

## Pulsating young brown dwarfs

F. Palla<sup>1</sup> and I. Baraffe<sup>2,3</sup>

<sup>1</sup> INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy  
e-mail: palla@arcetri.astro.it

<sup>2</sup> CRAL (UMR 5574 CNRS), École Normale Supérieure, 69364 Lyon Cedex 07, France  
e-mail: ibaraffe@ens-lyon.fr

<sup>3</sup> Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Brandenburg, Germany

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**Abstract.** We present the results of a nonadiabatic, linear stability analysis of models of very low-mass stars (VLMSs) and brown dwarfs (BDs) during the deuterium burning phase in the center. We find unstable fundamental modes with periods varying between  $\sim 5$  h for a  $0.1 M_{\odot}$  star and  $\sim 1$  h for a  $0.02 M_{\odot}$  BD. The growth time of the instability decreases with decreasing mass and remains well below the deuterium burning time scale in the mass range considered ( $0.1$ – $0.02 M_{\odot}$ ). These results are robust against variations of the relevant input physics in the evolutionary models. We identify possible candidates for pulsational variability among known VLMSs and BDs in nearby star forming regions whose location in the HR diagram falls within or close to the boundary of the instability strip. Finally, we discuss the possibility that the variability observed in a few objects with periods of  $\sim 1$  h can be interpreted in terms of pulsation.

**Key words.** stars: low-mass, brown dwarfs – stars: pulsation – stars: HR diagram

### 1. Introduction

Stellar pulsation represents a unique probe to study the internal structure and evolution of stars. This technique has been applied to many classes of stars, both on the main sequence and in earlier/later stages of their evolution (e.g., Gautschy & Saio 1995; Marconi & Palla 1998). New classes of pulsators are being discovered across the HR diagram from ground-based observations and with the advent of space missions (MONS, COROT) the potential of discovering solar-like oscillations in other stars promises a major improvement in our understanding of stellar interiors (e.g., Thompson et al. 2003).

In this Letter, we propose the identification of a new class of pulsators, VLMSs and BDs, in which the instability is induced by deuterium (D-) burning in their centers. Due to the high sensitivity of nuclear reactions on temperature, fully convective stars can become pulsationally unstable during the burning phases. Gabriel (1964) was the first to suggest that such mechanism, called  $\epsilon$ -mechanism, would make low-mass stars on the main sequence vibrationally unstable. Later on, Toma (1972) showed that pre-main-sequence (PMS) stars in the range  $0.2$ – $2.0 M_{\odot}$  could also become pulsationally unstable during the D-burning phase and suggested a possible relation of this phenomenon with the observed variability of T Tauri stars. In both cases, however, and for different reasons, the suggestion has not met with success and to date there is no observational evidence for the  $\epsilon$ -mechanism in any class of pulsating star where the destabilization is mainly induced by opacity effects in ionization regions near the stellar surface (the  $\kappa$ -mechanism).

Indeed, no periodic variability, which could be interpreted as pulsation, has been reported up to now in main sequence

low-mass stars, which may not be surprising, given the weak dependence of the  $pp$ -chains on temperature and the resulting long  $e$ -folding times for the  $\epsilon$ -mechanism. For young PMS stars, the main difficulty to confirm observationally the results of Toma (1972) is due to the very short D-burning time scale,  $\lesssim 1$  Myr, for stars with mass  $\geq 0.2 M_{\odot}$ . Moreover, the results obtained by Toma (1972) are optimised, in terms of D-burning time scale and  $e$ -folding time for the pulsation, since he adopted an initial D-abundance about ten times higher than the currently measured interstellar value and ignored D-depletion during protostellar accretion that can substantially reduce its abundance at the beginning of the PMS phase of low-mass stars. As we will show below, VLMSs ( $\leq 0.1 M_{\odot}$ ) and BDs in the earliest evolutionary stages have the appropriate physical conditions to circumvent the limitations of previous attempts.

### 2. Instability induced by D-burning in VLMSs and BDs

BDs are expected to begin the PMS phase with convective interiors and with the full amount of interstellar deuterium since during the preceding phase of protostellar accretion their centers are too cold to start any nuclear reaction. The ignition of deuterium requires temperatures around  $10^6$  K that can only be reached in protostars more massive than  $\sim 0.1$ – $0.2 M_{\odot}$ , depending on the mass accretion rate (Stahler 1988). Thus, very low-mass objects need to contract somewhat in the PMS phase before deuterium can start burning and being depleted. Once the critical temperature is achieved, the D-burning phase occurs on a time scale that varies between  $\tau_D \sim 2.5$  Myr for a  $0.1 M_{\odot}$

star and  $\tau_D \sim 20$  Myr for a  $0.02 M_\odot$  brown dwarf (Chabrier et al. 2000).

Since the energy generation rate,  $\epsilon_{\text{nuc}}$ , scales approximately with the 12-th power of the temperature, the rate of combustion is slower for the lowest mass objects. The same temperature sensitivity of  $\epsilon_{\text{nuc}}$  is at the root of the instability induced by any temperature variation: since  $\delta\epsilon_{\text{nuc}}/\epsilon_{\text{nuc}} \sim 12 \delta T/T$ , a small  $T$ -perturbation induces a variation of  $\epsilon_{\text{nuc}}$  which is an order of magnitude bigger. (Note that  $\epsilon_{\text{nuc}}$  is also linearly proportional to density, but no destabilizing effect is expected from variations in this quantity). In terms of pulsation analysis, the time scale for the growth of the instability,  $\tau_{\text{growth}}$ , is inversely proportional to  $\delta\epsilon_{\text{nuc}}$  and should be shorter than the D-burning time for the  $\epsilon$ -mechanism to operate. Therefore, in order to test its viability, it is important to follow numerically the growth of the instability in time since the onset of the D-burning phase.

### 3. Evolutionary models and pulsation analysis

Our analysis focuses on objects in the mass range  $0.1\text{--}0.02 M_\odot$ , close to the minimum value for D-burning ( $0.013 M_\odot$ , Chabrier et al. 2000). The evolutionary models are based on the input physics described in Baraffe et al. (1998) and on the so-called “NextGen” grainless atmosphere models (Hauschildt et al. 1999). Models are calculated for a solar metallicity, with an initial deuterium mass fraction  $D_0 = 2 \times 10^{-5}$ , characteristic of the local interstellar medium (Linsky 1998), and with mixing length parameter equal to the pressure scale height. During the early phase of D-burning, brown dwarfs are relatively hot, with  $T_{\text{eff}} \gtrsim 2300$  K, and their atmospheric properties are still well described by dust-free models.

#### 3.1. Linear stability analysis results

We performed a non-adiabatic linear stability analysis of the model structures during the D-burning phase, searching for the presence of unstable radial eigen modes. Unstable modes characterize oscillations around the hydrostatic equilibrium configuration. If perturbations have time to grow, they could reach large amplitudes and result in periodic phases of expansion and contraction, with a pulsation period related to the dynamical time scale of the object  $\tau_{\text{dyn}} \sim (G\bar{\rho})^{-1/2}$ . References on the pulsation code used for the present purpose can be found in Lee (1985) and Baraffe et al. (2001). In all models analyzed, we find unstable fundamental modes, the results being rather robust against variations of the relevant input physics (see Sect. 3.2). We also find unstable first overtones, but their stability properties are sensitive to the input physics and their growth rate is usually smaller than that of the fundamental mode. Higher overtones remain stable during the whole D-burning phase. We thus restrict the rest of our study to fundamental modes.

In the mass range of interest, fundamental mode periods  $P_0$  vary between  $\sim 1$  h and  $\sim 5$  h, close to  $\tau_{\text{dyn}}$ . For a given mass,  $P_0$  decreases during the D-burning phase, since contraction proceeds and  $\bar{\rho}$  increases. This is illustrated in Table 1 which summarizes the characteristics of VLMSs and BDs and their main pulsation properties during the D-burning phase for different masses. We define  $\tau_{\text{growth}}$  as the e-folding time characterizing

**Table 1.** Properties of VLMSs and BDs during D-burning.

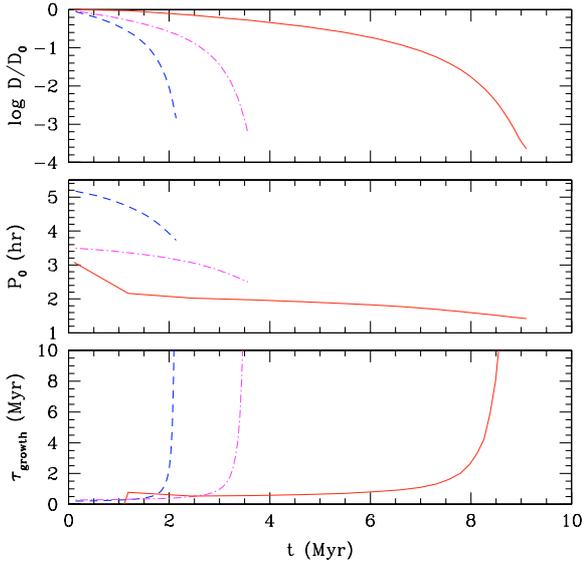
$M$ ( $M_\odot$ )	age (Myr)	$D/D_0$	$T_{\text{eff}}$ (K)	$\log L$ ( $L_\odot$ )	$P_0$ (h)	$\tau_{\text{growth}}$ (Myr)
0.02	2.22	0.982	2540	−2.516	1.67	3.03
	15.9	0.054	2450	−2.801	1.18	2.49
	18.9	0.002	2390	−2.927	1.04	25.1
0.03	1.18	0.936	2710	−2.138	2.16	0.78
	6.60	0.121	2690	−2.271	1.77	0.94
	8.49	0.004	2680	−2.380	1.52	8.02
0.04	1.23	0.66	2790	−1.915	2.52	0.41
	3.71	0.148	2790	−1.985	2.26	0.65
	5.16	0.004	2780	−2.092	1.92	5.92
0.06	0.86	0.644	2890	−1.567	3.41	0.31
	2.16	0.218	2890	−1.616	3.15	0.43
	3.36	0.005	2890	−1.728	2.63	4.10
0.08	0.65	0.642	2950	−1.322	4.25	0.26
	1.39	0.315	2940	−1.356	4.02	0.32
	2.54	0.006	2940	−1.475	3.27	3.32
0.1	0.56	0.618	3010	−1.125	5.04	0.23
	1.11	0.307	3000	−1.162	4.77	0.29
	2.00	0.008	3000	−1.281	3.92	2.40

the growth time scale of the pulsation amplitude for the fundamental mode. Figure 1 displays  $P_0$  and  $\tau_{\text{growth}}$  for a  $0.1 M_\odot$  VLMS, and  $0.06$  and  $0.03 M_\odot$  BDs. Figure 1 and Table 1 show that at the beginning of the D-burning phase,  $\tau_{\text{growth}}$  is shorter, by at least a factor 10, than the D-burning time scale  $\tau_D$ , which is 2.5, 4.2 and 9.3 Myr for  $0.1$ ,  $0.06$  and  $0.03 M_\odot$ , respectively. Note that only unstable models are shown in Fig. 1, since the structure becomes stable again before complete depletion of D. It remains small during a significant fraction of the D-burning phase in the lowest mass BDs, indicating that the perturbations may have time to grow to reach significant amplitudes. The location of the D-instability strip in the HR diagram is shown in the top panel of Fig. 2, along with evolutionary tracks of selected masses and isochrones. The curves of constant period cut the strip almost horizontally (nearly constant luminosity) and the shortest periods are found for the least massive BDs. Note that our models can also provide the locus of the D-instability strip in the color–magnitude diagram (CMD) for different bands for comparison with observations. We plan to present such diagrams in a forthcoming paper.

Inspection of the differential work integral  $dW/dm$  throughout the structure of D-burning objects reveals the exciting (positive  $dW/dm$ ) and the damping (negative  $dW/dm$ ) zones. This quantity is plotted in Fig. 3 for the  $0.03 M_\odot$  BD at the beginning of the D-burning phase. The positive work in the central region is due to the perturbation of the nuclear energy generation rate and characterizes the  $\epsilon$ -mechanism. As a rough approximation, the work integral in the central region follows

$$W \propto \epsilon_{\text{nuc}} \epsilon_T, \quad (1)$$

with  $\epsilon_{\text{nuc}}$  the nuclear energy generation rate and  $\epsilon_T \equiv \left( \frac{\partial \ln \epsilon_{\text{nuc}}}{\partial \ln T} \right)_\rho$ . The source of nuclear energy is due to the  ${}^2\text{H}(\rho, \gamma){}^3\text{He}$  reaction with  $\epsilon_T \approx 12\text{--}14$  in our objects, at temperatures  $T \approx 10^6$  K. It is the combination of such high sensitivity of the nuclear

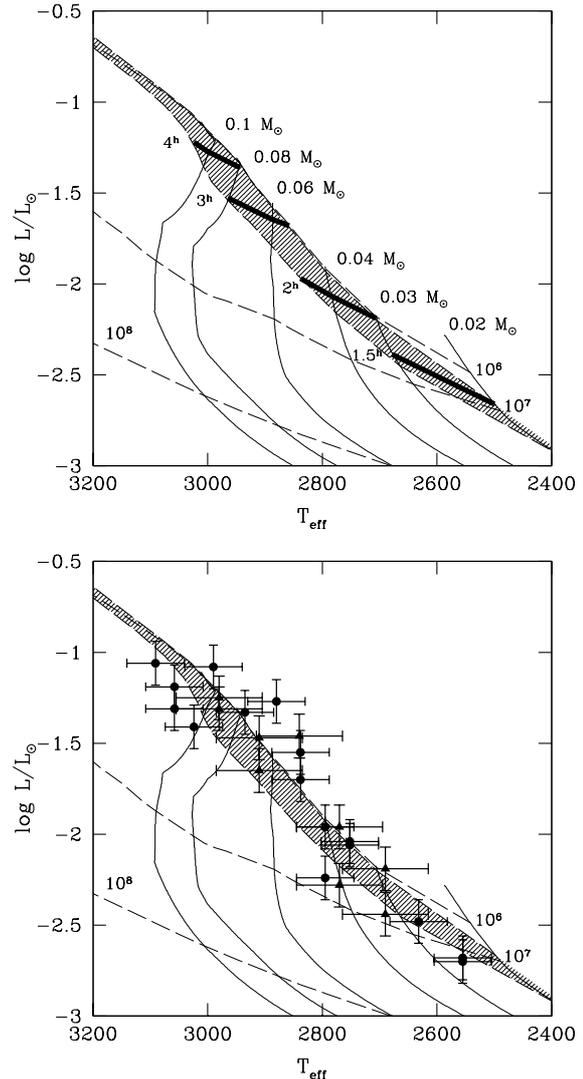


**Fig. 1.** Evolution of the D-abundance (in units of the initial abundance  $D_0 = 2 \times 10^{-5}$  in mass fraction), the fundamental mode period  $P_0$  (in h) and growth time scale  $\tau_{\text{growth}}$  (in Myr) as a function of time during the D-burning phase of a 0.1  $M_{\odot}$  star (dashed lines), and a 0.06  $M_{\odot}$  (dash-dotted line) and 0.03  $M_{\odot}$  (solid line) BD. Note that only unstable models are shown.

energy generation rate with temperature, and the fully convective structure of low-mass objects, which yields a less centrally condensed structure, that allows the excitation by the  $\epsilon$ -mechanism. Indeed, VLMSs and BDs are characterized by a low central condensation with a ratio of central to mean density  $\rho_c/\bar{\rho} \approx 4.5\text{--}6$ . This ratio decreases with mass and for a given mass it remains nearly constant with age. The  $\epsilon$ -mechanism is usually unimportant for radial pulsation in stars because of the small amplitudes that can develop in dense central regions where nuclear burning occurs. However, stars less centrally condensed are thought to be potential sites for the  $\epsilon$ -mechanism (Gabriel 1964). Finite amplitudes of the eigenfunctions can indeed be expected in the central regions, as illustrated by the behavior of the pulsation amplitude  $\delta r/r$  displayed in Fig. 3.

### 3.2. Uncertainties of the results

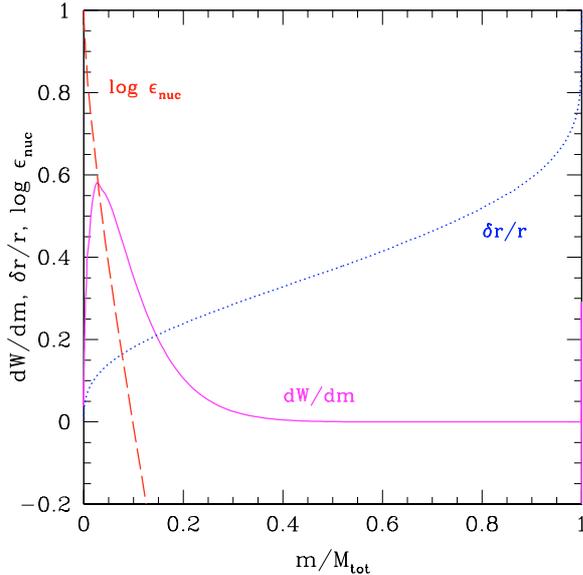
In order to analyze the sensitivity of the present instability to input physics, we have computed evolutionary models using atmosphere models based on different molecular line lists for TiO and H<sub>2</sub>O (see Chabrier et al. 2000 for more details). The main effect is a change of the effective temperature (by  $\sim 100$  K), and of the D-burning time scale. As a test on the initial conditions, we have constructed evolutionary sequences starting at temperatures  $T_c < 5 \times 10^5$  K before central D-ignition. Moreover, we have explored the effect of the mixing length ( $L_{\text{mix}} = 1\text{--}2 H_p$ ), since it can affect the early evolution of VLMSs and BDs (see Baraffe et al. 2002). All these variations yield only small quantitative differences, mainly in the D-burning lifetime and the pulsation growth time scale. However, the instability of the fundamental mode survives in all cases, with  $\tau_{\text{growth}} \ll \tau_D$  during most of the D-burning phase. Finally, adopting for the  ${}^2\text{H}(p, \gamma){}^3\text{He}$  reaction the rate of Caughlan & Fowler (1988) or



**Fig. 2.** *Top panel:* location of the D-instability strip (shaded area) in the HR diagram. Tracks for different masses and isochrones are indicated as labeled. The isoperiod curves (in h) are shown by the thick lines within the strip. *Bottom panel:* distribution of known VLMSs and BDs in Taurus (circles) and Cha I (triangles). Data points for Taurus are from Briceño et al. (2002), Luhman et al. (2003), and Luhman (2004), and for Cha I from Comerón et al. (2000).

that of the NACRE compilation (Angulo et al. 1999) has no consequence.

An important uncertainty stems from the treatment of convection, which is assumed frozen in the linear stability analysis, having neglected the perturbation of the convective flux in the linearized energy equation. Such standard approximation is only justified by the argument that the convective time scale in the inner structure of our objects ( $\tau_{\text{conv}} \approx 10^6\text{--}10^8$  s) is significantly larger than the pulsation periods ( $\lesssim 10^4$  s). Analysis of the effect of convection on the perturbation is beyond the scope of this study and in any case can only be qualitative given our poor knowledge of the interaction between convection and pulsation.



**Fig. 3.** Differential work integral  $dW/dm$ , in arbitrary units (solid line), as a function of interior mass (in units of the total mass) for a  $0.03 M_{\odot}$  BD at the beginning of the D-burning phase (D-abundance  $D/D_0 = 0.71$ , age = 2.4 Myr). The pulsation amplitude  $\delta r/r$  (dotted line), arbitrarily normalized to 1 at the surface, and the nuclear energy generation rate  $\epsilon_{\text{nuc}}$  (in erg/g/s, dashed line) are also displayed.

#### 4. Discussion

Our results show that the perturbations excited in the center of D-burning VLMSs and BDs have smaller growth time scale than that of the D-burning phase and may thus have time to grow to the level of observable amplitudes. Unfortunately, our linear models cannot be used to estimate the amplitude of the pulsations. More theoretical work is required and we hope that these initial results will stimulate the development of non-linear calculations in order to estimate pulsation amplitudes and of fully hydrodynamical models to construct synthetic light curves for comparison with observations. In any case, it is important to realize that it may be difficult to distinguish pulsations from other sources of photometric variability, such as rotation and spots or atmospheric events, that occur in VLMSs and BDs on similar time scales. Fortunately, numerous candidates exist which could provide good targets for detailed observational studies.

As an illustration, the lower panel of Fig. 2 displays the location in the HR diagram of 25 spectroscopically confirmed VLMSs and BDs drawn from larger surveys in Taurus and Chamaeleon I (Briceño et al. 2002; Comerón et al. 2000; Luhman et al. 2003; Luhman 2004). The rather large error bars indicate the current uncertainties in the conversion from spectral types to effective temperatures (see discussion in, e.g., Luhman 2004), but the overall distribution closely matches the predicted position of the instability strip down to the lowest masses with the shortest pulsational periods.

Evidence for photometric variability of young VLMSs and BDs both in the field and in young clusters has been already obtained by several groups in the last few years (Bailer-Jones & Mundt 2001; Joergens et al. 2003; Zapatero Osorio et al. 2003). The amplitude of the observed variations vary between

tens of mmag in the optical to  $\sim 0.05$ – $0.2$  mag in the near-IR where these cool objects emit most of their energy. In several cases, periodic variability has been reported with tentative periods in the range from half an hour to several hours. Very interesting results have been found in the  $\sigma$  Orionis clusters (age  $\sim 3$  Myr) where two objects (S Ori 27 and S Ori 28) have periods around 3 h and even shorter in the case of S Ori 31 ( $\sim 2$  h) and S Ori 45 ( $\sim 0.75$  h) (Bailer-Jones & Mundt 2001; Zapatero-Osorio et al. 2003). The minimum fundamental periods that we find are close to  $\sim 1$  h, corresponding to the lowest mass studied (cf. Table 1). Although the period of S Ori 45 is slightly shorter than 1 h, it is compelling that this object has precisely a mass which could be as low as  $0.02 M_{\odot}$  (Béjar et al. 1999). Several other candidates in the  $\epsilon$  Orionis cluster appear to share similar properties (Scholz & Eislöffel 2004). So far, the observed variability has been interpreted in terms of rotation periods, presence of photospheric cool or hot spots, interaction with accretion disks, and/or atmospheric events. For objects with the shortest periods ( $\sim 1$  h), the inferred rotational velocities would exceed  $\sim 100 \text{ km s}^{-1}$  at or above breakup (e.g., Joergens et al. 2003). The pulsational instability induced by D-burning thus offers a new interpretation that relies on fundamental (sub)stellar properties. It also has the potential of providing direct information on the otherwise inaccessible internal structure of VLMSs and BDs. More fundamentally, it could provide the first evidence for the existence of the  $\epsilon$ -mechanism.

#### References

- Angulo, C., Arnould, M., Rayet, M., et al. 1999, *Nucl. Phys. A*, 656, 3
- Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, *A&A*, 337, 403
- Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2002, *A&A*, 382, 563
- Baraffe, I., Heger, A., & Woosley, S. E. 2001, *ApJ*, 550, 890
- Béjar, V. J. S., Zapatero Osorio, M. R., & Rebolo, R. 1999, *ApJ*, 521, 671
- Briceño, C., Luhman, K. L., Hartmann, L., et al. 2002, *ApJ*, 580, 317
- Caughlan, G. R., & Fowler, W. A. 1988, *Atomic Data and Nucl. Data Tables*, 40, 283
- Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. H. 2000, *ApJ*, 542, 464
- Comerón, F., Neuhauser, R., & Kaas, A. A. 2000, *A&A*, 359, 269
- Gabriel, A. 1964, *Ann. Astrophys.*, 27, 141
- Gautschi, A., & Saio, H. 1995, *ARA&A*, 33, 75
- Hauschildt, P. H., Allard, F., & Baron, E. 1999, *ApJ*, 512, 377
- Joergens, V., Fernández, M., Carpenter, J. M., & Neuhauser, R. 2003, *ApJ*, 594, 971
- Lee, U. 1985, *PASJ*, 37, 261
- Linsky, J. 1998, *Space Science Rev.*, 84, 285, *A&A*, 416, 555
- Luhman, K. L. 2004, *ApJ*, in press
- Luhman, K. L., Briceño, C., Stauffer, J. R., et al. 2003, *ApJ*, 590, 348
- Marconi, M., & Palla, F. 1998, *ApJ*, 507, L141
- Scholz, A., & Eislöffel, J. 2004, *A&A*, 419, 249
- Stahler, S. W. 1988, *ApJ*, 332, 804
- Thompson, M. J., Cunha, M. S., & Monteiro, M. J. P. F. G. 2003, *Asteroseismology across the HR diagram* (Kluwer Acad. Publ.)
- Tompa, E. 1972, *A&A*, 19, 76
- Zapatero Osorio, M. R., Caballero, J. A., Béjar, V. J. S., & Rebolo, R. 2003, *A&A*, 408, 663