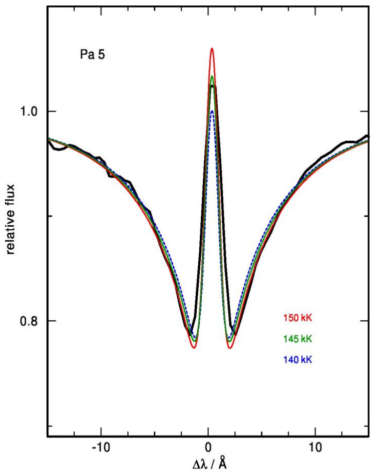
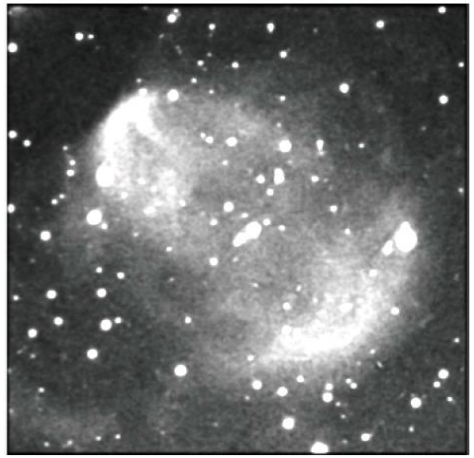
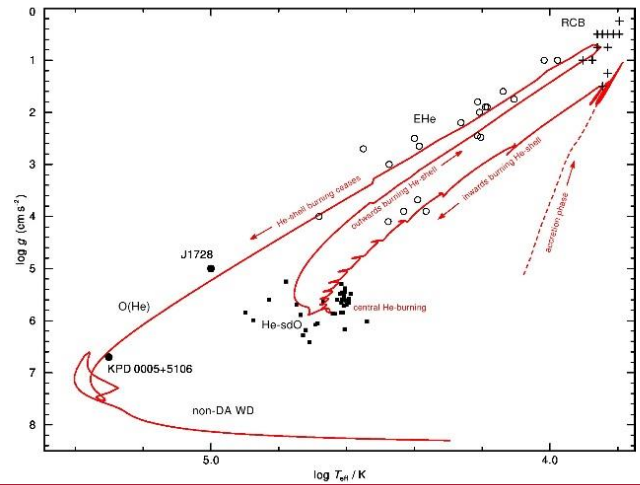
EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

FACULTY OF
SCIENCE

Institute for Astronomy and Astrophysics



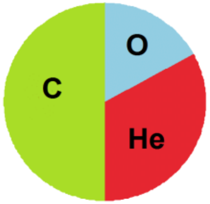




Recent Progress on our Understanding of He-Dominated Stellar Evolution

21.08.2015, N. Reindl

H-deficient stars

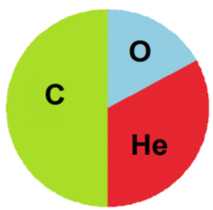


C-rich

He ~ 30-50%
C ~ 30-60%
O ~ 2-20%

VLTP evolution in the HRD.

H-deficient stars



C-rich

He ~ 30-50%
C ~ 30-60%
O ~ 2-20%

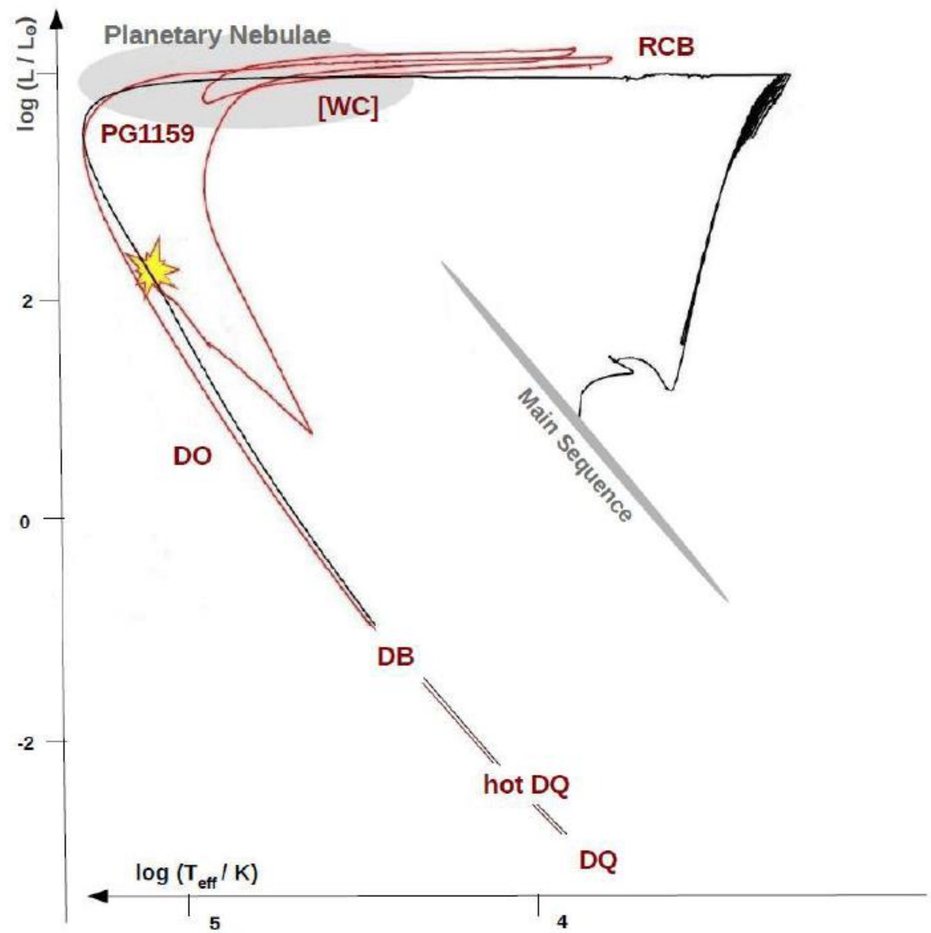
Surface abundaces can be explained by (very) late thermal pulse ((V)LTP) scenarios

RCB → [WC] → PG 1159 → DO → DB → DQ

Partly observed in real time

Sakurai's Object: VLTP → RCB
V605 Aquilae: VLTP → RCB → [WC]
FG Sge: LTP → RCB

Lo 4 : PG 1159 ⟷ [WC]

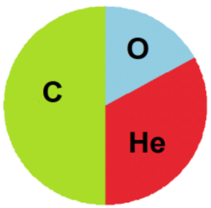


VLTP evolution in the HRD.

Introduction

H-deficient stars

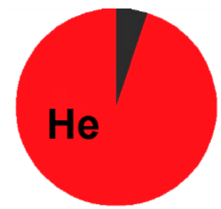
C-rich



He ~ 30-50%
C ~ 30-60%
O ~ 2-20%

RCB → [WC] → PG 1159 → DO → DB → DQ

He-dominated



He ≥ 90%

RCB stars

EHe stars

He-sdO stars

[WN]-type central stars

O(He) stars

Introduction

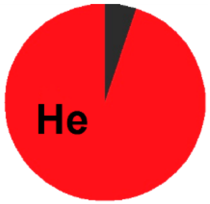
H-deficient stars

- H-poor supergiants, T_{eff} = 4000 - 8000 K, log g = 0.5 -1.5, log(L/ $L_{\odot}$) = 3.2 – 4.0
- ≈ 68 in the Galaxy,

  ≈ 25 in the Magellanic Clouds

  ≈ 4 in M31

He-dominated



He ≥ 95%

RCB stars

EHe stars

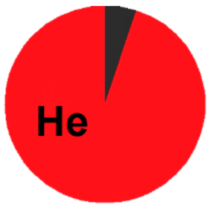
He-sdO stars

[WN]-type central stars

O(He) stars

H-deficient stars

He-dominated



He ≥ 95%

RCB stars

Early type supergiants of spectral type A and B

≈ 17 objects known

EHe stars

He-sdO stars

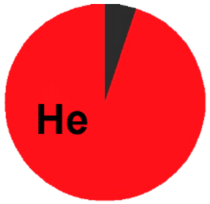
[WN]-type central stars

O(He) stars

Introduction

H-deficient stars

He-dominated



He ≥ 95%

- Very similar element abundances

  He-dominated, C ≈ 1%, N≈1% (by mass)

RCB stars

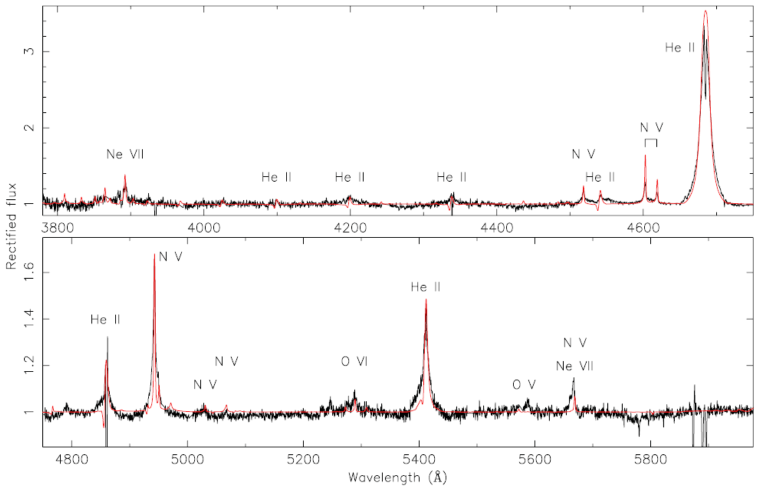
EHe stars

He-sdO stars

[WN]-type central stars

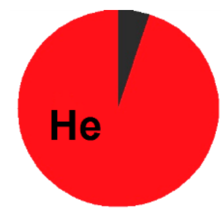
O(He) stars

H-deficient stars



Optical spectrum of the CS of IC 4663: observation (black) versus synthetic CMFGEN NLTE spectrum (red, Miszalski et al., 2012).

He-dominated



He ≥ 95%

RCB stars

EHe stars

He-sdO stars

[WN]-type central stars

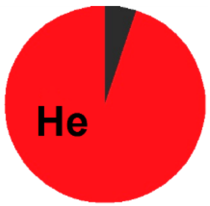
O(He) stars

- He-dominated central stars of planetary nebulae (CSPNe)
- Enriched in N (1-5% by mass)
- Strong stellar wind
- Only two objects known so far: **IC 4463** (Miszalski et al., 2012) and **Abell 48** (Todt et al., 2013; Frew et al., 2014).

O(He) stars

H-deficient stars

He-dominated



He ≥ 95%

RCB stars

EHe stars

He-sdO stars

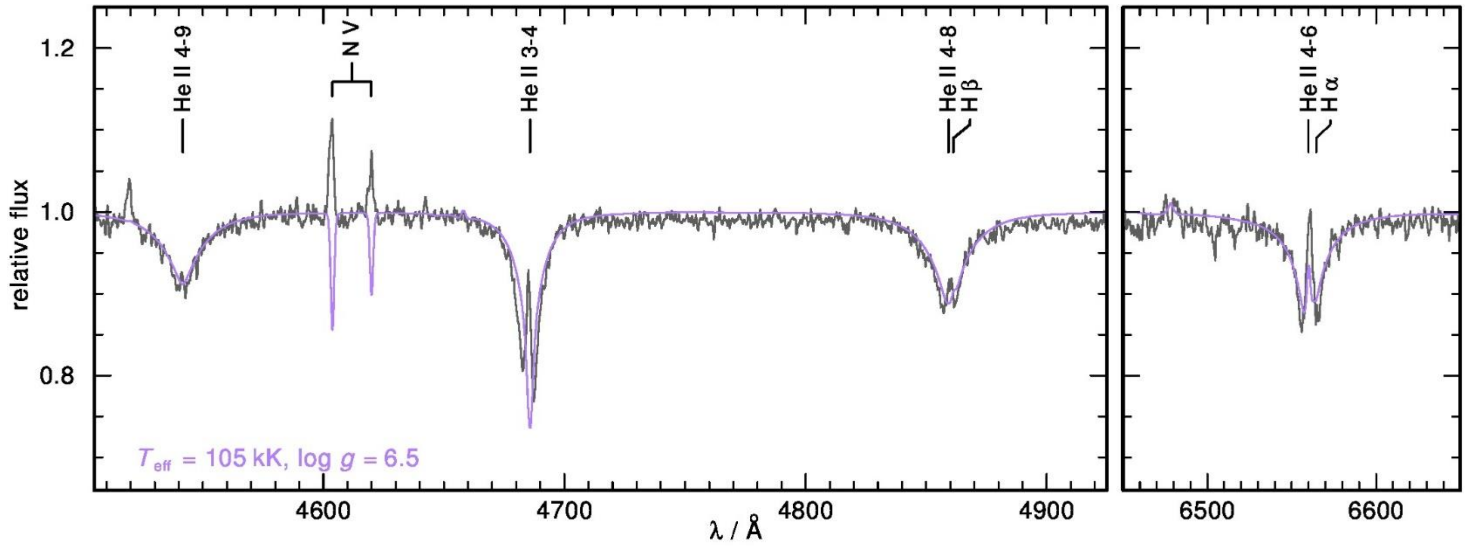
[WN]-type central stars

O(He) stars

- Extremely hot (Teff ≥ 80 kK) pre-white dwarfs
- Found in the post-AGB region in the T_{eff} - log g diagram, just amongst the luminous PG 1159 stars and H-rich CSPNe

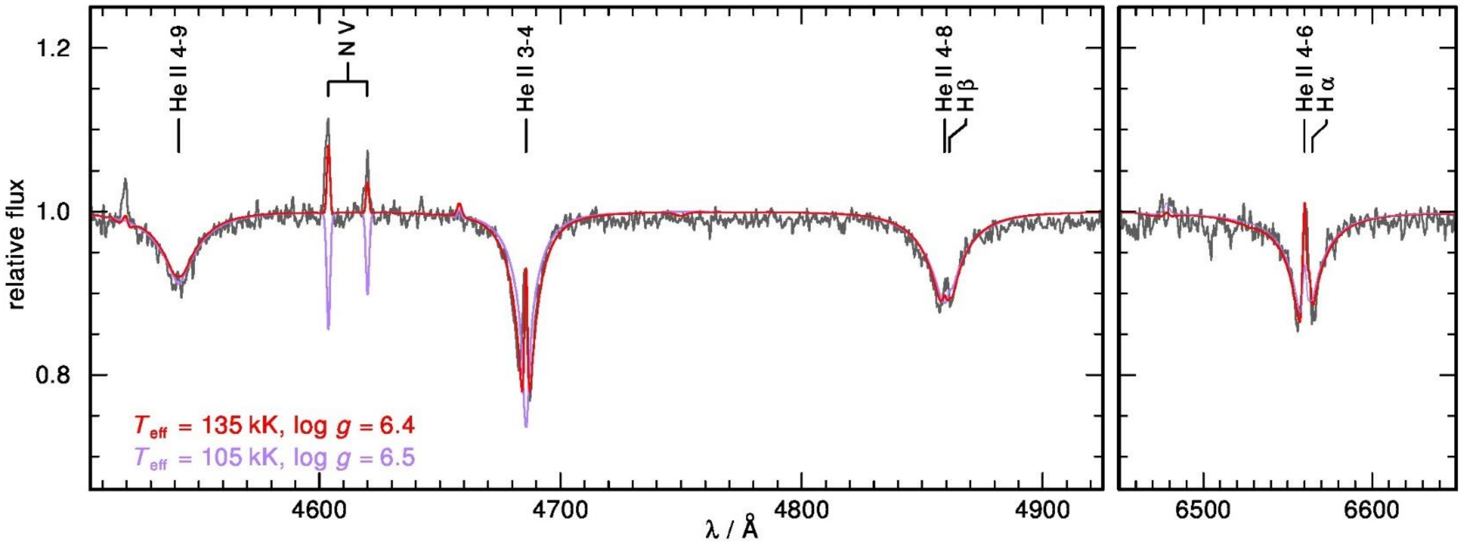
O(He) stars

- First known O(He) stars: CSPNe **K1-27** and **LoTr4**, and **HS 1522+6615** and **HS 2209+8229**
- Rauch et al. (1994, 1996, 1998): First non-LTE-analysis with HHe (+CNO) models based on optical spectra (resolution ≈ 3 Å)
- Reindl et al. (2014): Reanalysis with HHeCNONe (+FSiPSFe) models based on new optical spectra (resolution ≈ 1.5 Å) for K1-27 and LoTr4, FUSE, and HST/COS spectra (all stars, resolution ≈ 0.1 and 0.9 Å)
- **K1-27**: Problem with He II λ 4686 Å and N V lines solved



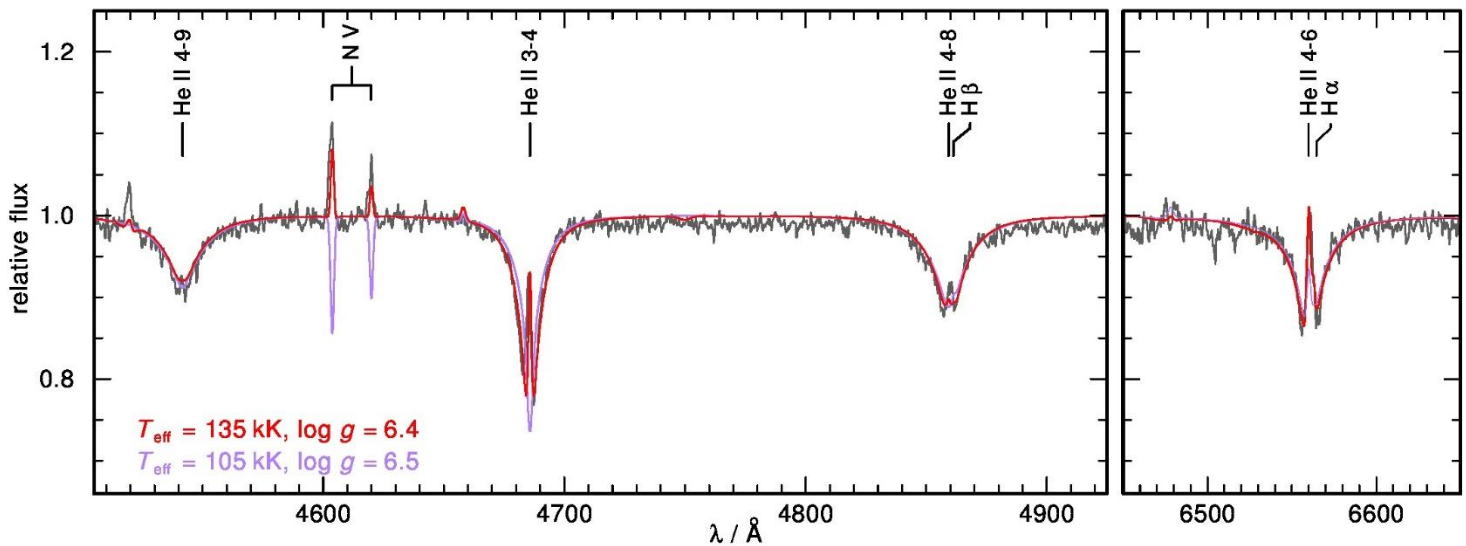
O(He) stars

- First known O(He) stars: CSPNe **K1-27** and **LoTr4**, and **HS 1522+6615** and **HS 2209+8229**
- Rauch et al. (1994, 1996, 1998): First non-LTE-analysis with HHe (+CNO) models based on optical spectra (resolution ≈ 3 Å)
- Reindl et al. (2014): Reanalysis with HHeCNONe (+FSiPSFe) models based on new optical spectra (resolution ≈ 1.5 Å) for K1-27 and LoTr4, FUSE, and HST/COS spectra (all stars, resolution ≈ 0.1 and 0.9 Å)
  - **K1-27**: Problem with He II λ 4686 Å and N V lines solved



O(He) stars

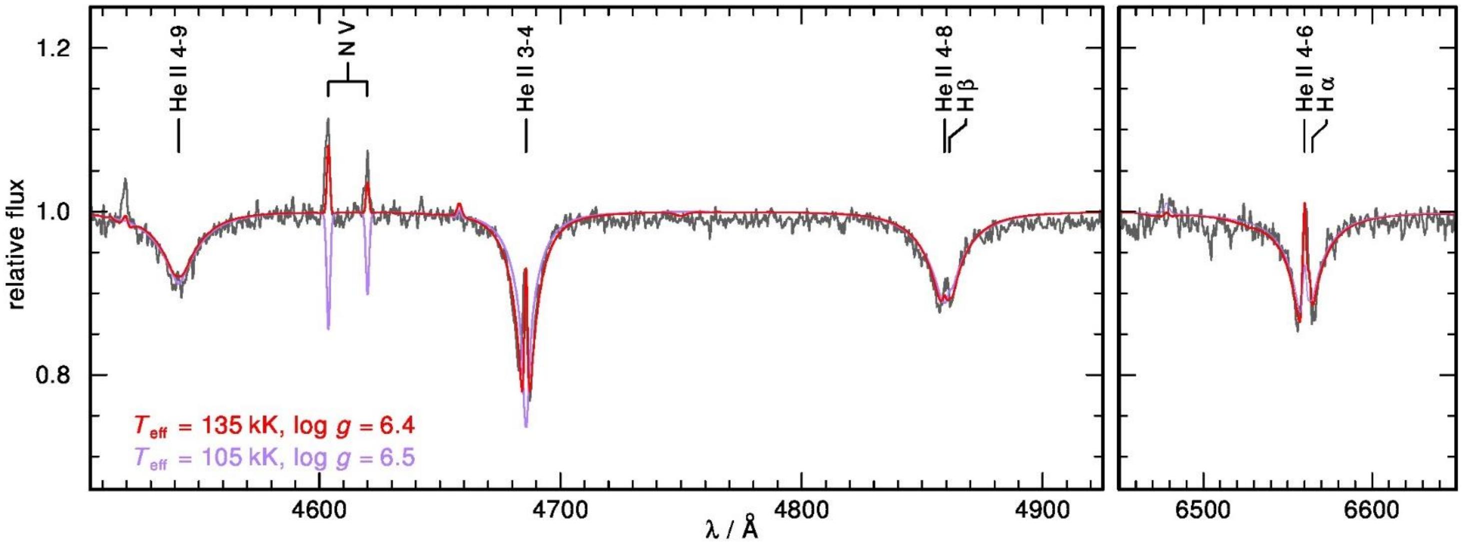
- First known O(He) stars: CSPNe **K1-27** and **LoTr4**, and **HS 1522+6615** and **HS 2209+8229**
- Rauch et al. (1994, 1996, 1998): First non-LTE-analysis with HHe (+CNO) models based on optical spectra (resolution ≈ 3 Å)
- Reindl et al. (2014): Reanalysis with HHeCNONe (+FSiPSFe) models based on new optical spectra (resolution ≈ 1.5 Å) for K1-27 and LoTr4, FUSE, and HST/COS spectra (all stars, resolution ≈ 0.1 and 0.9 Å)
  - **K1-27**: Problem with He II λ 4686 Å and N V lines solved



→ Systematical error of 30 kK

O(He) stars

- First known O(He) stars: CSPNe **K1-27** and **LoTr4**, and **HS 1522+6615** and **HS 2209+8229**
- Rauch et al. (1994, 1996, 1998): First non-LTE-analysis with HHe (+CNO) models based on optical spectra (resolution ≈ 3 Å)
- Reindl et al. (2014): Reanalysis with HHeCNONe (+FSiPSFe) models based on new optical spectra (resolution ≈ 1.5 Å) for K1-27 and LoTr4 FUSE, HST/COS spectra (all stars, resolution ≈ 0.1 and 0.9 Å)
  - **K1-27**: Problem with He II λ 4686 Å and N V lines solved



- For more than 15 years no other O(He)-star was discovered...

O(He) stars

- KPD0005+5106: first classified as a DO white dwarf
  - Wassermann et al. (2010): T_{eff} = 200 kK, log g = 6.7
    → pre-white dwarf
  - 98% He (by mass) → O(He) star

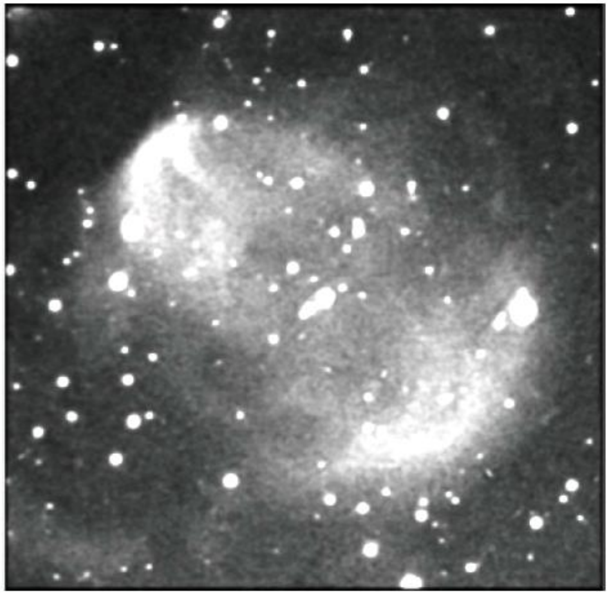
O(He) stars

- KPD0005+5106: first classified as a DO white dwarf
  - Wassermann et al. (2010): T_{eff} = 200 kK, log g = 6.7 → pre-white dwarf
  - 98% He (by mass) → O(He) star
- Werner et al. (2014): Discovery of 4 new O(He) stars in the SDSS DR10: J0757, J1418, J1719, and J1728
  - NLTE analysis with HHe (+CNOSi) models based on SDSS spectra (resolution ≈ 2.5 Å)

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

O(He) stars

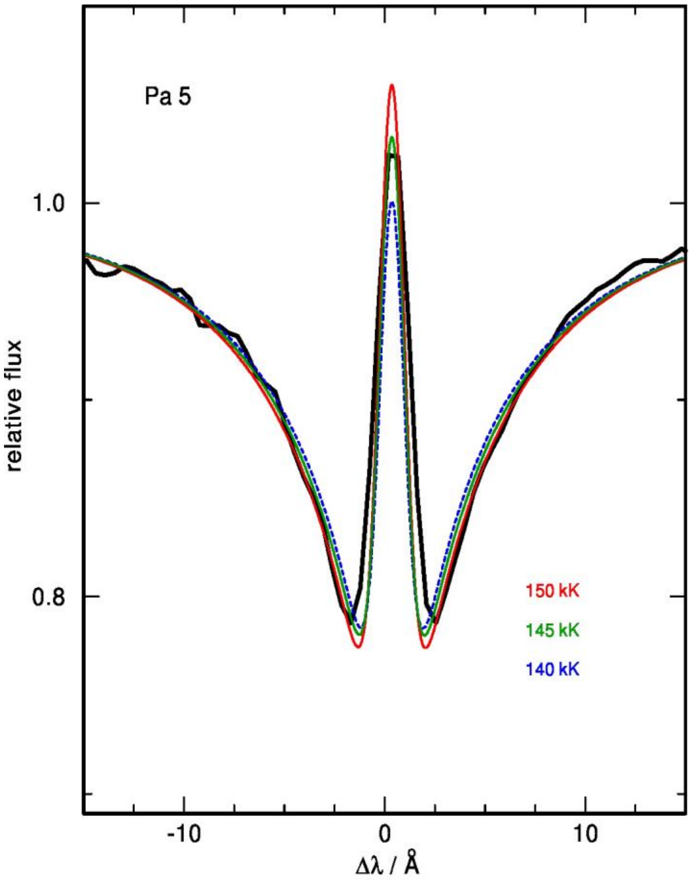
- KPD0005+5106: first classified as a DO white dwarf
  - Wassermann et al. (2010): $T_{\rm eff}$ = 200 kK, log g = 6.7 → pre-white dwarf
  - 98% He (by mass) → O(He) star
- Werner et al. (2014): Discovery of 4 new O(He) stars in the SDSS DR10: J0757, J1418, J1719, and J1728
  - NLTE analysis with HHe (+CNOSi) models based on SDSS spectra (resolution ≈ 2.5 Å)
- De Marco et al. (2015): Discovery of the new O(He)-type central star Pa 5



Hα image of the newly discovered O(He)-type CSPN Pa 5 (De Marco et al. 2015)

O(He) stars

- KPD0005+5106: first classified as a DO white dwarf
  - Wassermann et al. (2010): T_{eff} = 200 kK, log g = 6.7 → pre-white dwarf
  - 98% He (by mass) → O(He) star
- Werner et al. (2014): Discovery of 4 new O(He) stars in the SDSS DR10: J0757, J1418, J1719, and J1728
  - NLTE analysis with HHeCNO models based on SDSS spectra (resolution ≈ 2.5 Å)
- De Marco et al. (2015): Discovery of the new O(He) type central star Pa 5
  - NLTE analysis with HHeCNONe models
    - T_{eff} = 145 kK, log g = 6.7



Observed He II λ 4686 Å line compared to synthetic spectra with different T_{eff} .

Trichotomy

A trichotomy exists amongst He-dominated stars

(not only a dichotomy)

N-rich (N ≈ 1%)

- N-rich O(He) stars
  K1-27, LoTr4, Pa 5, and HS 2209+8229
- N-rich He-sdO stars
  e.g., LSE 236, HE 1258+0113
- N-rich DO WDs
  e.g., PG 0038+199, PG 1034+001
- [WN]-type CSPNe
  IC 4463, Abell 48

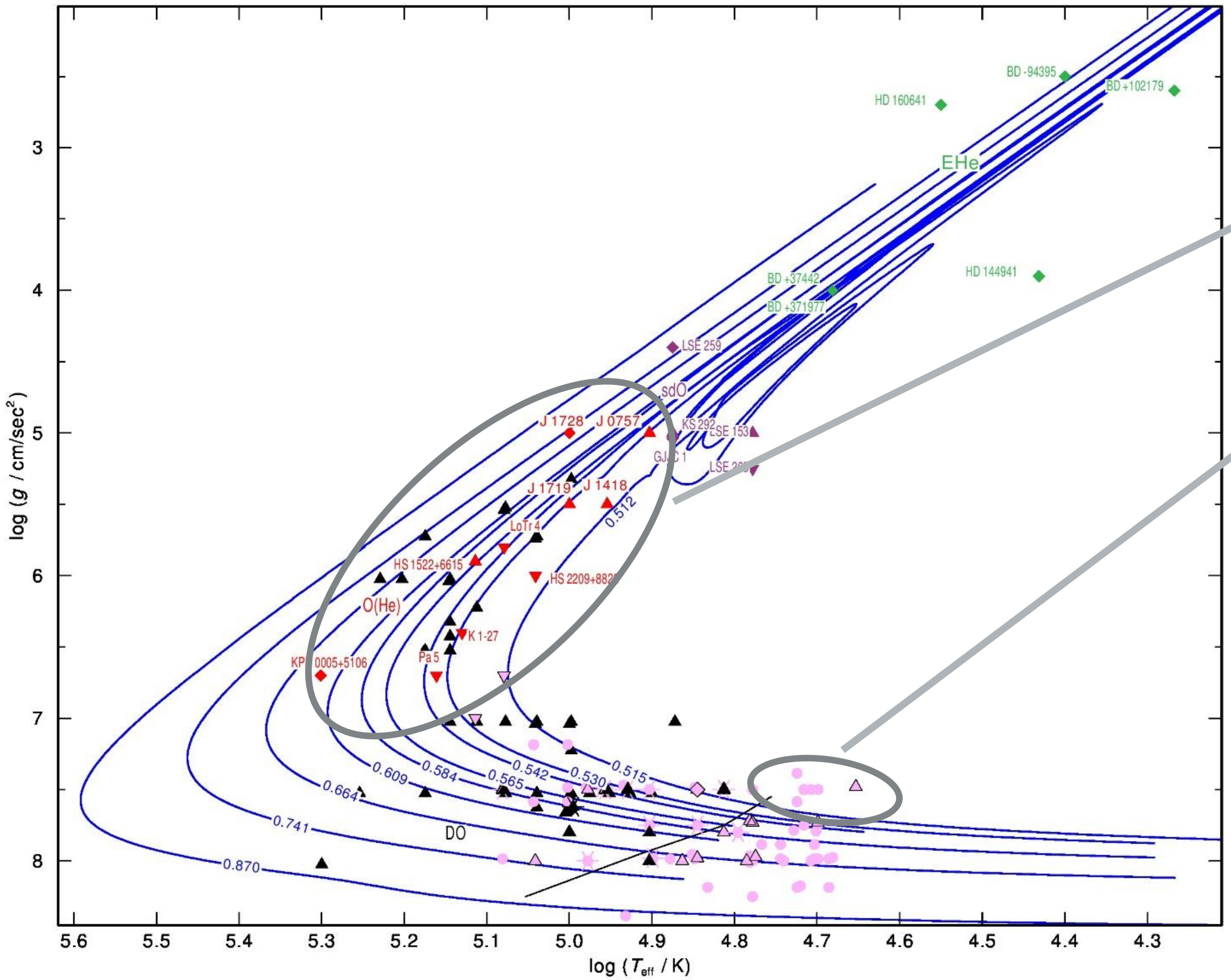
C-rich (C ≈ 1%)

- C-rich O(He) stars
  HS 1522+6615, J1719, J1418, J0757
- C-rich He-sdO stars
  e.g., LSE 153, HE 1203-1024
- C-rich DO WDs
  e.g., PG 0108+101, HS 0111+0012

C- and N-rich (C ≈ 1%, N ≈ 1%)

- C&N-rich O(He) stars
  KPD 0005+5106, J1728
- C&N-rich He-sdO stars
  e.g., LSE 256, HE 0111-1526
- C&N-rich DO WD
  RE 0503-289
- RCB stars
- EHe stars

Evolutionary status



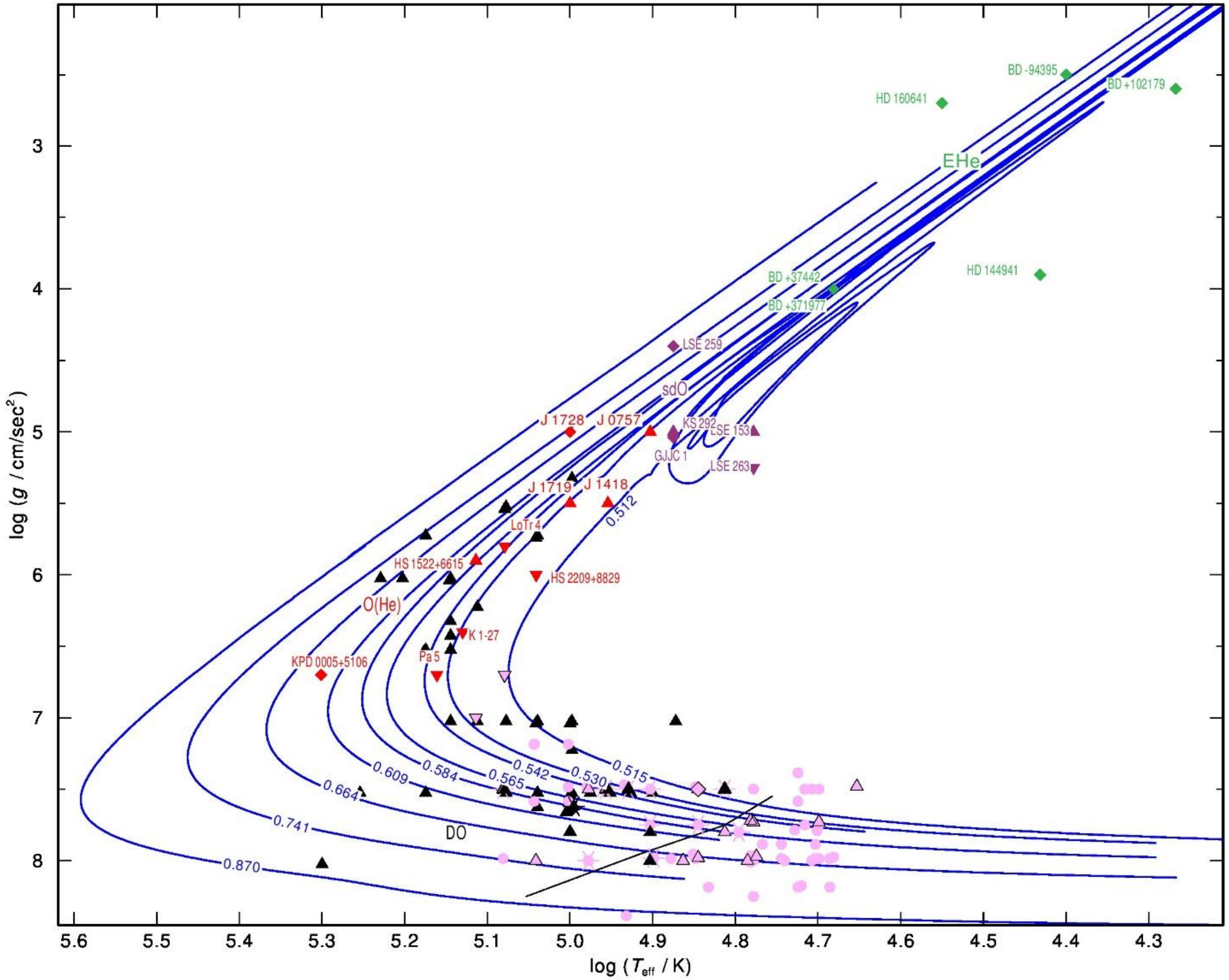
Locations of EHe stars, luminous He-sdO-stars, O(He) stars, PG 1159 stars and DO WDs in the log T_{eff} – log g plane compared with VLTP evolutionary tracks of Miller Bertolami & Althaus (2006).

40 % O(He) stars
60 % PG1159 stars

≈ 13 % of the cool DO white dwarfs have $M < 0.5\ M_\odot$

→ not post-AGB stars!

Evolutionary status



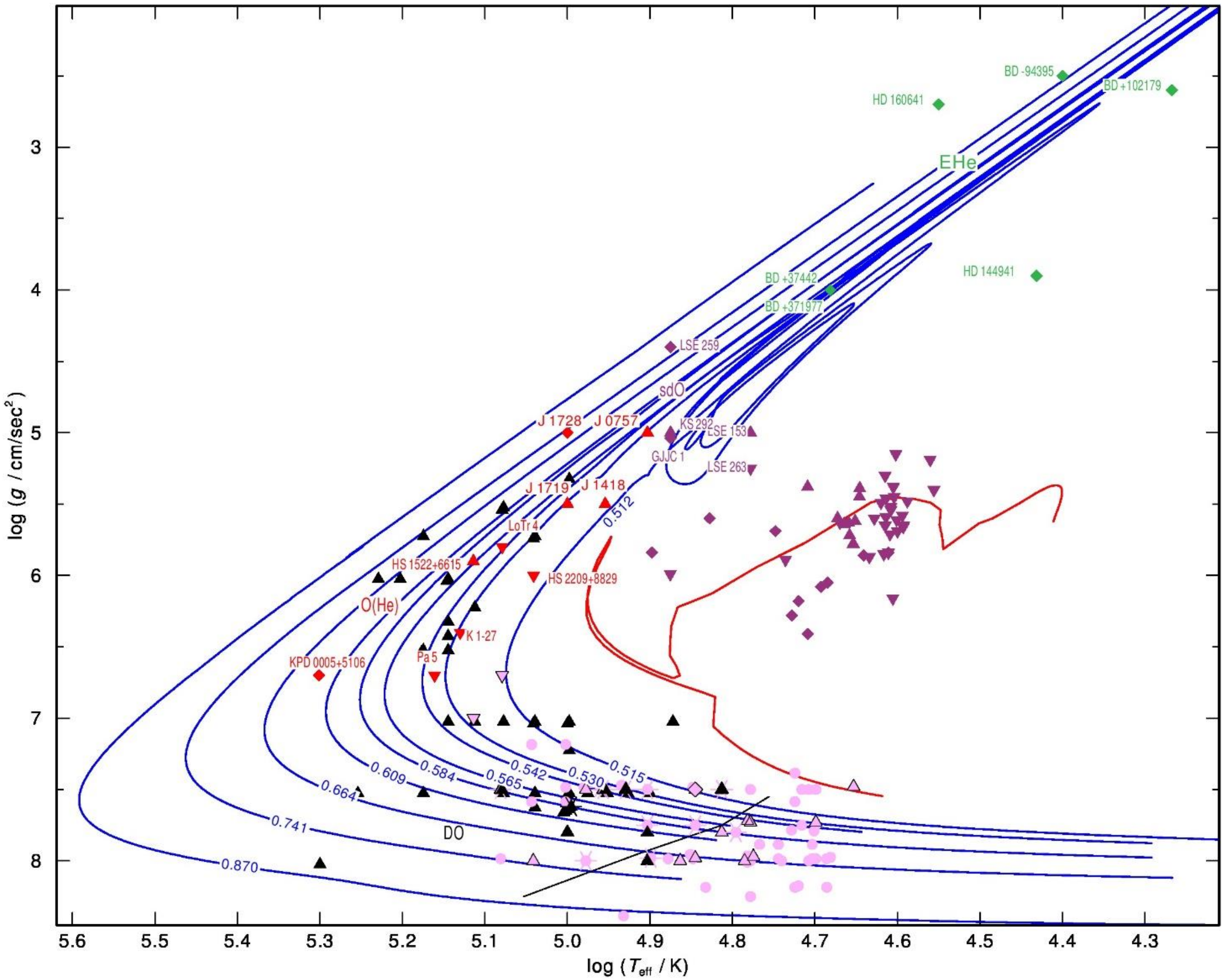
Locations of EHe stars, luminous He-sdO-stars, O(He) stars, PG 1159 stars and DO WDs in the log T_{eff} – log g plane compared with VLTP evolutionary tracks of Miller Bertolami & Althaus (2006).

He-dominated stars **cannot** be explained by (V)LTP scenarios

→ predict very high C abundances (> 20% C, by mass)

↯ He-dominated stars show < 3% C

Evolutionary status



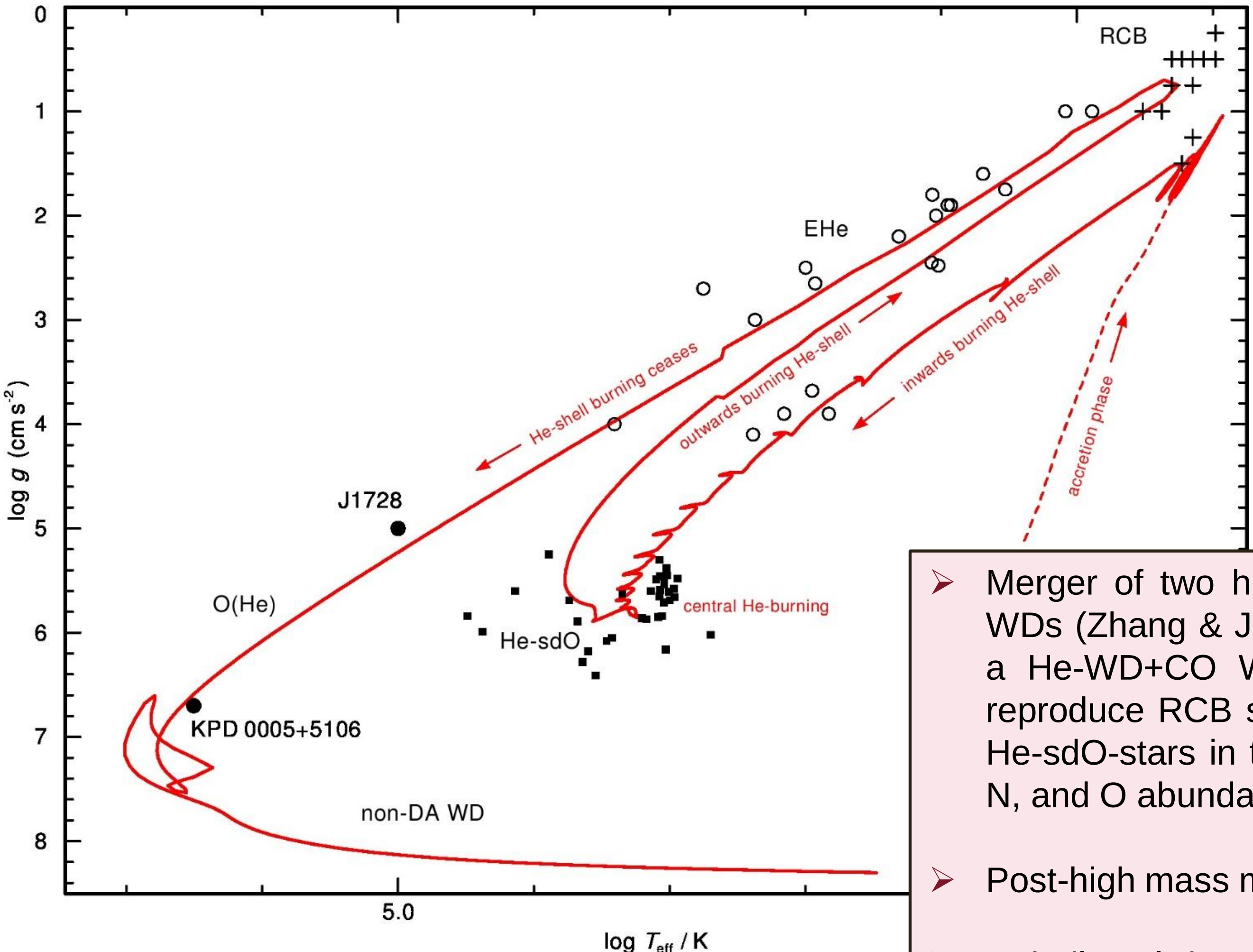
Locations of EHe stars, luminous and compact He-sdO-stars, O(He) stars, PG 1159 stars and DO WDs in the log T_{eff} – log g plane compared with VLTP evolutionary tracks of Miller Bertolami & Althaus (2006) and a post-EHB trackt of Dorman et al. (1993).

- Considering post-AGB and post-EHB evolution (late hot flasher scenarios) only:
  No possible connection between compact He-sdO stars and O(He) stars

- However, their surface abundances are extremely similar

By chance ?

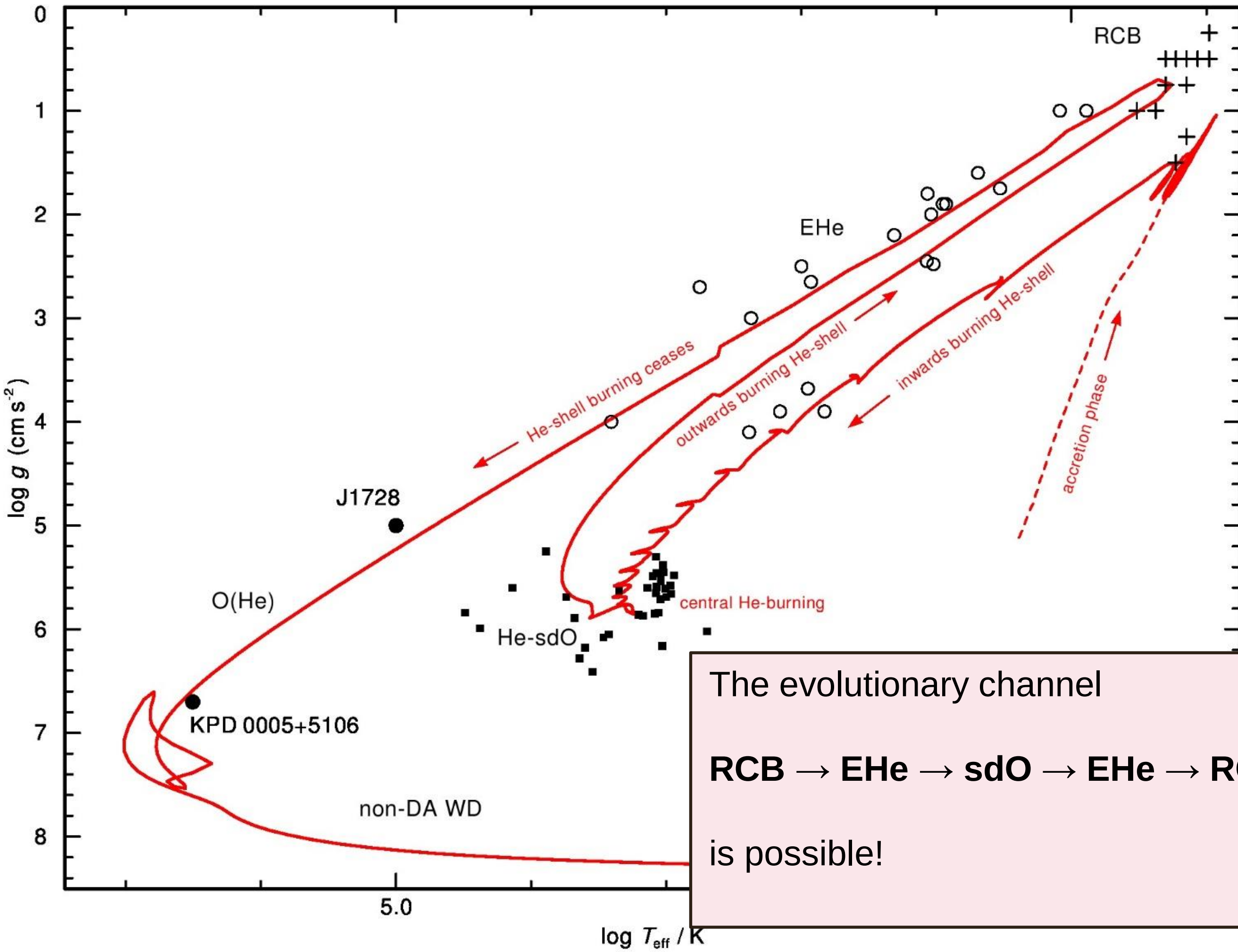
Evolutionary status



Locations of RCB stars, EHe stars, He-sdO stars, and the two C&N rich O(He) stars compared with an evolutionary track of a 0.8 M He-WD+He-WD merger (Zhang & Jeffery 2012a).

- Merger of two higher mass (0.4+0.4 $M_{\odot}$) He-WDs (Zhang & Jeffery 2012a) or the merger of a He-WD+CO WD (Zhang et al. 2014) can reproduce RCB stars, EHe stars, and compact He-sdO-stars in terms of $T_{\rm eff}$, log g and He, C, N, and O abundances.
- Post-high mass merger produce C&N-rich stars
- Reindl et al. (2014):
  C&N rich O(He) stars (= high mass O(He) stars!) can also be reproduced in this way

Evolutionary status



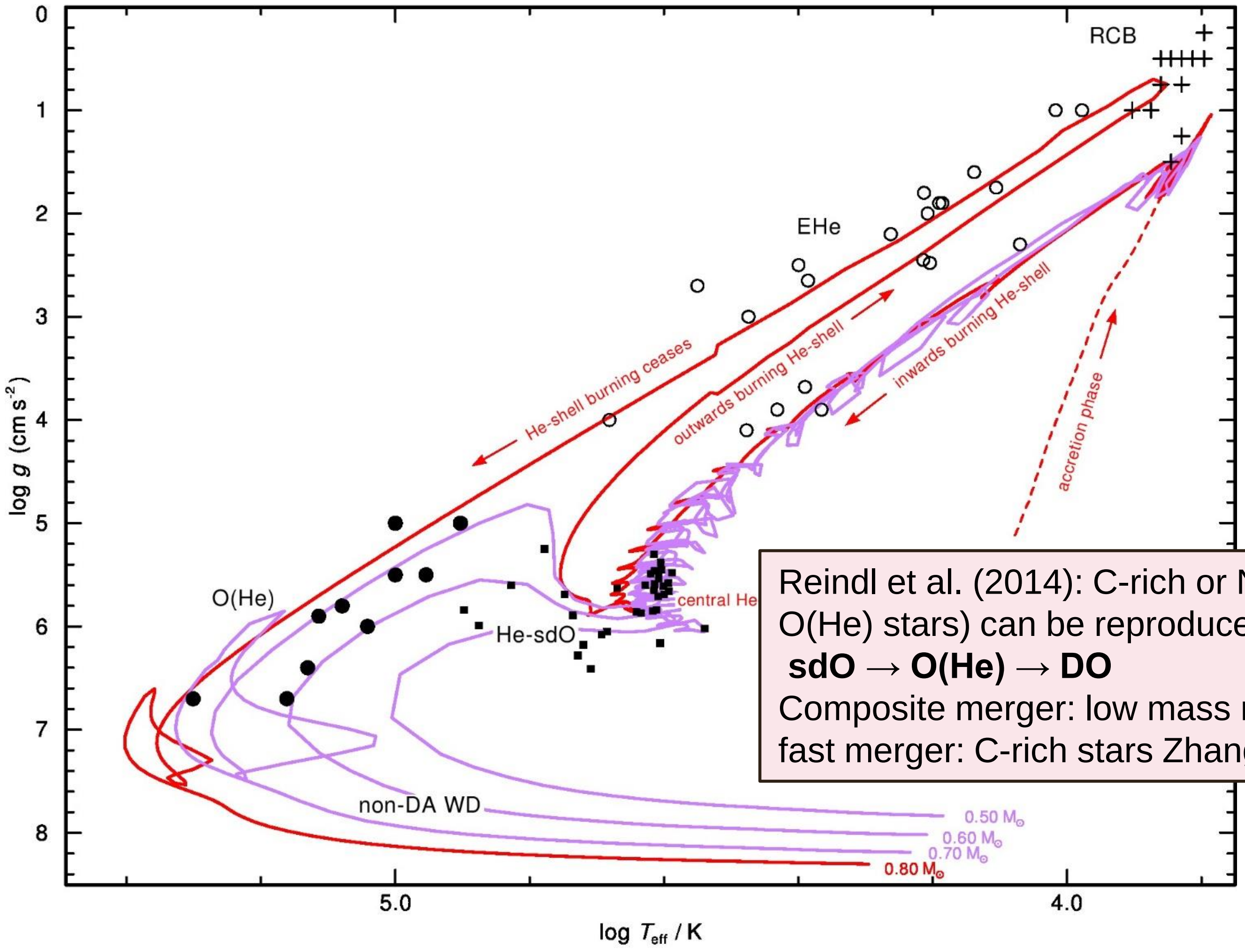
The evolutionary channel

RCB → EHe → sdO → EHe → RCB → EHe → O(He) → non DA

is possible!

Locations of RCB stars, EHe stars, He-sdO stars, and the two C&N rich O(He) stars compared with an evolutionary track of a 0.8 M He-WD+He-WD merger (Zhang & Jeffery 2012a).

Evolutionary status



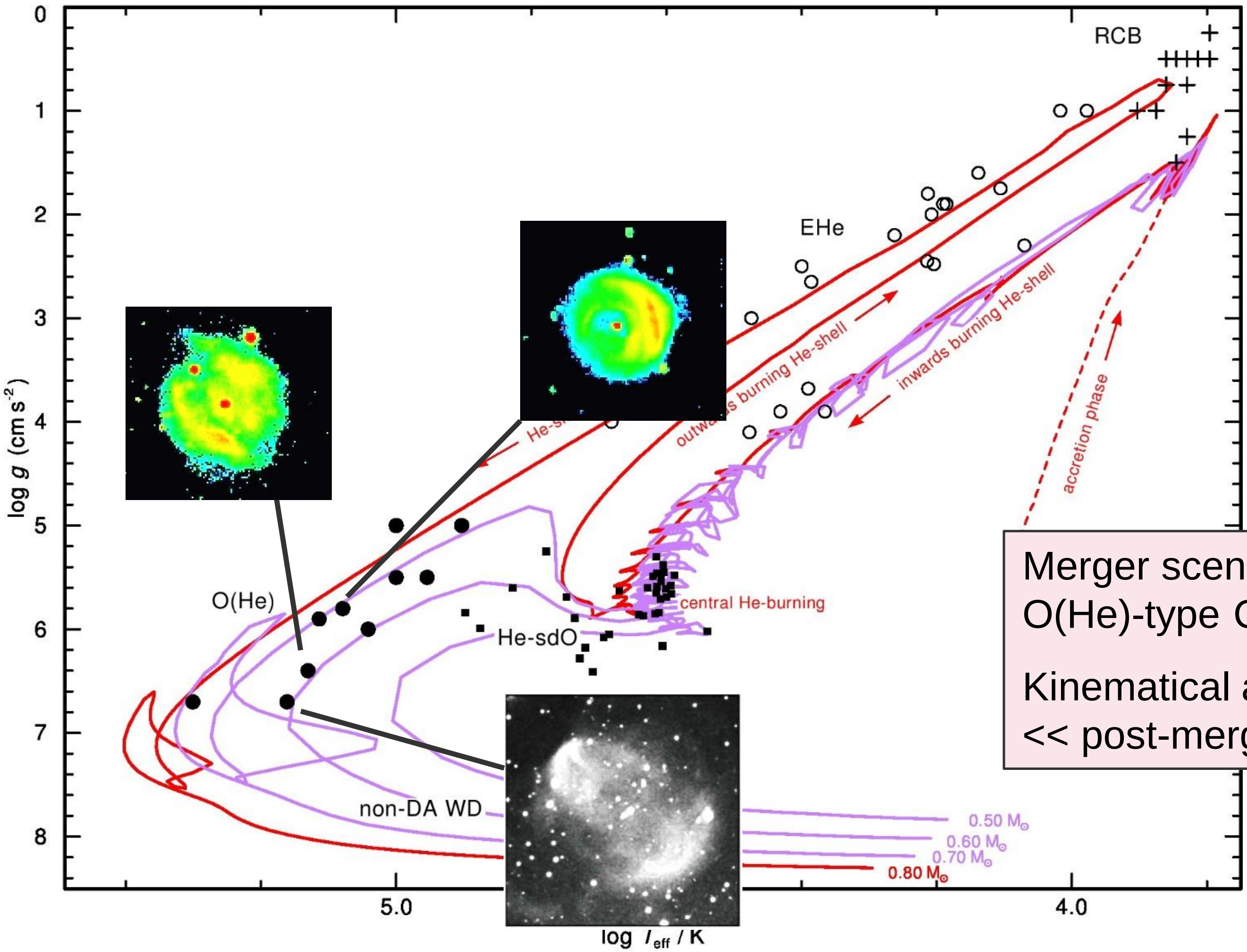
Reindl et al. (2014): C-rich or N-rich O(He) stars (= low mass O(He) stars) can be reproduced via

sdO → O(He) → DO

Composite merger: low mass mergers result in N-rich stars, fast merger: C-rich stars Zhang & Jeffery (2012)

Locations of RCB stars, EHe stars, He-sdO stars, and all O(He) stars compared with He-WD+He-WD merger evolutionary tracks (Zhang & Jeffery 2012a, b).

Evolutionary status



Locations of RCB stars, EHe stars, He-sdO stars, and all O(He) stars compared with He-WD+He-WD merger evolutionary tracks (Zhang & Jeffery 2012a, b).

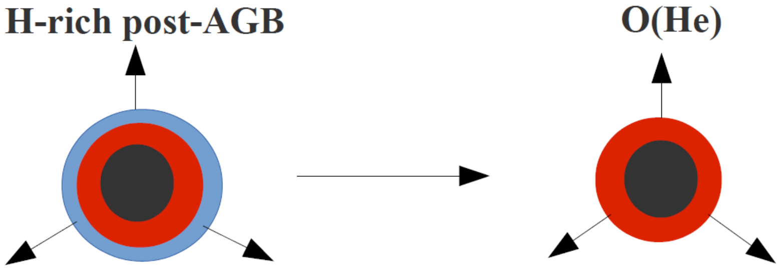
Merger scenario not possible for O(He)-type CSPNe!

Kinematical age of the PNe (10^4 yrs) << post-merger times (10^7 yrs)

Evolutionary status

Different evolutionary channel for (N-rich) O(He) type CSPNe?

Enhanced mass-loss removed the H-envelope of the O(He) stars (Rauch et al. 1998)
→ Artificially increased mass-loss rate is needed (numerical experiment of Miller Bertolami & Althaus 2006)



Evolutionary status

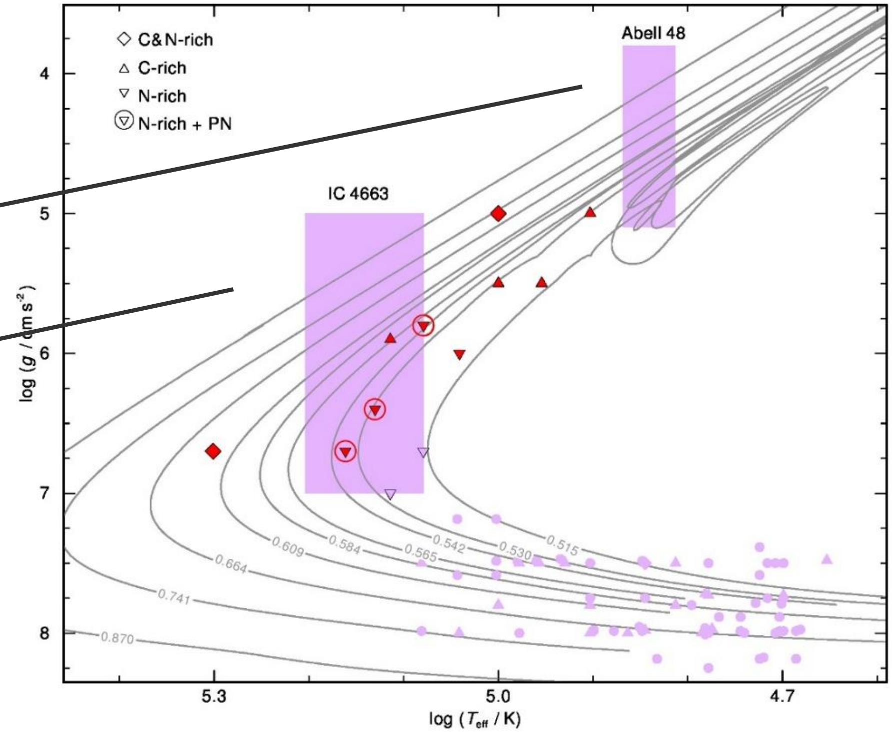
Are O(He) stars really the successors of [WN] type central stars?

✓ Very similar elemental abundances

✓ In earlier evolutionary stage than the O(He) stage

☹ Similar or even later evolutionary stage than the O(He) stars

? Why do [WN] show so much higher mass loss-rates compared to the O(He) stars?



Locations of O(He) stars and [WN] central stars in the log T_{eff} – log g plane compared with VLTP evolutionary tracks of Miller Bertolami & Althaus (2006).

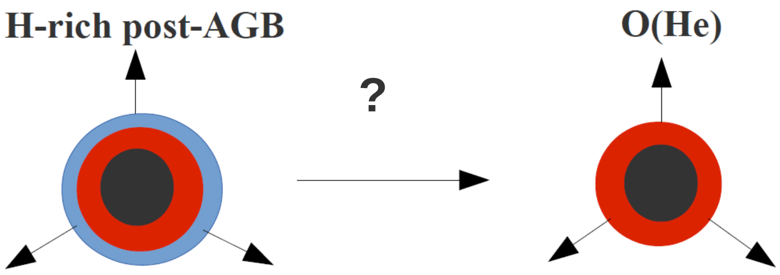
Possible solution:
[WN] stars have **higher masses** than O(He) stars

→ According to Pauldrach et al. (1988): high mass-loss rate of IC 4663 and Abell 48 would correspond to $M \approx 0.7\ M_\odot$ and $M > 1.0\ M_\odot$, respectively.

Evolutionary status

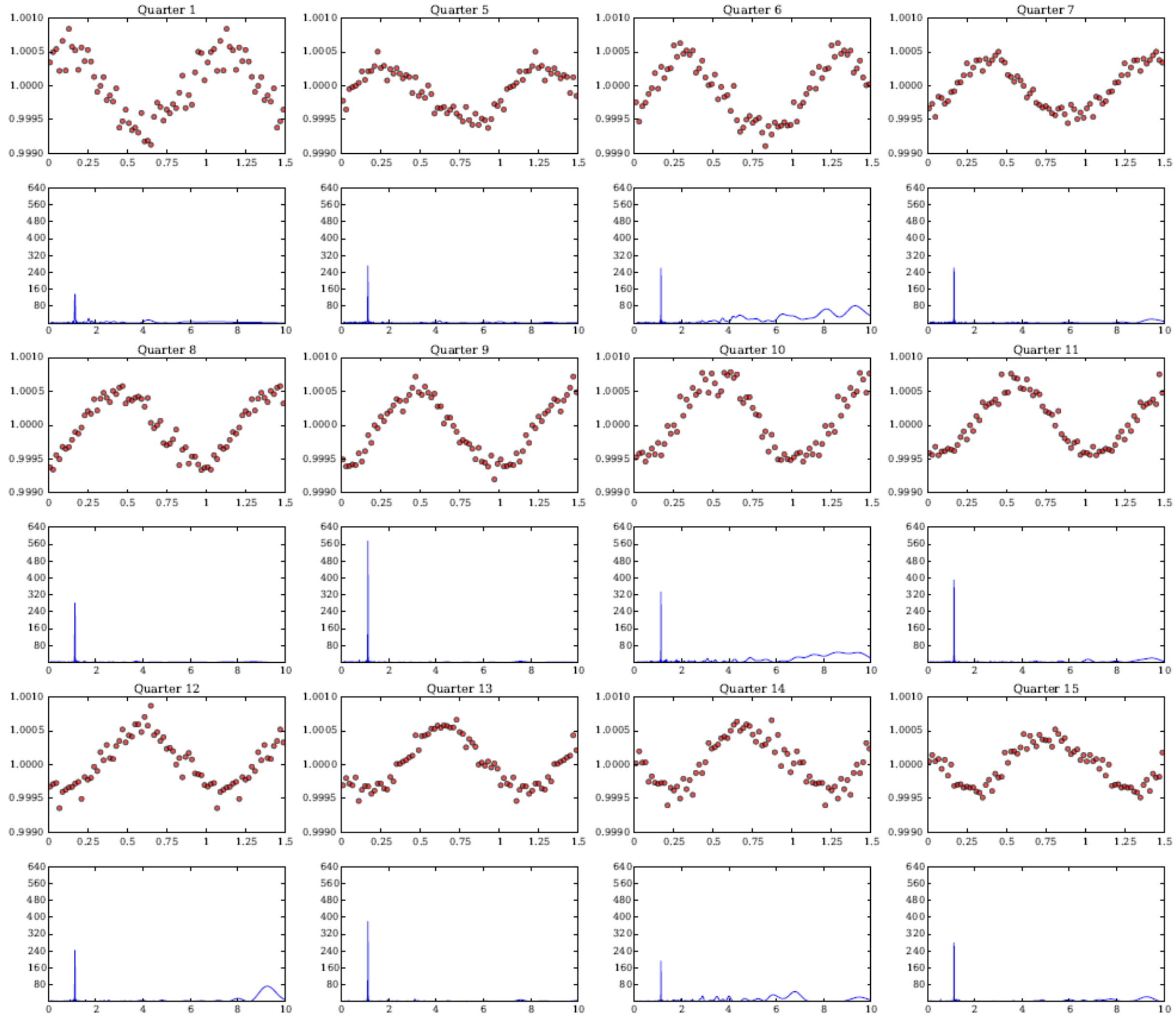
Different evolutionary channels for (N-rich) O(He) type CSPNe?

Enhanced mass-loss removed the H-envelope of the O(He) stars (Rauch et al. 1998)
→ Artificially increased mass-loss rate is needed (numerical experiment of Miller Bertolami & Althaus 2006)



Ejection of a common envelope in a previous evolutionary stage triggered enhanced mass-loss?

Evolutionary status



→ The light curve of Pa 5 gives a consistent period of 1.12 d with an amplitude of 0.5mmag (De Marco et al. 2015)

Folded Kepler light curves (upper rows) and periodograms (lower rows) of Pa 5 (De Marco et al. 2015).

Evolutionary status

- However, no radial velocity variability detected larger than 5 km/s
- Planetary mass companion?
  - Have been announced around post-giant stars (e.g., Silvotti et al. 2014)
  - Doubtful that a planet can survive common envelope evolution
- Variability caused by a spot of constant size, temperature, and location on the surface of the star?
  - Relatively narrow spectral lines do not show evidence of a strong magnetic field and the effective temperature is much too high to expect a convective atmosphere which may help produce spots
- Most plausible hypothesis: Pa 5 has an evolved companion in a nearly pole-on orbit ($i < 2.5^{\circ}$)

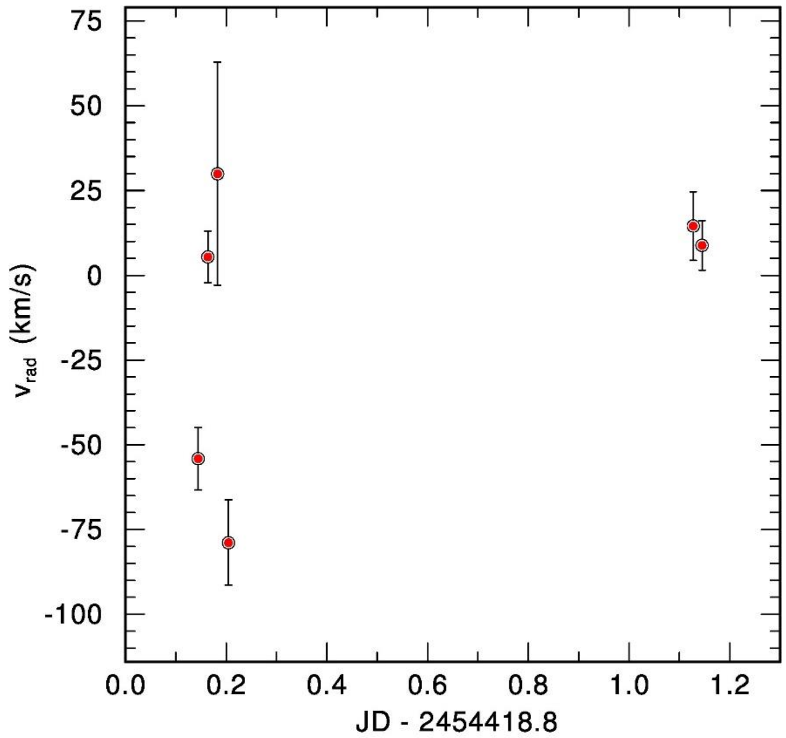
Evolutionary status

- Another candidate for a post-common envelope binary: J0757
- Discovered by Werner et al. (2014)
- MUCHFUSS project:

Δ RV$_{max}$ = 107 ± 22 km/s

within only 31min!

- First radial velocity variable O(He) star
- Have O(He) stars lost their H-rich envelope via common-envelope evolution?



Radial velocities of J0757 measured from six SDSS spectra.

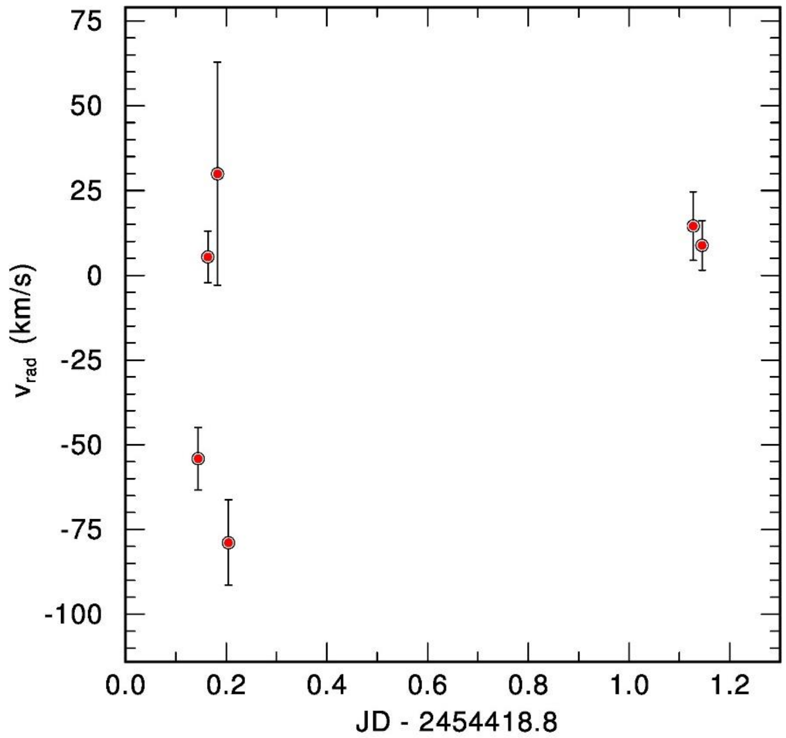
Evolutionary status

- Another candidate for a post-common envelope binary: J0757
- Discovered by Werner et al. (2014)
- MUCHFUSS project:

$\Delta RV_{max} = 107 \pm 22$ km/s

within only 31min!

- First radial velocity variable O(He) star
- Have O(He) stars lost their H-rich envelope via common-envelope evolution?
- Currently ≈ 50 H-rich central stars, one PG 1159 star and one [WC] type CSPN known which have short orbital periods
- What was the difference in their evolution?



Radial velocities of J0757 measured from six SDSS spectra.

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

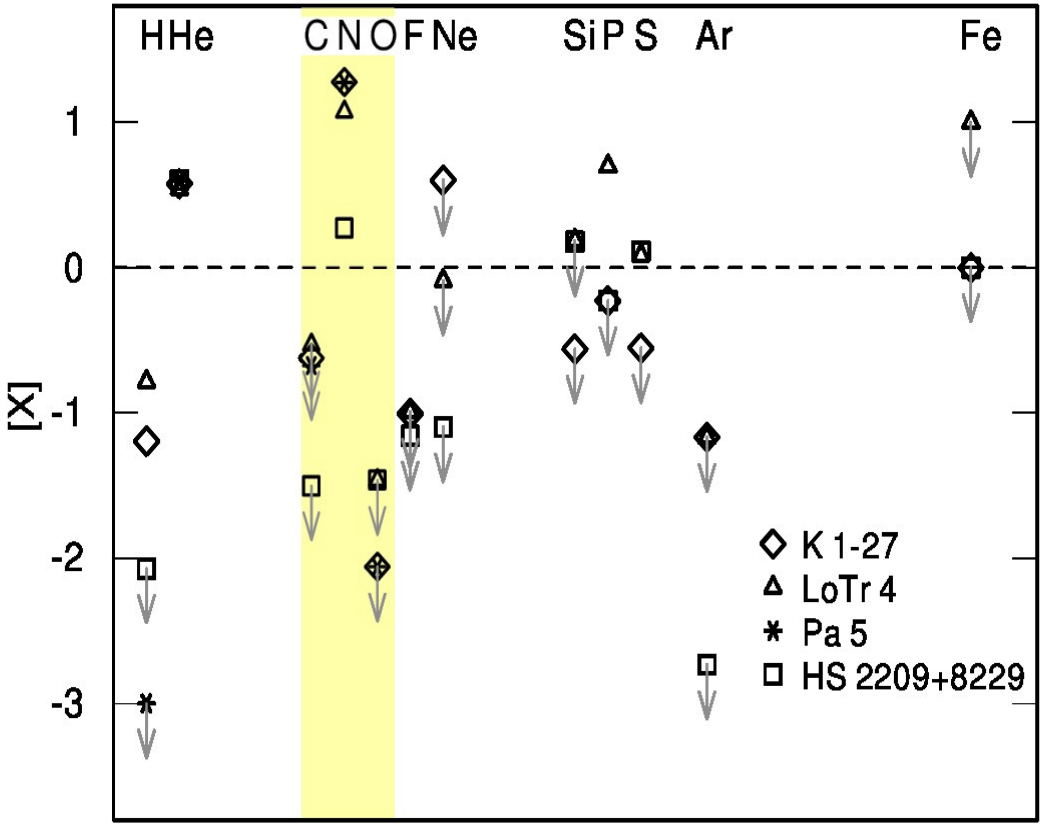
Conclusions

- Number of known O(He) stars has doubled since last year
- First hints for close binary systems found in two of the 10 known O(He) stars
- Trichotomy exists amongst He-dominated stars: C-rich / N-rich / C&N-rich
- Evolutionary status still unclear, but most likely various formation scenarios produce He-dominated stars
  - Late hot flasher scenario can only be valid only for He-sdO and low mass He-WDs
  - Stars enriched in C-rich or N-rich without PN: He-WD+He-WD merger, close binary evolution?
  - For stars enriched in C&N: high mass He-WD+He-WD or He-WD+CO-WD merger
  - (N-rich) CSPNe: Enhanced mass-loss, possible triggered by a close companion

O(He) stars – Spectral Analysis

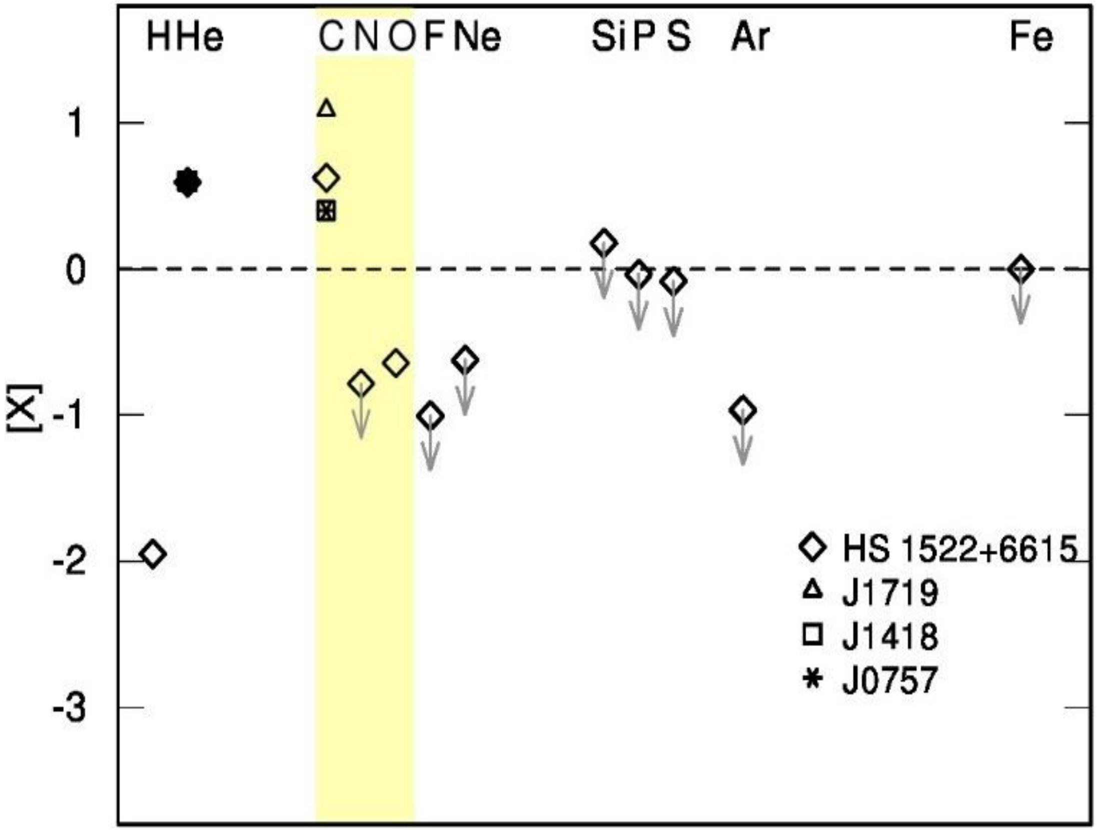
N-rich O(He) stars: K1-27, LoTr4, Pa5, and HS2209+8229

CSPNe no PN



Elemental abundances of the O(He) stars, given in logarithmic mass fractions relatively to the solar value.

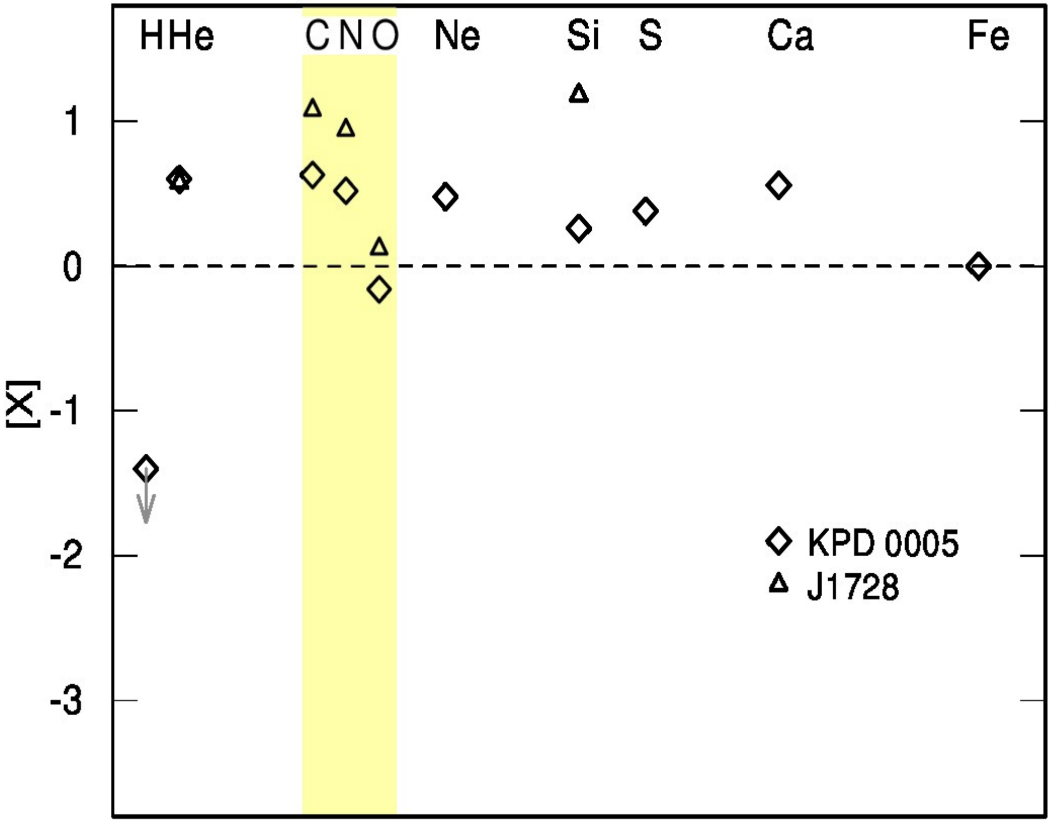
C-rich O(He) stars: HS1522+6615, J1719, J1418, J0757



Elemental abundances of the O(He) stars, given in logarithmic mass fractions relatively to the solar value.

O(He) stars – Spectral Analysis

C&N-rich O(He) stars: KPD 0005 and J1728



Elemental abundances of the O(He) stars, given in logarithmic mass fractions relatively to the solar value.