Latest news on white dwarf pulsators in the light of space- and ground-based observations

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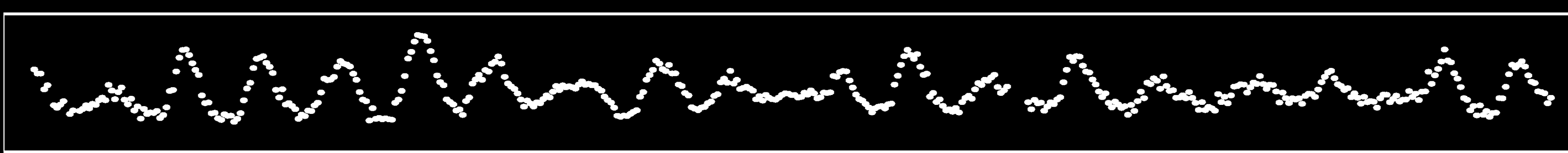
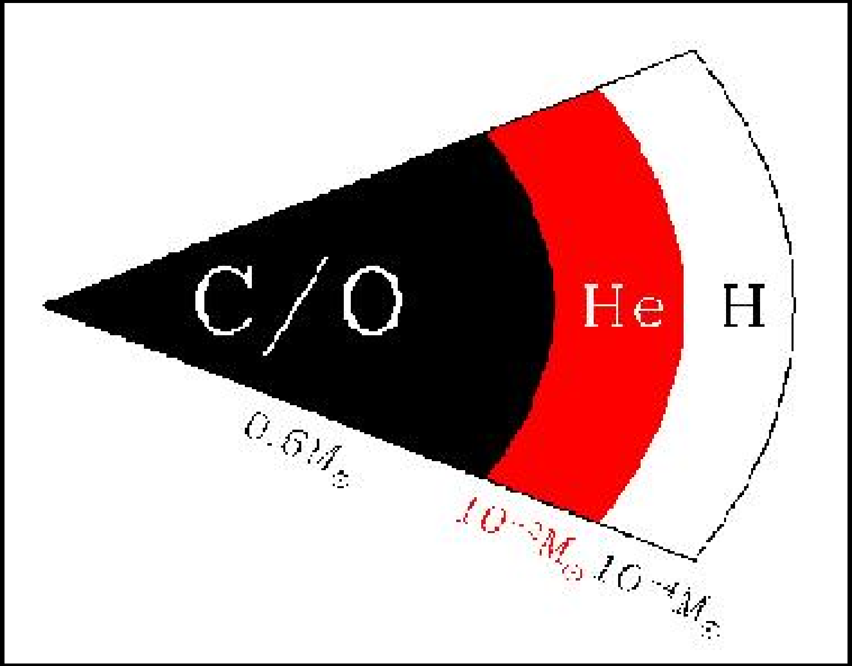
AZ INNOVÁCIÓ LENDÜLETE

AZ NKFI ALAPBÓL MEGVALÓSULÓ PROJEKT



Pulsating WDs – introduction

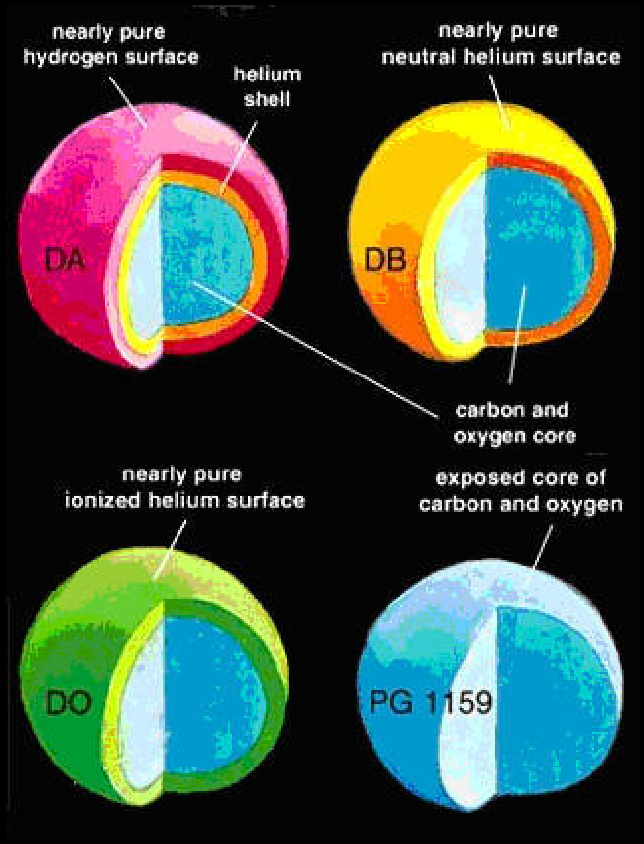


- the C/O core contains more than 99% of the mass
  (degenerate electron gas + non-degenerate ion component),
- Chandrasekhar-limit!
- 60-100 km non-degenerate gas envelope
- average mass: 0.6-0.7 solar mass
  (O-Ne core: 1-1.3 Msun)
- the thin gas envelope controls the cooling of the WD

Pulsating WDs – introduction

Spectral types:
- **DA** (>85%) H dominated envelope
- **DO** (> 45 000 K), **DB** (30 000–12 000 K): He
- "hybrid types" (pl. DBA)
- heavier elements in the spectra:
DQ, DZ types (<12 000 K)

In general: the observed atmospheric composition is influenced by the convection, diffusion and accretion processes.



Pulsating WDs – introduction

- 3 major groups: GW Vir, DBV (V777 Her), DAV (ZZ Ceti)

- the first pulsating WD discovered: HL Tau 76 (Arlo U. Landolt, 1964) → short period, low amplitude, multiperiodic light variations, caused by nonradial g-mode pulsations (1972)

- systematic observations → ZZ Ceti stars (~12 000 K)

- zone of excitation of pulsations: where H is partly ionized + convection

- DBV stars: predicted theoretically (~20 000 K), then confirmed by observations (Winget et al. 1982)

mode excitation: ionization of He+convection

- in the meantime: light variations of PG 1159-035 (GW Vir) (McGraw et al. 1979)

excitation mech.: cyclic ionization of part of the C and O

- temperature ranges:

GW Vir: 75 000 – 170 000 K, DBV: 22 000 – 29 000 K, DAV: 10 500 – 13 000 K

Pulsating WDs – introduction

New types of variables:

- hot DQ WDs, 18 000 – 23 000 K (Dufour et al. 2007), atmosphere dominated by C

The excitation of g-mode pulsations was theoretically predicted and then observed (Montgomery et al. 2008; relatively strong magnetic field, ~10^6 G) → DQV stars

P ~ 150 – 1100 s

5 members

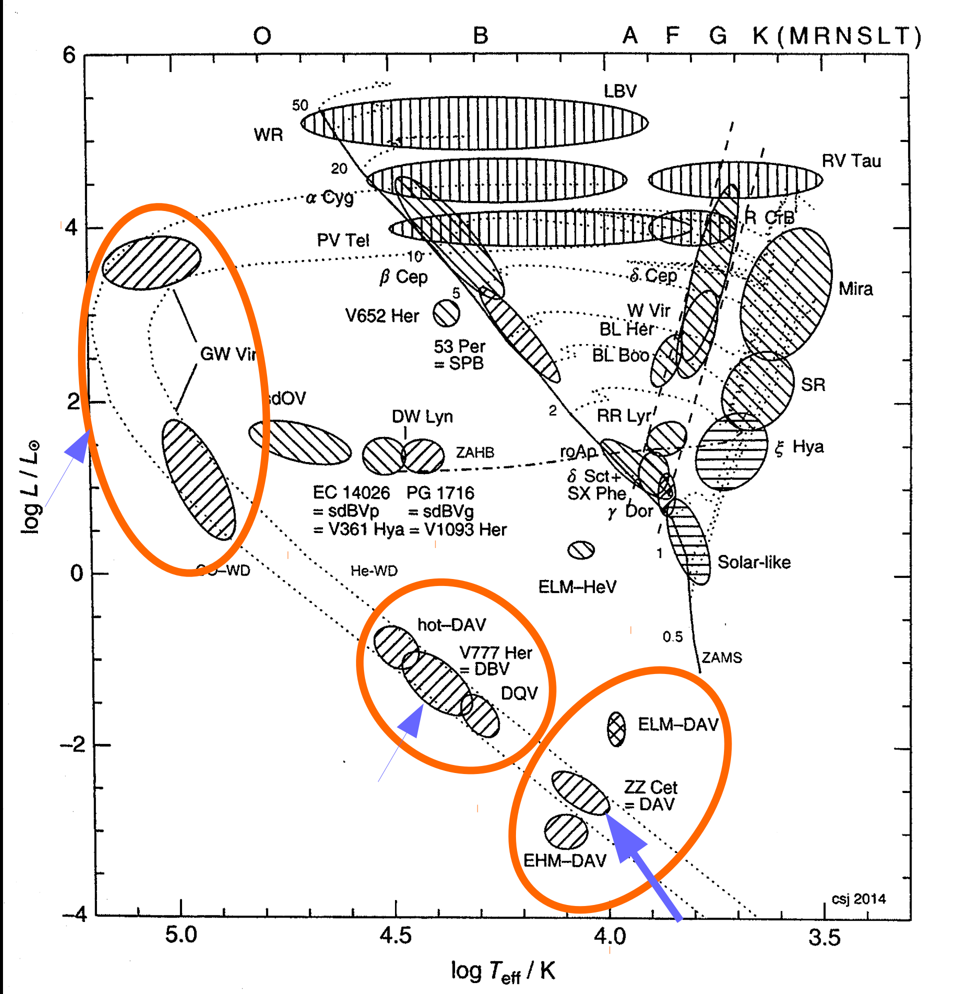
- hot DAV stars: also predicted and observed, g-mode pulsations around 30 000 K in DA stars (Shibahashi 2007, (Kurtz et al. 2008)

P ~ 150 – 700 s, A ~ 1 mmag

3 members

- ELM (“extremely low-mass”; 0.16 – 0.23 Msun, He core, 5 members) and EHM (“extremely high-mass”; O-Ne core) DAV stars

Pulsating WDs – introduction

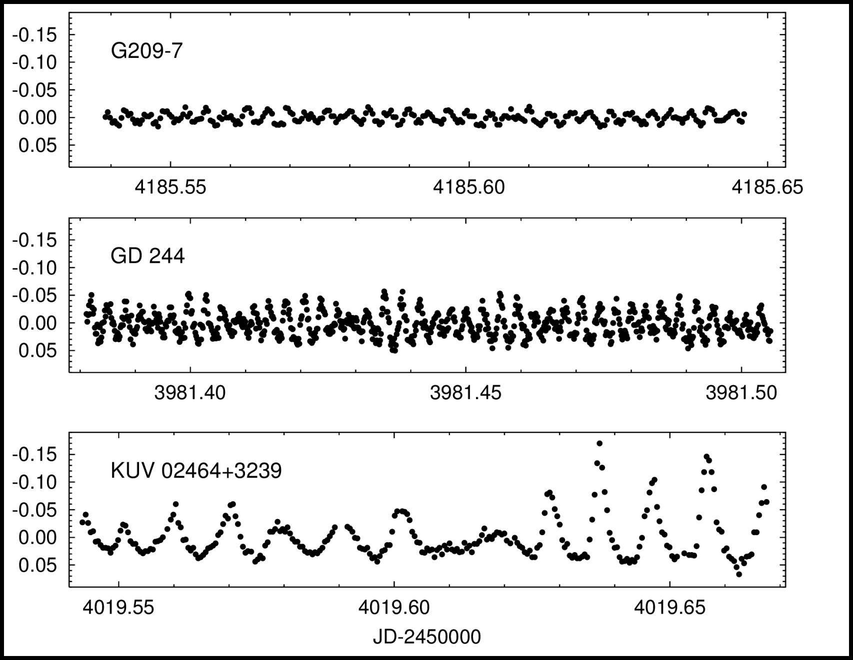


Pulsating WDs – introduction

- pulsation periods: GW Vir: 300 – 6000s; DBV, DAV: 100 – 1500s

- trend observed at DAV stars: lower temperature → longer periods

- the main physical parameters affecting the pulsation periods: stellar mass, effective temperature, core composition, masses of the H and He shells



Ground-based observations

- WET (Whole Earth Telescope), 1st campaign:1988
- single-site (e.g. Konkoly Observatory)

  extended observations on DAV and DBV stars (2006-):

  KUV 02464+3239

  GD 154

  GD 244

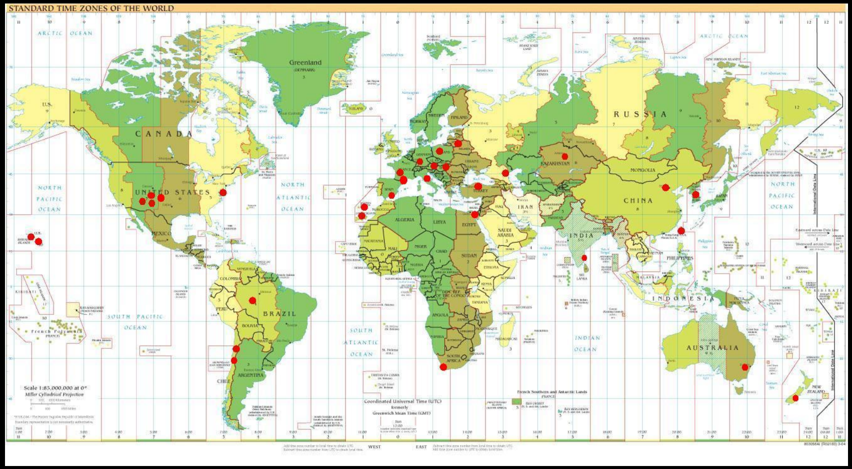
  G 207-9

  LP 133-144

  Ross 808

  HS 0733+4119

  KUV 05134+2605 (DBV)



Space-based observations: *Kepler* and *K2* mission

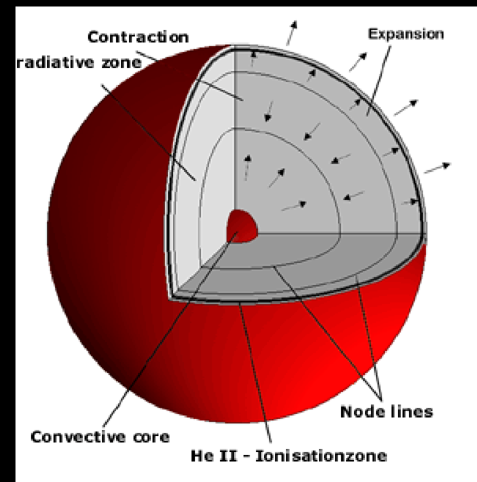
- 31 ZZ Ceti, 2 DBV
  (*Kepler* + *K2,* up to Cycle 8)

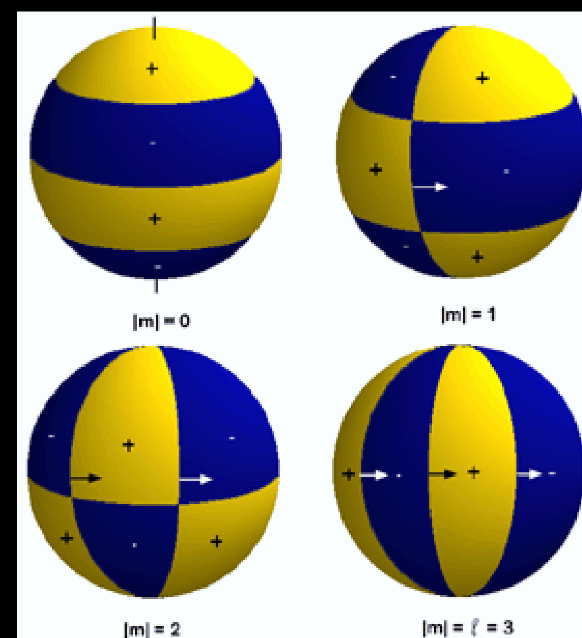
- High duty cycles, precise photometry, relatively large number of objects → in-depth investigations of the important topics:
  - mode identification (*l*, *m*) and investigations of stellar rotation
  - studies of mode stability:
    mode line widths in the Fourier transforms (FTs);
    amplitude and frequency modulations caused by nonlinear resonant mode couplings?
    outbursts in cool DAVs.
  - characterization of the DAV instability strip

Theoretical outlook

- pulsations: can be described by spherical harmonic and radial wave functions ($Y_{l,m}$, R_n)
  - *n* (or *k*): radial order - number of nodal surfaces in the radial direction (n = 0,1,2,...)
  - *l*: spherical degree - the total number of node lines on the stellar surface (l = 0,1,2,...)
  - *m*: azimuthal order - the number of node lines in longitude (m = −l,...,l)

- we typically observe l=1,2 modes



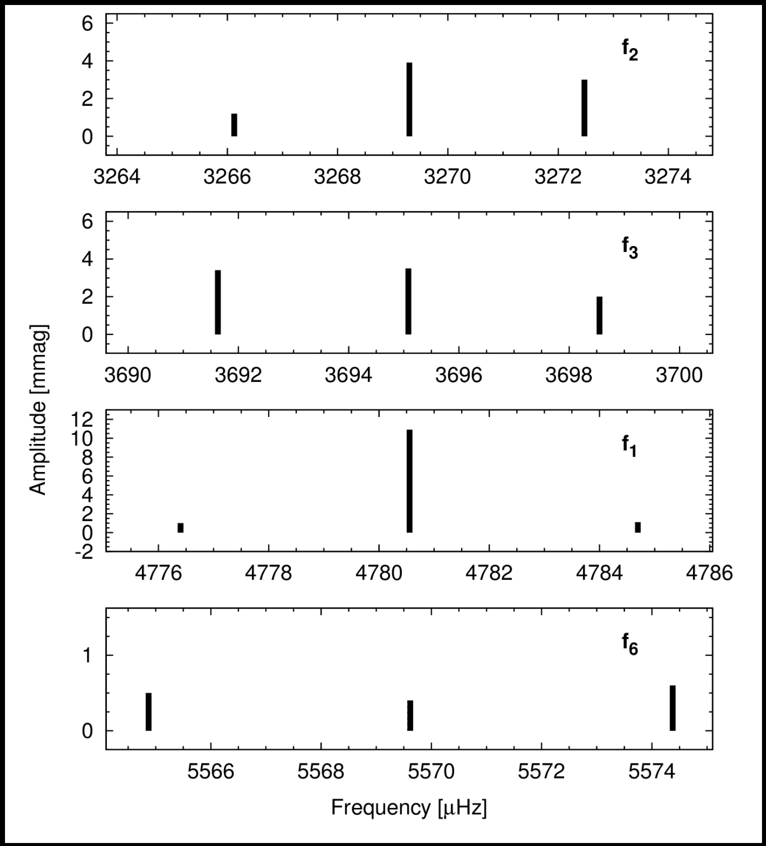


Stellar rotation

- stellar rotation causes a lifting of degeneracy in the pulsation frequencies, causing a mode to separate into 2l+1 components in m → triplets (l=1), quintuplets (l=2)

- $\delta f = \delta m(1-C_{k,l})\Omega$

$C_{k,l} \rightarrow 1/[l(l+1)]$ for high k (0.5), but lower for low-k modes



the frequency separations are ~4 μHz → the rotational period of LP 133-144 is ≃42 h observed at Piszkéstető Observatory

Stellar rotation

The Astrophysical Journal Supplement Series, 232:23 (28pp), 2017 October Hermes et al.

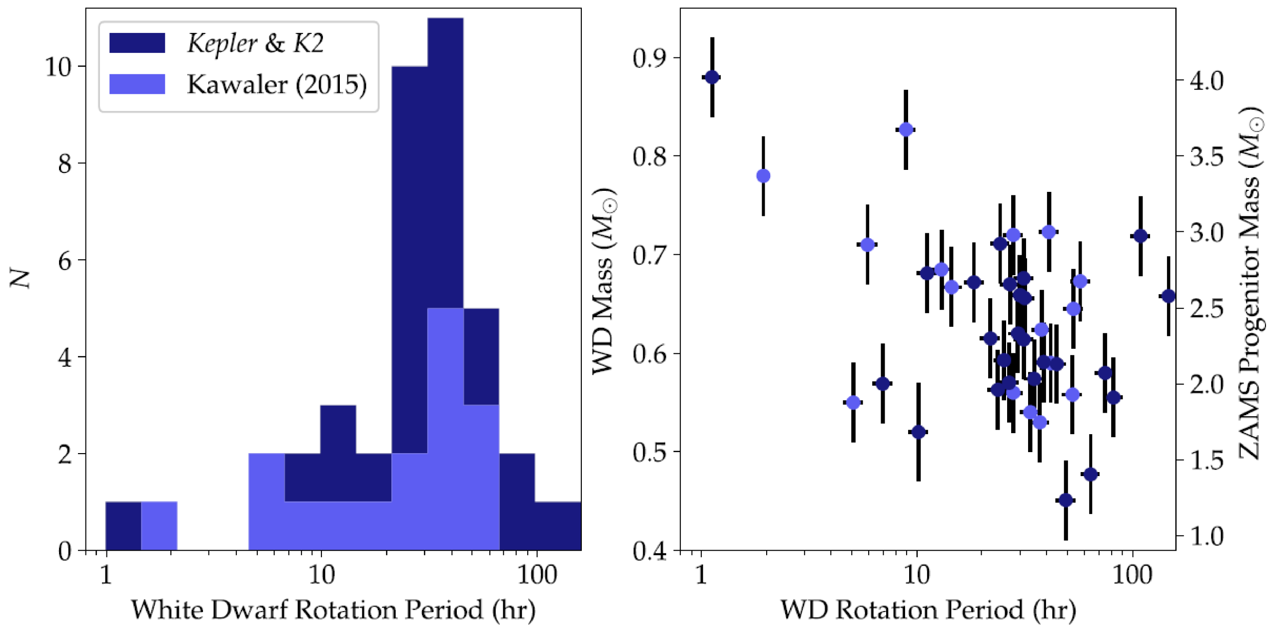


Figure 8. We compare asteroseismically determined rotation periods for all known pulsating white dwarfs, detailed in Table 4. All white dwarfs presented here appear to be isolated stars, so these rotation periods should be representative of the endpoints of single-star evolution; we excluded the only known close binary (a WD+dM in a 6.9 hr orbit), EPIC 201730811 (SDSS J1136+0409, Hermes et al. 2015a). The left histogram shares the color coding of the right panel, which compares white dwarf rotation as a function of mass. Estimates of the ZAMS progenitor masses for each white dwarf are listed on the right axis. Notably, EPIC 211914185 (SDSS J0837+1856) is more massive ($0.88 \pm 0.03\ M_\odot$) and rotates faster (1.13 ± 0.02 hr) than any other pulsating white dwarf (Hermes et al. 2017c); we see evidence for a link between high mass and fast rotation, but require additional massive white dwarfs to confirm this trend.

0.51–0.73 Msun white dwarfs, which evolved from 1.7–3.0 Msun ZAMS progenitors, have a mean rotation period of 35 +/- 28 hr with notable exceptions for higher-mass white dwarfs

Mode stability investigations

- mode line widths

The Astrophysical Journal Supplement Series, 232:23 (28pp), 2017 October Hermes et al.

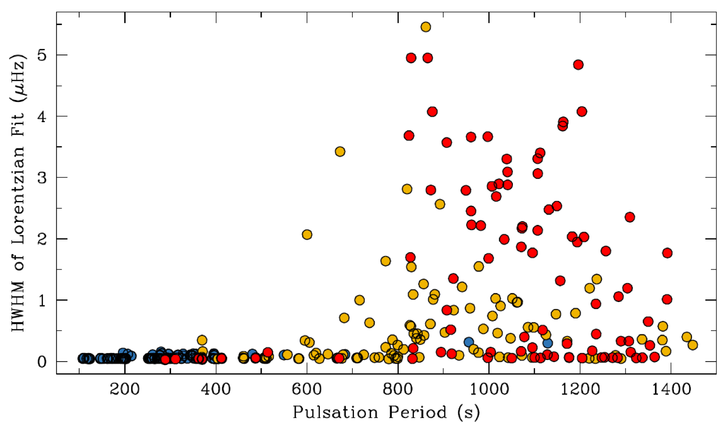
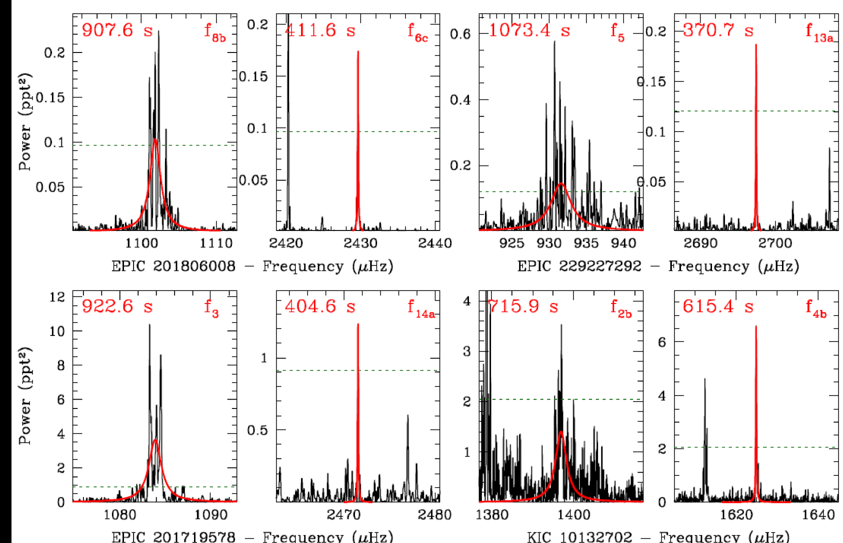


Figure 5. Half-width at half-maximum (HWHM) of Lorentzian functions fit to all significant peaks in the power spectra of the 27 DAVs observed through *K2* Campaign 8 by the *Kepler* space telescope; our procedure is described in Section 5. We use the same color classification as in Figure 3, where blue denotes objects with WMP < 600 s, gold with WMP > 600 s, and red those with outbursts (see Section 6). We excluded any nonlinear combination frequencies in this analysis. We see a sharp increase in HWHM at roughly 800 s, indicating that modes with relatively high radial order ($k > 15$ for $\ell = 1$ modes) are not coherent in phase, similar in behavior to stochastically excited pulsators. We save a discussion of the possible physical mechanisms behind this phenomenon for a future work (M. H. Montgomery et al. 2017, in preparation).

The Astrophysical Journal Supplement Series, 232:23 (28pp), 2017 October Hermes et al.

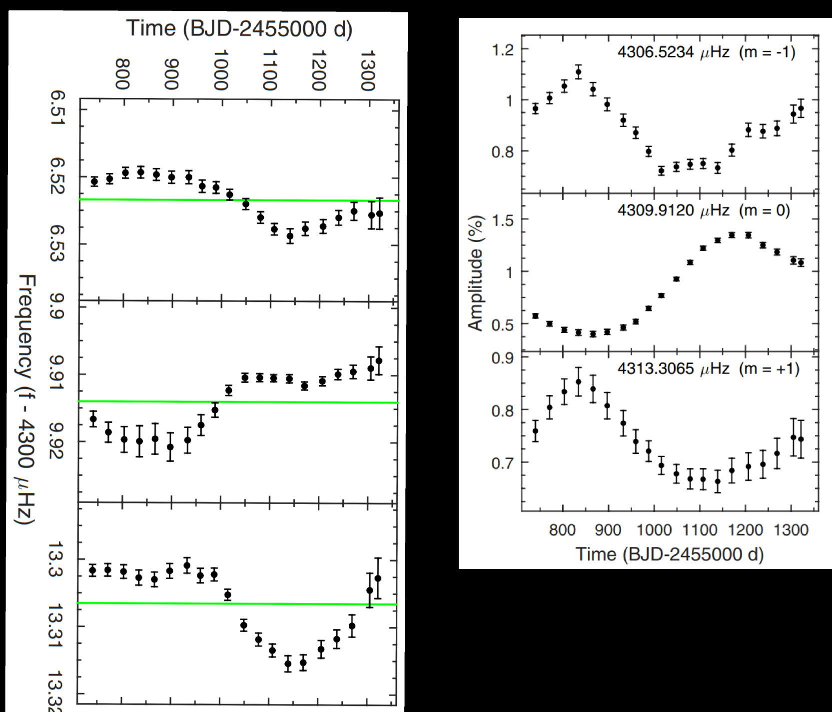


- white dwarf pulsations with periods exceeding 800 s have substantially broader mode line widths

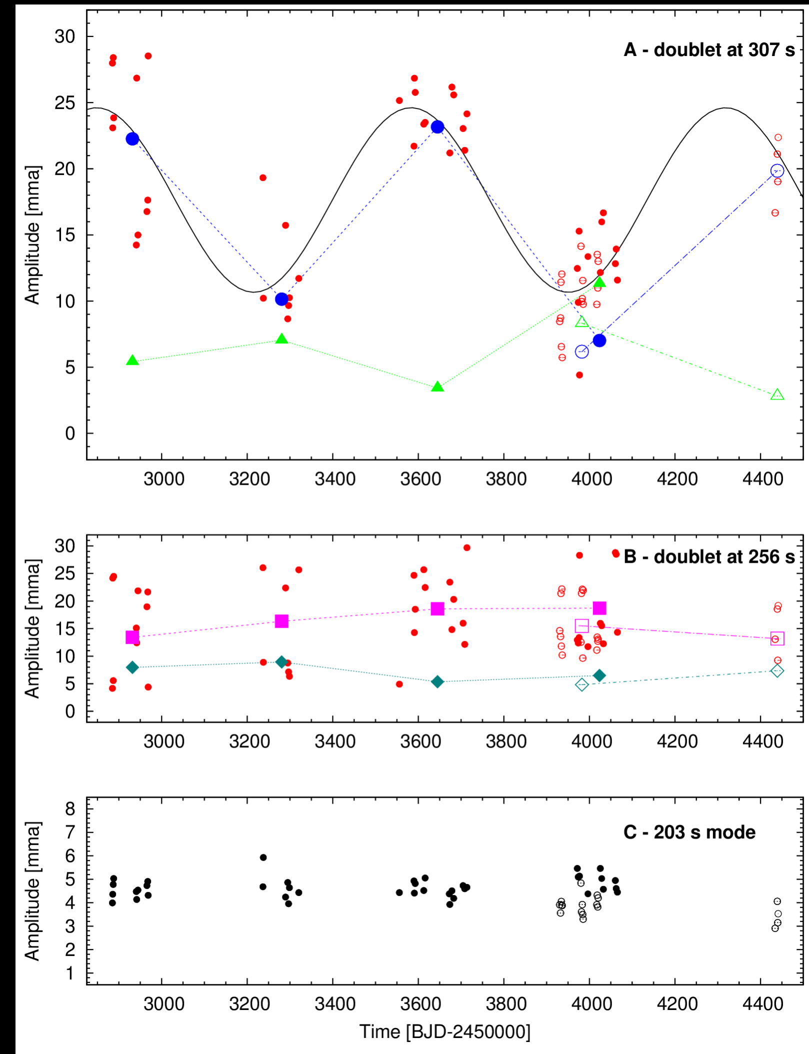
Mode stability investigations

- amplitude and frequency modulations

caused by nonlinear resonant mode couplings?



KIC 08626021 (DBV)



GD 244 (DAV)

Mode stability investigations

- amplitude and frequency modulations

caused by nonlinear resonant mode couplings?

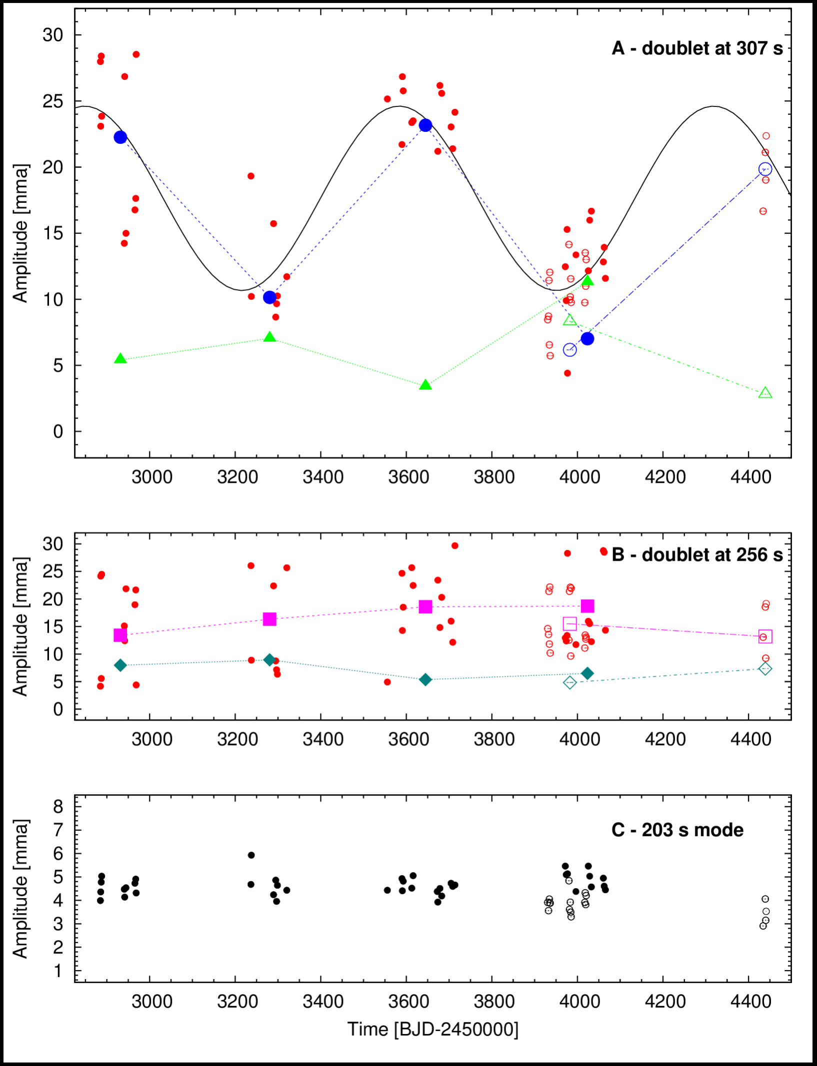


Figure 1. Amplitudes of different frequency components. *Filled* and *open circles*: McDonald and Konkoly Observatory data, respectively. *Small red* (panels A and B) and *black* (panel C) *dots*: daily values. *Large blue dots* and *green triangles* (panel A), *magenta squares* and *teal diamonds* (panel B): yearly amplitudes of the 307.1, 306.6, 256.6 and 256.2 s peaks, respectively. The standard errors of the fits are smaller than the sizes of the symbols used. *Black solid line* (panel A): sine wave fit to the daily data. The frequency used for the fit was fixed according to the frequency separation of the two closely spaced peaks found at f_6 by the combined 2003–2006 McDonald Observatory data ($\delta f = 0.00136\,\mathrm{d}^{-1}$, $P \simeq 735$ d, see Sect. 4).

GD 244 (DAV)

Outbursts of cool DAV stars

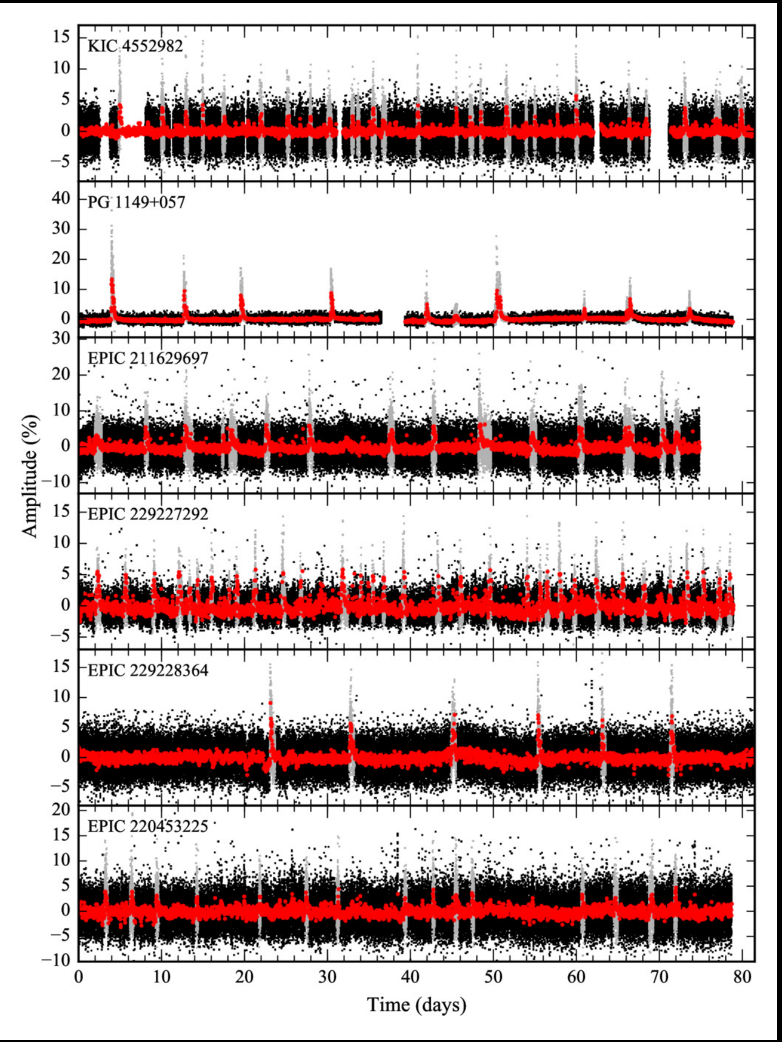
- “outburst”

How?

- the mean stellar flux increases up to 15% in about 1 hour
- duration: hours – 1 day
- recurrence: in a couples of days or in a week
- there are no regularities

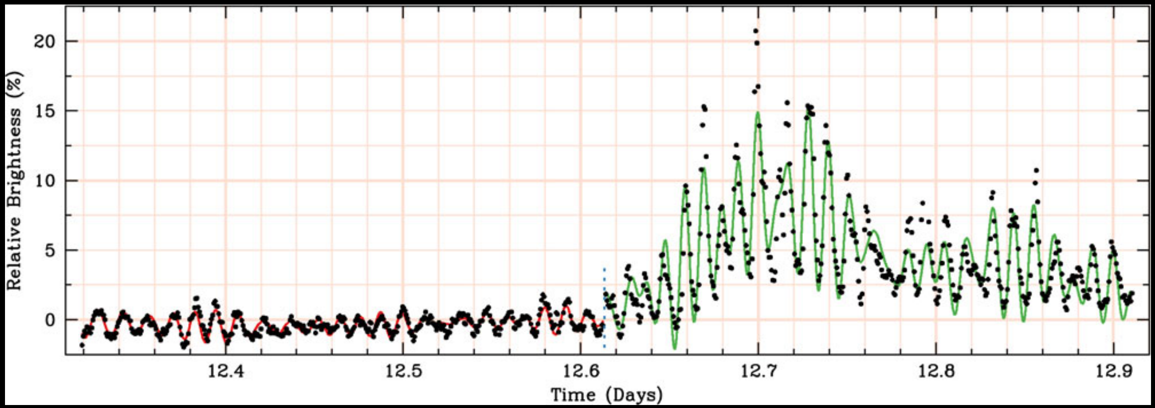
What causes these phenomenon?

nonlinear mode coupling; “in this model, a resonant coupling can transfer energy from a driven parent mode into two daughter modes. If these daughter modes are damped at the base of the convection zone, they will deposit their energy there, heating the surface of the star.”

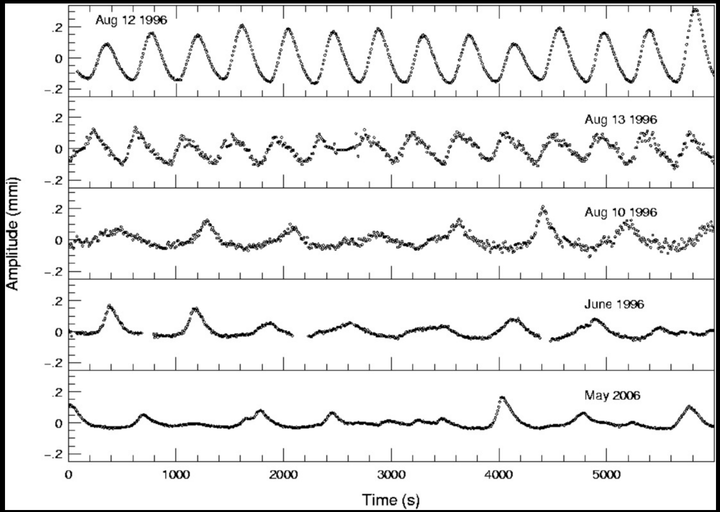


Outbursts of cool DAV stars

PG 1149+057



GD 358
(ground-based observation)



Characterization of the DAV instability strip

(a) DAVs begin pulsating at the blue edge of the Instability strip with low-k modes from roughly 100–300 s and relatively low amplitudes (~1 ppt).

(b) relatively short-period pulsations but their observed amplitudes increase. Extremely long mode lifetimes, and most modes with periods shorter than 400 s appear coherent in phase.

(c) DAVs in the middle of the instability strip: very high-amplitude modes and the greatest number of nonlinear combination frequencies.

(d) *Kepler* observations: a new phase in the evolution of DAVs as they approach the cool edge of the instability strip: aperiodic outbursts.

(e) DAVs do not experience large-scale flux excursions, suggesting that not all DAVs outburst at the cool edge of the instability strip.
The coolest DAVs tend to have the longest-period pulsations with relatively low amplitudes.