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Pulsations induced by deuterium-burning in young brown dwarfs

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Abstract. Very low-mass stars (VLMSs) and brown dwarfs (BDs) can undergo pulsational instability excited by central deuterium burning during the initial phases of their evolution. We present the results of evolutionary and nonadiabatic linear stability models that show the presence of unstable fundamental modes. The pulsation periods vary bewteen ~5 hr for a 0.1 $M_\odot$ star and ~1 hr for a 0.02 $M_\odot$ brown dwarf. The results are rather insensitive to variations in the input physics of the models. We show the location of the instability strip in the HR and c-m diagrams and discuss the observational searches for young pulsators in nearby star forming regions.

Key words. Stars: low-mass, brown dwarfs – Stars: pulsation – Stars: HR and c-m diagrams

1. Introduction

Evidence for photometric variability of young VLMSs and BDs in star forming regions has been obtained by several groups in the last few years (Bailer Jones & Mundt 2001, Joergens et al. 2003, Zapatero Osorio et al. 2003; see also Eislöffel in this volume). The amplitudes of the observed variations range from tens of mmag in the optical to ~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 recently in the ϵ and σ Orionis clusters with several objects showing periods in this range (e.g. Caballero et al. 2004, 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. However, for the objects with the shortest periods ($\lesssim$1 hr), the inferred rotational velocities would exceed ~100 km s^{-1} the breakup speed where gravitational and centrifugal forces balance, thus making the rotation interpretation less likely.

In this contribution, we present the initial results of a study of the stability of young VLMSs and BDs during the initial phases of their contraction. In particular, we find that once the central temperatures allow the ignition of deuterium (D-)burning (T~ 10^6 K), the whole interior can become *pulsationally unsta-*

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ble due to the high sensitivity on temperature of the energy generation rate. Such instability, called ϵ-mechanism, was originally suggested by Gabriel (1964) to occur in fully convective, low-mass stars on the main sequence. Later on, Toma (1972) showed that 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, and for different reasons, the original suggestion has not met with success and to date there is no observational evidence for the existence of the ϵ-mechanism in any class of objects. As we will see below, VLMSs and BDs in the earliest evolutionary stages have the appropriate physical conditions to undergo D-induced instabilities on time scales from few hours to about an hour, similar to those observed in some objects in nearby star forming regions (SFRs).

2. The early evolution of VLMSs and BDs

These objects 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 (Stahler 1988). In fact, the ignition temperature of $\sim 10^6$ K can be reached only in protostars more massive than ~0.2 $M_\odot$, depending on the accretion history. Thus, lower mass objects need to contract somewhat in the PMS phase before deuterium can start burning and being depleted. Once the critical tempearture is achieved, the D-burning phase occurs on a time scale that varies between $t_{\rm burn}$ ~2 Myr for a 0.1 $M_\odot$ star and $t_{\rm burn}$ ~20 Myr for a 0.02 $M_\odot$ brown dwarf (Baraffe et al. 1998). Since the energy generation rate, ϵ, scales approximately with the 12-th power of temperature, the rate of combustion is slower for the lowest mass objects. The same temperature sensitivity of ϵ is at the root of the instability induced by any temperature variation: since $\delta\epsilon/\epsilon \sim 12\,\delta T/T$, a small T-perturbation induces a variation of ϵ which is an order of magnitude bigger. In terms of pulsation analysis, the time scale for the growth of the instability, τ_d, is inversely proportional to $\delta\epsilon$ and should be shorter than the D-burning time, $t_{\rm burn}$, for the 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. Evolution and stability of VLMSs and BDs

Evolutionary models of objects with mass between 0.1 and 0.02 $M_\odot$ have been computed using the Lyon code that provides a careful treatement of both the inner structure and the external layers (atmosphere). The initial D-mass fraction is set equal to 2×10^{-5} (e.g. Linsky 1998) and the atmosphere is assumed to be dust free since BDs are relatively hot during the initial evolution ($T_{\rm eff} \gtrsim 2300$ K).

For the nonadiabatic, linear stability analysis we have used the models of Baraffe et al. (2001) that search for the presence of unstable radial eigen modes, characterizing oscillations around the hydrostatic equilibrium configuration. If the 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 $\tau_{\rm dyn} \sim (G\bar{\rho})^{-1/2}$.

4. Results

The main results of the stability analysis (Palla & Baraffe 2004) are the following: (1) D-burning does induce the expected pulsations; (2) the period of the fundamental mode of the pulsation is short and varies between ~4 hr for a 0.1 $M_\odot$ star and ~1 hr for a 0.02 $M_\odot$ BD; (3) the growth time is short compared to the evolutionary time and decreases substantially for smaller masses. The models find a ratio $\tau_d/t_{\rm burn} \lesssim 10$ in the BD regime, satisfying the requirement for the growth of the instability. Therefore, the mechanism can operate effectively before all the available deuterium is consummed.

Fig. 1 displays the time variation of the period of the fundamental mode for four BD

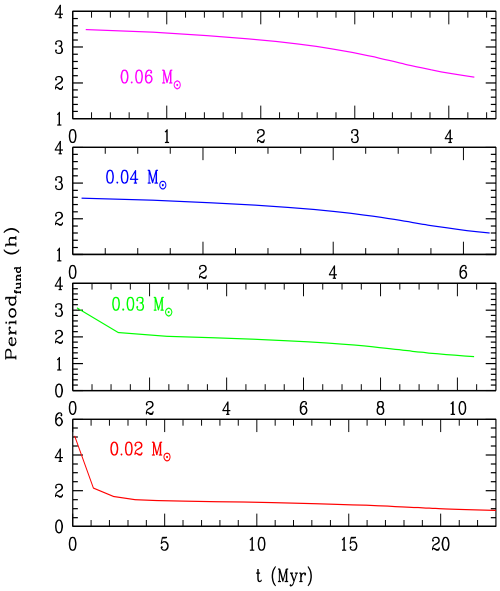

Fig. 1. Variation of the period of the fundamental mode with time for BD models in the mass interval 0.06 to 0.02 $M_{\odot}$. Note the different tome scale in the various panels.

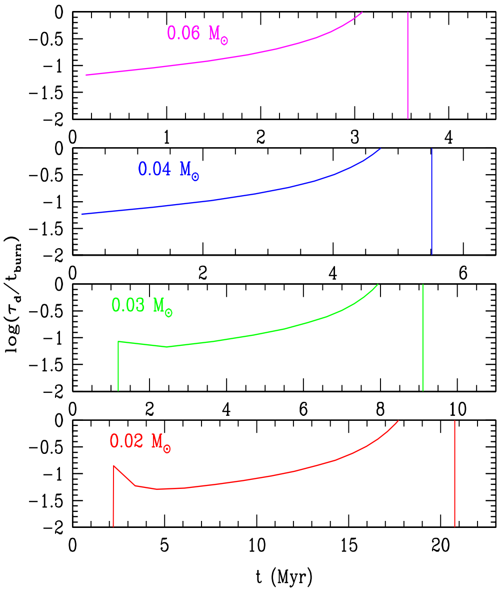

Fig. 2. Time variation of the ratio of the D-burning and growth times for the same models of Fig. 1.

models. In all cases, the pulsation period remains constant during the main D-burning phase and slowly decreases with time in the final stage of complete depletion. The comparison between the growth time of the oscillation and the D-burning time for the same models is displayed in Fig. 2. Note how the growth time remains well below $t_{\rm burn}$, thus guaranteeing that the oscillation can grow to significant amplitudes. Unfortunately, the results of the linear analysis cannot be used to calculate the expected amplitudes of the pulsations. For this, a nonlinear study should be carried out, but these (very complicated) models are still not available. However, considering that the perturbation is produced in the deep interior, we expect small amplitudes in all cases (below ∼0.1 mag).

The results on the instability are robust against uncertaintites in the stellar input physics, such as atmospheric models (NextGen vs. COND models which use different molecular linelists), nuclear reaction rates (Caughlan & Flower vs. NACRE), and initial conditions (above or at the D-ignition). Changes in these quantities may affect the duration of the D-burning phase or the growth time of the instability, but the pulsational properties remain the same. On the other hand, the treatment of convection is a delicate issue, since convection is expected to damp the acoustic waves. However, since the convective time scale (≫yr) is much longer than the pulsation period (∼hr), the standard assumption that convection is frozen with the pulsation appears reasonable. To appreciate the (in)sensitivity of the results on the assumed atmospheric model and initial central temperature (below D-ignition), Fig. 3 shows the variation of various quantities for the 0.03 $M_{\odot}$ case. Both the duration of the D-burning phase and the magnitude of the pulsation growth time remain basically unchanged.

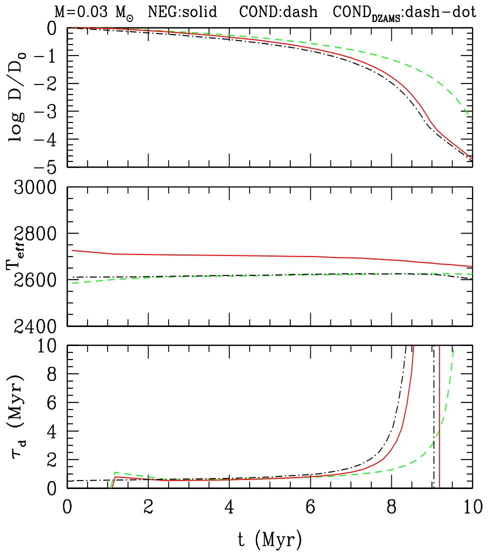

Fig. 3. Effects of variations in the input physics in the 0.03 $M_\odot$ case. Atmospheric models: NEG (solid) vs. COND (dash). The dash-dotted line is for a COND model with initial central temperature close to the D-ignition value.

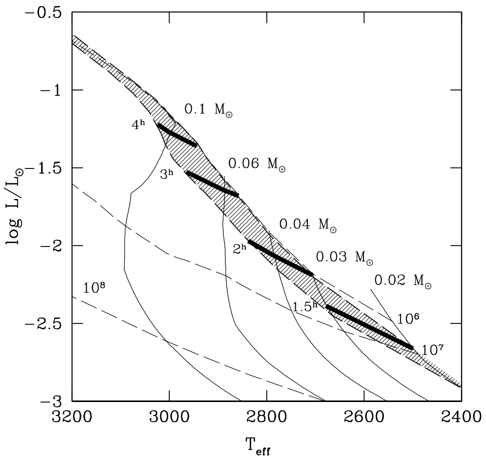

Fig. 4. Location of the D-instability strip in the HR diagram. Evolutionary tracks for different masses are as labeled. Selected isochrones are for 10^6, 10^7, and 10^8 yr. The heavy solid lines represent the curves of constant period for 4, 3, 2 and 1.5 hr.

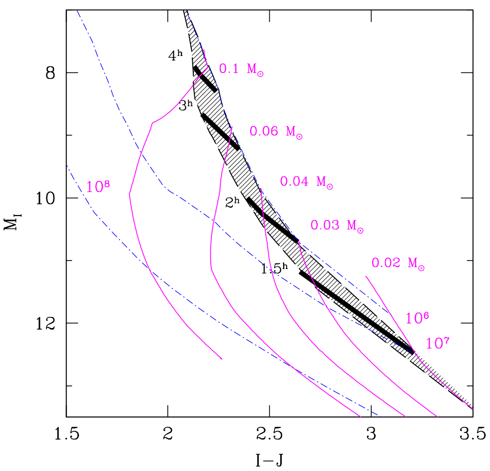

Fig. 5. The D-instability strip in the $(I, I-J)$ diagram. Heavy solid lines have the same meaning as in Fig. 4.

5. The D-instability strip in the HR and CM diagrams

The location of the D-instability strip in the HR diagram is shown in Fig. 4, along with tracks of selected masses and isochrones. The curves of constant period of the fundamental mode cut the strip almost horizontally at nearly constant luminosity and the shortest periods are found for the least massive BDs. Since the evolutionary models also provide the flux emitted by the BDs at different wavelengths, we show the corresponding color-magnitude diagram in Fig. 5 for the $I-$ and $J-$bands. Both plots can be conveniently used for comparison with observations.

6. The observational search for young pulsators

As a result of deep and extended surveys both in the optical and near-IR, young brown dwarfs have been discovered in large numbers in nearby clusters and associations (e.g., Martín et al. 2004, López Martí et al. 2004, Slesnick et al. 2004) with the conclusion that there are almost as many BDs as regular stars (Chabrier 2004). Since age spreads in SFRs are similar to the duration of the D-burning phase in VLMSs and BDs (between a few Myr and $\lesssim$20 Myr), there is ample choice of potential candidates for the discovery of pulsations, despite the relatively narrow extent of the instability strip (see Fig. 4 and Fig. 5.)

As an example, Fig. 6 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 but the overall distribution closely matches the predicted position of the instability strip down to the lowest masses with the shortest pulsational periods. Interestingly, the sample of BDs in Cha I does not show sign of residual accretion indicating that the interaction with the circumstellar environment should not affect their surface properties (Natta et al. 2004). This is an important advantage for searches of intrinsic periodic variability.

The case for the Orion Nebula Cluster is also promising, particularly after the spectroscopic confirmation of a rather large sample of VLMSs and BDs (Slesnick et al. 2004). However, not all SFRs have the suitable population of such objects. For example, the ρ Ophiuchi BD sample appears too young (Natta et al. 2004) with all BDs lying well above the D-instability strip. Thus, care must be taken in the selection of the candidates for pulsation.

In addition to global stellar properties, it is important to consider the information already available on BD variability in young SFRs. The case for σ Orionis is particularly interesting for the relatively young age (~3 Myr) and the rich harvest of substellar objects. Several multi-epoch photometric studies of spectroscopically confirmed BDs have shown that variability occurs in about 50% of the sources on a variety of time scales (from few hours to days and years, e.g. Caballero et al. 2004). In several cases, short-term periodic variations have also been found (or claimed). This is the case for S Ori 27 (period: 2.8±0.4 hr), S Ori 28 (3.3±0.6 hr), S Ori 31 (1.8±0.2 hr), and S Ori 45 (0.5±0.2 hr) (Béjar et al. 2001, 2004; Bailer-Jones & Mundt 2001; Zapatero-Osorio et al. 2003; Caballero et al. 2004). The location of the four sources in the CM diagram is shown in Fig. 7. The two data points for each source refer to measurements from different epoch and underline the large uncertainty still existing in the colors. With the exception of S Ori 28, all three BDs lie very close to the instability strip and their estimated periods compare well with the locus of the isoperiods, considering the errors on the period determination. In spite of the encouraging results, we would like to stress that owing to the limited time coverage and 1-day alias problem that plague all variability studies from ground-based observations, these periods are still to be considered tentative and long-term, multi-band, multi-site monitoring in the future are necessary to confirm their presence. On the other hand, more reliable measurements of the BD colors are also essential for a better comparison with the predicted periods. In turn, these high quality data can be used to place stronger constraints on the input physics of both the evolutionary and stability models.

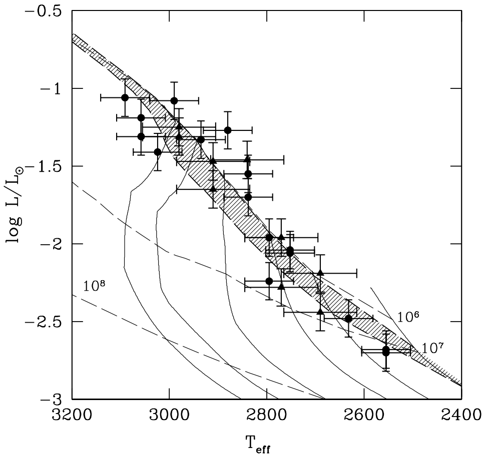

Fig. 6. Distribution of known VLMSs and BDs in Taurus (circles) and Cha I (triangles). Data points for Taurus are from (Briceño et al. (2002), Luhman et al. (2003), Luhman (2004), and for Cha I from Comerón et al. (2000).

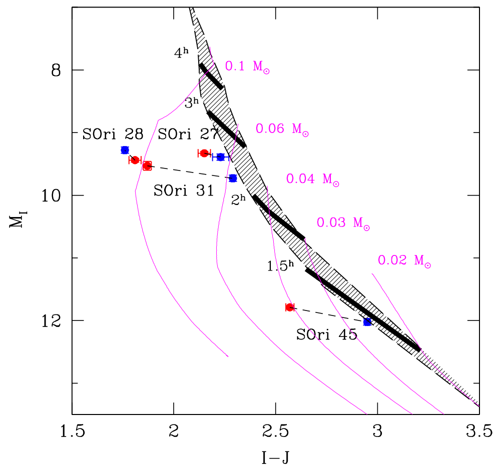

Fig. 7. Position in the $(I, I-J)$ diagram of the σ Ori members with known periods.

7. Conclusions

Perturbations excited in the center of D-burning VLMSs and BDs have time to grow and persist during this ephemeral, but important nuclear interlude. More theoretical work is required to confirm and extend the initial results obtained here. In particular, it is important to develop nonlinear models for the estimate of the pulsation amplitude and fully hydrodynamical calculations to produce syntheic light curves to compare with observations. In general, the reliable identification of the pulsation signature will not be an easy task, considering the other sources of periodic varabiltiy at play in such objects. Notwithstanding these difficulties, the pulsational instability induced by D-burning offers a new interpretation that relies on fundamental (sub)stellar properties. As such, it has the potential of providing direct information on the otherwise inaccesible internal structure of VLMSs and BDs. More fundamentally, it could provide the first evidence for the existence of the ϵ-mechanism in any astronomical object.

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