with the previously found which gives us confidence on a possible detection. However, more observations are needed to confirm or deny its pulsating nature with confidence. Regarding object 2, the amplitude spectra was noisier than the previous one, so no conclusions can be drawn so far.

4 Stability analysis

We wanted to explore theoretically the possibility of driving pulsation modes in sdOs. With this aim, models of sdOs were constructed using the evolutionary code described in [19]. These models provide the input to the GRACO non-adiabatic oscillations code [20], which gives the theoretical mode spectrum as well as determining which modes are excited.

Table 1 shows some relevant properties of the sdO models. These models were made to account for the physical parameters of the promising pulsating sdOs,

Model number	T_{eff} (K)	log g	M (M $\odot$)	η_R	X(H)	X(He)	X(C)	Z
1	79 000	5.70	0.478	0.675	0.21	0.72	3.4E-02	0.07
2	90 000	6.50	0.478	0.675	0.20	0.73	3.5E-02	0.07
3	79 000	5.95	0.491	0.650	0.68	0.30	3.0E-03	0.02
4	55 000	5.89	0.471	0.685	0.43	0.55	9.6E-04	0.02
5	55 000	5.95	0.471	0.690	0.33	0.65	6.3E-04	0.02
6	55 200	5.98	0.471	0.695	0.27	0.71	9.0E-04	0.02
7	55 000	6.02	0.470	0.700	0.18	0.78	1.5E-02	0.04
8	45 000	4.95	0.497	0.600	0.59	0.36	7.3E-03	0.05
9	70 000	5.95	0.497	0.600	0.59	0.36	7.3E-03	0.05
10	45 000	5.26	0.469	0.650	0.59	0.36	7.4E-03	0.05
11	70 000	6.22	0.468	0.650	0.59	0.36	7.4E-03	0.05
12	45 000	6.13	0.454	0.700	1.63E-03	0.93	1.1E-02	0.07
13	70 000	6.34	0.453	0.700	1.63E-03	0.93	1.1E-02	0.07
14	45 000	4.18	0.479	0.675	0.26	0.60	6.0E-02	0.14
15	45 000	4.36	0.480	0.675	0.48	0.45	2.8E-02	0.07
16	70 000	5.16	0.479	0.675	0.19	0.65	7.1E-02	0.16
17	70 000	5.20	0.479	0.675	0.16	0.66	7.5E-02	0.18
18	70 000	5.43	0.480	0.675	0.48	0.45	2.8E-02	0.07
19	90 000	5.86	0.479	0.675	0.11	0.70	8.4E-02	0.19
20	90 000	6.58	0.480	0.675	0.48	0.45	2.8E-02	0.07

Table 1: Main physical parameters of the sdO stellar models.

and also to cover the range of physical parameters in the sdO domain. The models were constructed by evolving 1 M$\odot$ stars from the Main Sequence (with initial heavy element abundances Z = 0.02 and 0.05) with enhanced mass loss on the Red Giant Branch (RGB). The models are evolved through the helium core flash to the extended horizontal branch (EHB) phase, which provides models appropriate to subdwarf B stars. Further evolution to the helium shell burning phase then gives the sdO models. In some cases, those with the highest RGB mass loss rates, the helium core flash occurs after the model has reached the white dwarf cooling sequence. Flash-driven convection mixes core and envelope material, increasing Z in the envelope above its initial value. These models then evolve directly to sdOs, bypassing the EHB/sdB phase.

We used the non-adiabatic pulsation code to calculate modes from l=0 to l=4 with frequencies between 0.3 and 15 mHz ($\sim$ 60—3000 seconds), searching for both excited short and long periods.

We use the growth rate parameter (η) defined as:

$$\eta = \frac{\int_0^R \frac{dW}{dr} dr}{\int_0^R |\frac{dW}{dr}| dr} \tag{3}$$

as an indicator of the stability or instability of the mode. As $\frac{dW}{dr} > 0$ in the driving regions, $\eta > 0$ indicates driving.

Figure 5 (left) shows the growth rate vs. frequency for model 1. All of the computed modes were found stable, but we note 3 *stability regions*: two regions where η achieves less negative values and hence the modes have a tendency to instability. The one at low frequencies ($\sim$ 0.5 to 2 mHz) corresponds to high radial order *g*-modes and the other one at high frequencies ($\sim$9 to 12 mHz) corresponds to low radial order *p*-modes. Modes in the region in between ($\sim$ 2 to 9 mHz) were found highly stable.

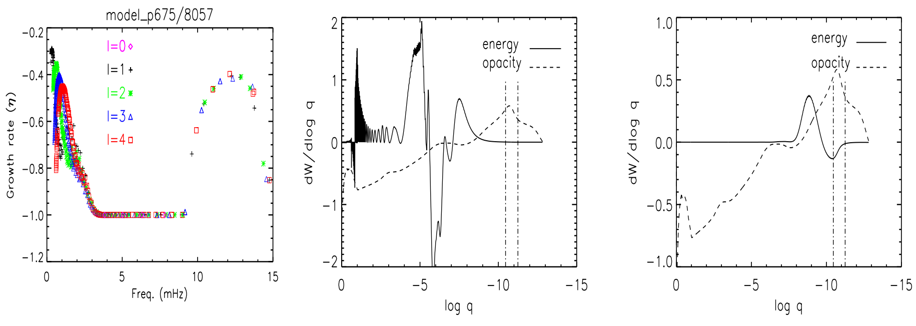

Figure 5: Left: Growth rate parameter vs. frequency of model 1 for l=0, 1, 2, 3 & 4. Center & Right: Energy and opacity for the g99 ($|n| = 99, |n| = |N_p - N_g|$, N_p and N_g are the number of p and g-nodes) and p3 mode respectively. The dashed-dotted line depicts the convection zone.

Figure 5 (center and right) plot the derivative of the work integral, which gives the net amount of energy locally gained or lost by the displaced material during one pulsation cycle (dW/dlog q) and opacity vs. log q, for a representative quadrupole mode at low and high frequency regions respectively. A negative (positive) value at a given location in the model indicates that this region contributes locally to driving (damping) of the mode.

At low frequencies (see Figure 5 (center)) the energy concentrates around log q$\sim$-6 in the proximity of a small bump in the opacity profile. At this depth in the star the density and temperature are high, and therefore this is an important contributing zone in the overall driving of pulsations. This opacity bump is due to the C/O partial ionization zone, and the κ-mechanism associated with it is the responsible for driving the pulsations found in the GW Vir stars. We speculate that enhancement of the heavy element abundance, and hence the magnitude of the opacity bump, in this important region for the driving of oscillations will lead to unstable modes.

At high frequencies the energy shifts even more to the surface (see Figure 5 (right)) at log q∼-10, approaching the biggest opacity bump, and the modes have again a tendency to instability. However, we would not expect unstable modes as, although strong, the opacity bump is also very near the stellar surface where the density is too low for pulsational driving. Also the low ratio of thermal to dynamical time scales makes energy redistribution too efficient for the mode to become unstable.

In Figure 6 (left) we show the growth rate vs. frequency for a quadrupole in the region of interest for model 14, the only one for which we find driving so far.

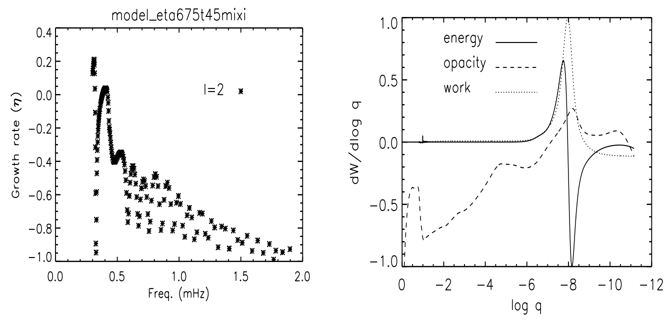

Figure 6: Left: Growth rate parameter vs. frequency of model 14 for a quadrupole. Right: Energy, work and opacity for the g190 mode of model 14.

Unstable modes were found between 0.3—0.32 and 0.38—0.42 mHz which correspond to high radial order g-modes. Figure 6 (right) is representative of the unstable modes: the total work done in one pulsation cycle is shown by the dotted line. It has a negative value at the surface of the star meaning that it is an unstable mode. The energy, showed by the solid line, gathers at log q=-8, where there is the biggest bump in the opacity profile. This bump corresponds to the heavy element ionization zone which is able then to excite modes in this model. Following our expectations it is a model with increased metallicity (Z=0.14) although the opacity bump is not caused by the C/O ionization zone, but by the heavy element ionization zone.

5 Summary and conclusions

We have observed 78 objects in search for oscillations. Two of these objects show evidence for pulsations well above the 3σ level and need further observations to confirm variability.

Out of 20 sdO structural models used as input for a non-adiabatic pulsation code, only one was found to have unstable modes. Driving of pulsations is due to the κ-mechanism associated with an iron opacity bump. This is the same mechanism as is believed responsible for driving oscillations in long and short period sdB variables.

The model with unstable modes has Z = 0.14 in its envelope. This raises a number of interesting questions, such as if high Z is necessary for pulsational driving, and whether any sdOs have high Z. To get a clearer picture we suggest:

- To construct more sdO models with different heavy element abundances to pin down the lowest Z at which we are able to drive oscillations.
- To perform more spectroscopic analyses to derive reliable heavy element abundances for sdOs.
- It may be that we need to boost Z only in the driving region and not in the whole envelope, as is the case in theoretical models of sdBs invoking microscopic diffusion.

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