Pulsating young brown dwarfs

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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 $\sim 5$ hr for a 0.1 $M_{\odot}$ star and $\sim 1$ hr 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 $\sim 1$ hr 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, Cunha & Monteiro 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 ($\lesssim 0.1$ $M_{\odot}$) 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 ~0.1–0.2 M⊙, 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 τD ~2.5 Myr for a 0.1 M⊙ star and τD ~20 Myr for a 0.02 M⊙ brown dwarf (Chabrier et al. 2000).

Since the energy generation rate, εnuc, 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 εnuc is at the root of the instability induced by any temperature variation: since δεnuc/εnuc ~ 12 δT/T, a small T-perturbation induces a variation of εnuc which is an order of magnitude bigger. (Note that εnuc 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, τgrowth, is inversely proportional to δεnuc and should be shorter than the D-burning time for the ε-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 0.1–0.02 M⊙, close to the minimum value for D-burning (0.013 M⊙, 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 D0 = 2 × 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_{eff} ≥ 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 τdyn ~ (Gρ)^{-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 P0 vary between ~1hr and ~5 hr, close to τdyn. For a given mass, P0 decreases during the D-burning phase, since contraction proceeds and ρ 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 τgrowth as the e-folding time characterizing the growth time scale of the pulsation amplitude for the fundamental mode. Fig. 1 displays P0 and τgrowth for a 0.1 M⊙ VLMS, and 0.06 and 0.03 M⊙ BDs. Figure 1 and Table 1 show that at the beginning of the D-burning phase, τgrowth is shorter, by at least a factor 10, than the D-burning time scale τD, which is 2.5, 4.2 and 9.3 Myr for 0.1, 0.06 and 0.03 M⊙, 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⊙ 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 ε-mechanism. As a rough approximation, the work integral in the central region follows

$$W \propto \epsilon_{nuc} \epsilon_T,$$

with εnuc the nuclear energy generation rate and εT ≡ (∂ln T/∂ln ρ). The source of nuclear energy is due to the 2H(p, γ)3He reaction with εT ≈ 12–14 in our objects, at temperatures T ≈ 10^6 K. It is the combination of such high sensitivity of the nuclear 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 ε-mechanism. Indeed, VLMSs and BDs are characterized by a low cen-
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 hr) 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.

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 linelists for TiO and H\(_2\)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 (\(L_{\text{mix}} = 1 - 2 H_P\)), 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 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 (\(\tau_{\text{conv}} \approx 10^6 - 10^8\) s) is significantly larger than the pulsation periods (\(< 10^4\) s). Analysis of the effect of convection on the perturbation is beyond the scope of this study and

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 isopериод curves (in hr) 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).
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. 3 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 in any case can only be qualitative given our poor knowledge of the interaction between convection and pulsation.

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

| M (M⊙) | age (Myr) | D/D₀ | T_{eff} (K) | log L (L⊙) | P₀ (hr) | \( τ_{growth} \) (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   |                      |

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