The instability strip of ZZ Ceti white dwarfs

Valerie Van Grootel\(^{(1)}\)

G. Fontaine\(^{(2)}\), P. Brassard\(^{(2)}\), and M.A. Dupret\(^{(1)}\)

---

(1) Université de Liège, Belgium
(2) Université de Montréal, Canada

- Introduction of Time-Dependent Convection (TDC):
- Extension to Extremely Low Mass (ELM) pulsators:
Pulsations in DA white dwarfs
Pulsating DA white dwarfs

Empirical ZZ Ceti instability strip (classic view)

- Observed pulsator; O non-variable DA white dwarf

- Multiperiodic pulsators, observed period range: 100-1500 s (g-modes)

- Reliable atmospheric parameters: work of Bergeron et al., Gianninas et al., here with $ML2/\alpha=0.6$

- (most probably) a pure strip

- $\log g/T_{\text{eff}}$ correlation (with a more pronounced slope for red edge): the lower $\log g$, the lower edge $T_{\text{eff}}$
Pulsating DA white dwarfs

Empirical ZZ Ceti instability strip (2014 view)

non variable (<10mmag); • pulsator

Hermes et al. (2012, 2013a,b):
5 ELM pulsators
(SDSS J1840, J1112, J1518, J1614, J2228)

Multiperiodic pulsators, 1500-6000 s

Hermes et al. (2013c):
1 UHM pulsator
(GD 518)

Multiperiodic pulsator, 425-595 s
Excitation mechanism of ZZ Ceti stars (general picture)

- Don Winget (1981): 
  H recombination around $T_{\text{eff}} \approx 12,000$ K 
  $\Rightarrow$ envelope opacity increase 
  $\Rightarrow$ strangle the flow of radiation 
  $\Rightarrow$ modes instabilities

- Pulsations are destabilized at the base of the convection zone 
  (details: e.g. Van Grootel et al. 2012)

“convective driving”

Pulsations are driven when the convection zone is sufficiently deep and developed
The theoretical instability strip

- Evolutionary DA White Dwarf Models
Evolutionary DA models

- A standard DA white dwarf structure model (C/O core)

“onion-like” stratification

- Evolutionary tracks computed for 0.4M_\odot to 1.2M_\odot (0.1M_\odot step)
- from T_{\text{eff}}=35,000 K to 2,000 K (~150 models)
- with ML2 version (a=1, b=2, c=16); \alpha = 1 (ie l = Hp)
Our evolutionary models have the same T stratification as the complete (1D) model atmospheres
⇒ “feedback” of the convection on the global atmosphere structure

- Standard grey atmosphere
- Detailed atmosphere
Evolutionary DA models

• Extremely Low Mass (ELM) DA white dwarf:
  H envelope on top of He core

ELM white dwarfs come from stars that never experienced any He-flash, because of extreme mass loss on RGB (from binary interactions or due to high Z)

• 2 kinds of evolutionary tracks computed here:
  I. Standard C core models, but for 0.125\(M_\odot\) and 0.15-0.4\(M_\odot\) (steps 0.05\(M_\odot\))
  II. Pure He core/H envelope models, for the same masses, thick envelopes

Instability strip location in \(T_{\text{eff}}\)-log \(g\) plane insensitive to detailed core composition and envelope thickness
The theoretical instability strip

- Evolutionary DA White Dwarf Models
- Time-Dependent Convection (TDC) Approach
The Time-Dependent Convection approach

For a standard 0.6M\textsubscript{s} DA model:

- \(T_{\text{eff}} \sim 12,000\) K: convective turnover timescale \(\tau_{\text{conv}} \ll \sigma\) (pulsation periods) ⇒ convection adapts quasi-instantaneously to the pulsations

- \(T_{\text{eff}} \sim 11,000\) K: \(\tau_{\text{conv}} \approx \sigma\) ⇒ NEED full Time-Dependent Convection (TDC)

- Frozen convection (FC), i.e. \(\tau_{\text{conv}} \gg \sigma\): NEVER justified in the ZZ Ceti \(T_{\text{eff}}\) regime

\((FC\ is\ the\ usual\ assumption\ to\ study\ the\ theoretical\ instability\ strip)\)
The Time-Dependent Convection theory

• Full development in Grigahcène et al. (2005), following the theory of M. Gabriel (1974, 1996), based on ideas of Unno et al. (1967)
• The Liege nonadiabatic pulsation code MAD (Dupret 2002) is the only one to implement convenient TDC treatment
• The timescales of pulsations and convection are both taken into account
• Perturbation of the convective flux taken into account here:

\[ \delta F_C = F_C \left( \frac{\delta \rho}{\rho} + \frac{\delta T}{T} \right) + \bar{\rho} \bar{T} \left( \delta \Delta s V + \Delta s \delta V \right) \]

• Built within the mixing-length theory (MLT), with the adopted perturbation of the mixing-length:

\[ \frac{\delta l}{l} = \frac{1}{1 + (\sigma \tau_c)^2} \frac{\delta H_p}{H_p} \]

if \( \sigma >> \tau_{\text{conv}} \) (instantaneous adaption): \( \delta l/l \rightarrow \delta H_p/H_p \)

if \( \sigma << \tau_{\text{conv}} \) (frozen convection): \( \delta l/l \rightarrow 0 \)
The theoretical instability strip

- Evolutionary DA White Dwarf Models
- Time-Dependent Convection (TDC) Approach
- Results
Results: computing the theoretical instability strip

- We applied the MAD code to all evolutionary sequences
  - “normal” CO-core DA models, 0.4 – 1.2M\(_s\), log q(H)=-4.0
  - ELM, C-core models: 0.125-0.4 M\(_s\), log q(H)=-4.0
  - ELM, He-core models: 0.125-0.4 M\(_s\), log q(H)=-2.0
  - 0.17Ms, He-core models, “thin” envelope log q(H)=-3.7

  with ML2/\(\alpha\) = 1, detailed atmospheric modeling, and TDC treatment

- We computed the degree \(l=1\) in the range 10-7000 s (\(p\)- and \(g\)-modes)

- For the red edge (long-standing problem):
  based on the idea of Hansen, Winget & Kawaler (1985): red edge arises when

\[
\tau_{th} \sim P_{\text{crit}} \alpha (l(l+1))^{-0.5}
\]

(\(\tau_{th}\): thermal timescale at the base of the convection zone),

which means the mode is no longer reflected back by star’s atmosphere
Valerie Van Grootel - EUROWD14, Montreal

Empirical ZZ Ceti instability strip (2014 view)

- non variable (<10mmag);
- pulsator

Spectroscopic estimates:
- ELM white dwarfs: D. Koester models (Brown et al. 2012)
- UHM white dwarf: Gianninas et al. (2011)
- Standard ZZ Ceti: P. Bergeron et al.

But all $ML2/\alpha = 0.6$

(must be consistent)

+ standard ZZCeti: spectroscopic observations gathered during several cycles of pulsations
Theoretical instability strip (g-modes l=1)

- non variable (<10mmag); ● pulsator

- TDC blue edge
- Red edge

- Narrower strip at low masses (larger slope for the red edge)

- Structure models:
  - ML2/α = 1
  - Narrower strip at low masses (larger slope for the red edge)

- Model atmospheres:
  - ML2/α = 0.6
  - Convective efficiency increases with depth?

NB: evolutionary and atmospheric MLT calibrations are dependent

Valerie Van Grootel - EUROWD14, Montreal
Theoretical instability strip (g-modes $l=1$)

Is the whole ZZ Ceti instability strip pure?

**YES**

- Need only small fine-tuning
- J2228 is a little bit tricky
- Consistency between ML calibrations atmospheres $\Leftrightarrow$ structure models
- Spectra must cover a few pulsational cycles!

**BUT**

- Are all ELM pure H (DA) white dwarfs or with traces of He?
Instability strips of WDs with H/He atmospheres

The instability strip is dependent of the amount of H and He

Details in poster of Van Grootel et al.
The theoretical instability strip

- Evolutionary DA White Dwarf Models
- Time-Dependent Convection (TDC) Approach
- Results
- Convective Driving
Theoretical instability strip (g-modes $l=1$)

- non variable (<10mmag);
- pulsator

Van Grootel et al. (2013)
Convective Driving (≠ κ-mechanism or convective blocking)

TDC and FC blue edges are not dramatically different, but:

1. The difference (~250 K) is not negligible!

Width of instability strip: ~1000 K at log g = 8 and ~600 K at log g = 6

2. Van Grootel et al. (2012) and Saio (2012, Liege colloquium)

Eigenfunctions TDC/FC are really different, and excitation mechanisms too:

- TDC: convective driving (convective flux can be modulated)
- FC: κ-mechanism with radiative luminosity (<<L_{conv})

But both mechanisms occur at the same layers (partial ionization zone)
Conclusion and prospects
Conclusions:

• **Excellent agreement** between theoretical and observed instability strip:
  - Blue edge, TDC approach
  - Red edge, by energy leakage through the atmosphere
• ELM pulsators are low mass equivalent to standard ZZ Ceti pulsators excited by **convective driving**
  ⇒ such pulsators exist from 0.15 to 1.2 $M_\odot$ ($\log g = 5 – 9$)
• Is ML2/$\alpha=1.0$ the good flavor for convection inside white dwarfs? Related to spectroscopic calibration (here ML2/$\alpha=0.6$) and 3D hydrodynamical simulations (Tremblay et al. 2011, 2012, this conference)

Prospects:

• Is the ZZ Ceti instability strip **pure**? Traces of He in ELM white dwarfs?
• Instability strip with structure models including 3D atmospheres?
• Asteroseismology of ELM/standard/UHM ZZ Ceti white dwarf pulsators
Supp. Slides
Universality of the instability domain

Tracks:
- Solid lines: He core, thick env.
- Dotted lines: C-core, thin env.
- Dashed line: 0.17$M_\odot$, thin env.

Edges:
- Edges C-core tracks
- Edges He-core tracks
- Edges 0.17$M_\odot$ track

Instability domain is insensitive to the exact core composition and envelope thickness for models with same $T_{\text{eff}}$/logg
Qualitative fit to the observed periods of the 3 ELM pulsators

SDSS J1840+6423
$T_{\text{eff}} \sim 9140 \pm 170$ K, $\log g \sim 6.16 \pm 0.06$
He-core model, $\log q(H)=-2.0$

SDSS J1518+0658
$T_{\text{eff}} \sim 9810 \pm 320$ K, $\log g \sim 6.66 \pm 0.06$
He-core model, $\log q(H)=4.0$ and -2.0

SDSS J1112+1117
$T_{\text{eff}} \sim 9400 \pm 490$ K, $\log g \sim 5.99 \pm 0.12$
He-core model, $\log q(H)=-2.0$

Adiabatic properties are sensitive to exact interior structure