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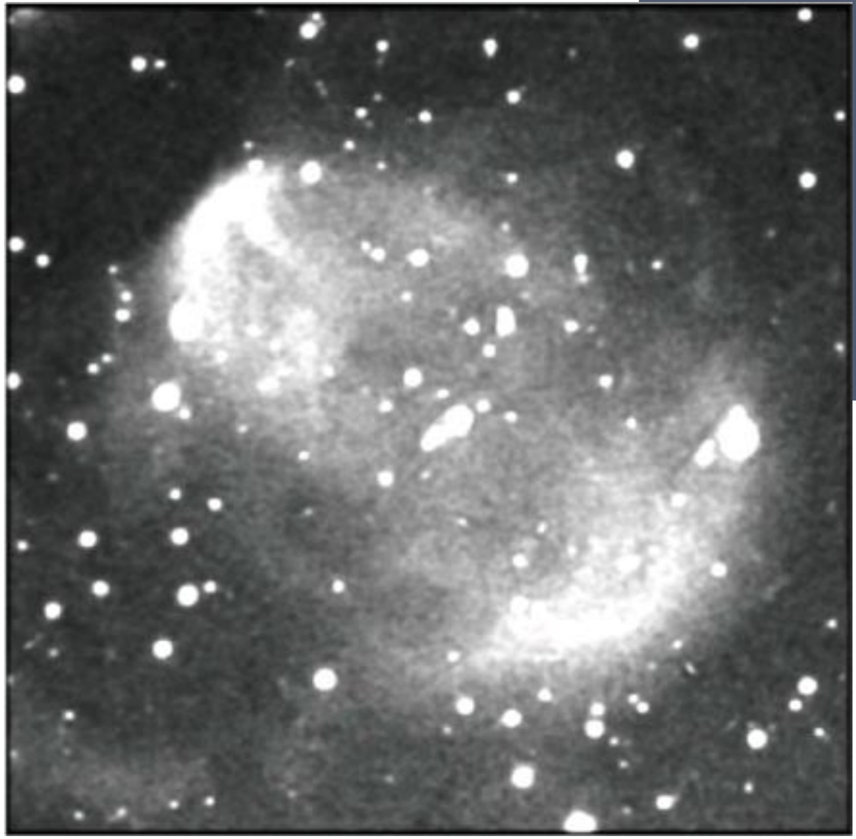
ROYAL COMMISSION EXHIBITION OF 1851

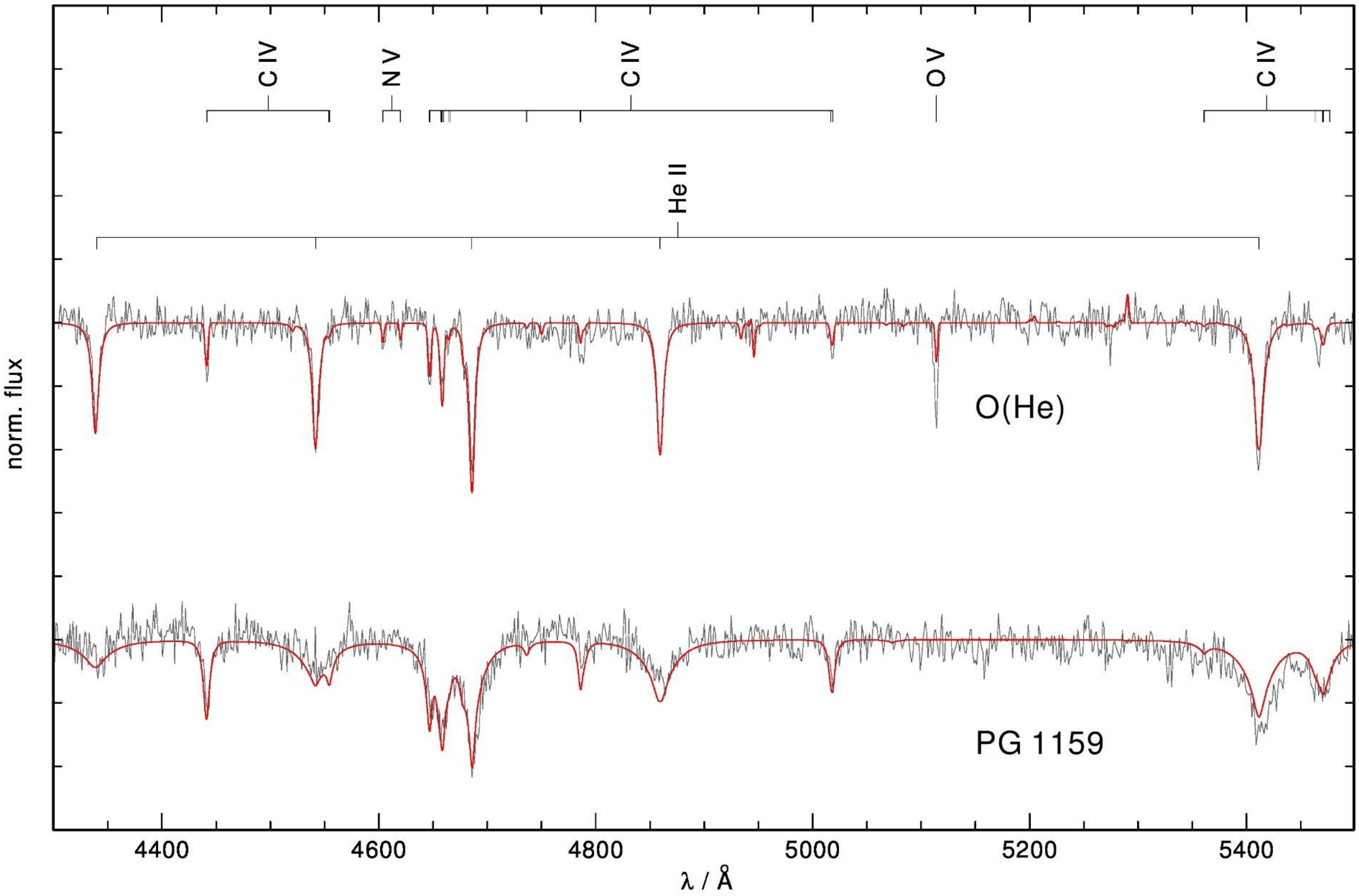
LEICESTER INSTITUTE OF SPACE & EARTH OBSERVATION

Recent Progress on our Understanding of PG1159 and O(He) stars

Nicole Reindl



Introduction



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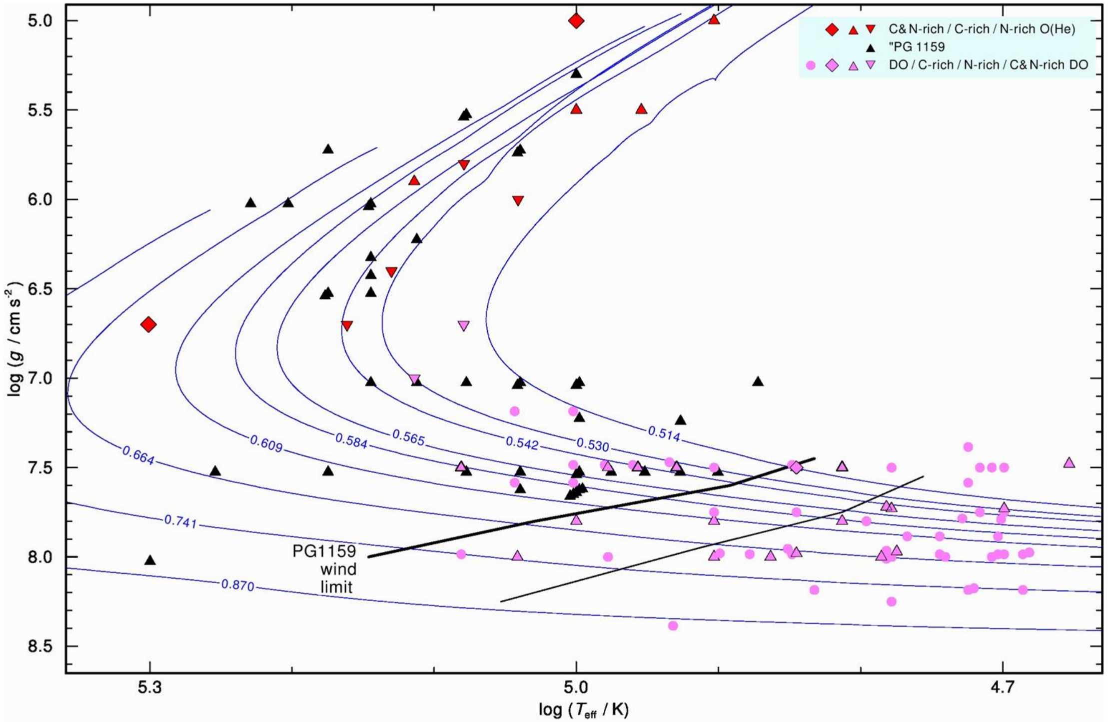
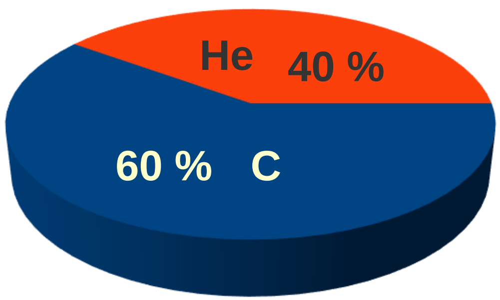
He- to C-dominated (pre-) WD ratio



→ **The non-DA WD channel may be fed by PG 1159 stars and O(He) stars in a similar extent**



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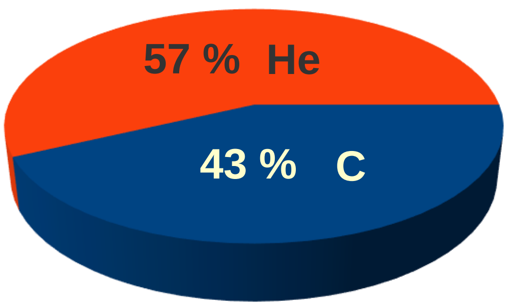


Based on all hot, H-deficient objects before the wind limit within the SDSS DR10 spectroscopic sample

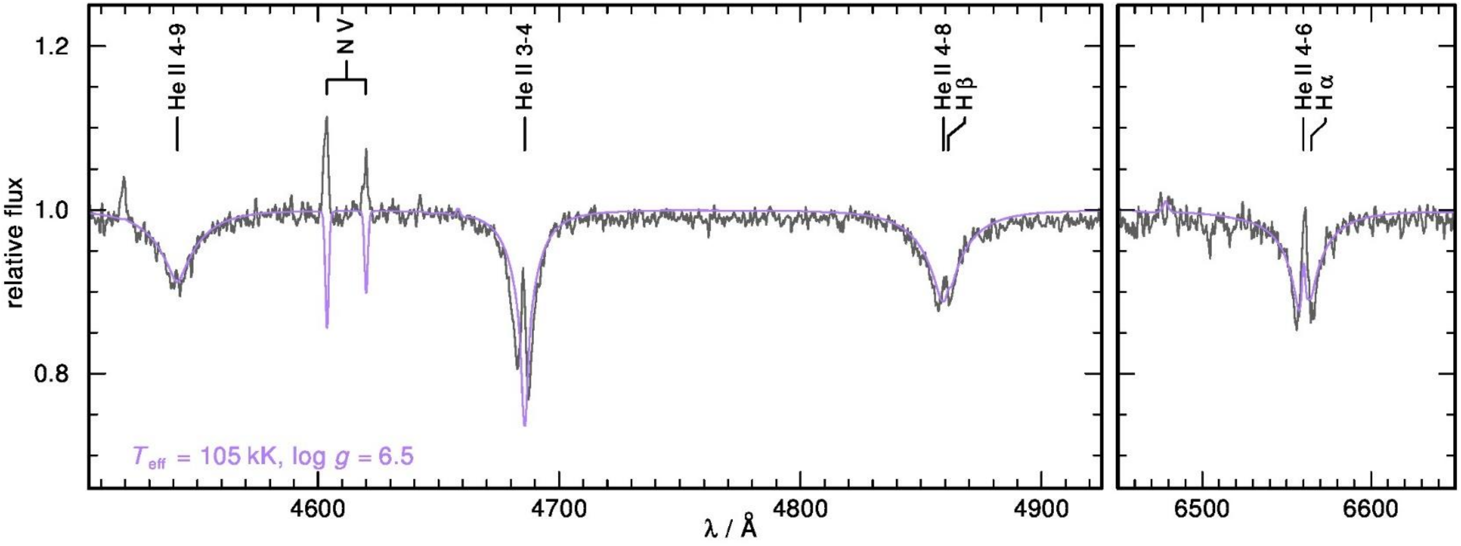
log *g* > 7.0 objects only:

Observations

- Large surveys are needed to detect and improve the statistics of these rare objects
- Main sources: PG Survey, Hamburg Quasar Survey, SSDS, follow-up of blue central stars of planetary nebula (PN)
- Optical spectra (4-10 m class telescopes): T_{eff}, log g, H/He, C, N, O, Ne, Si abundances
- UV spectra: Metal abundances, more precise T_{eff}, log g
  For some central stars of PNe: $\dot{M}$, v_{∞}

Spectral analysis

- Spectral analysis hindered by the occurrence of non-LTE and metal-line blanketing effects
  → high computational times



Optical spectrum of the O(He)-type central star K 1-27.

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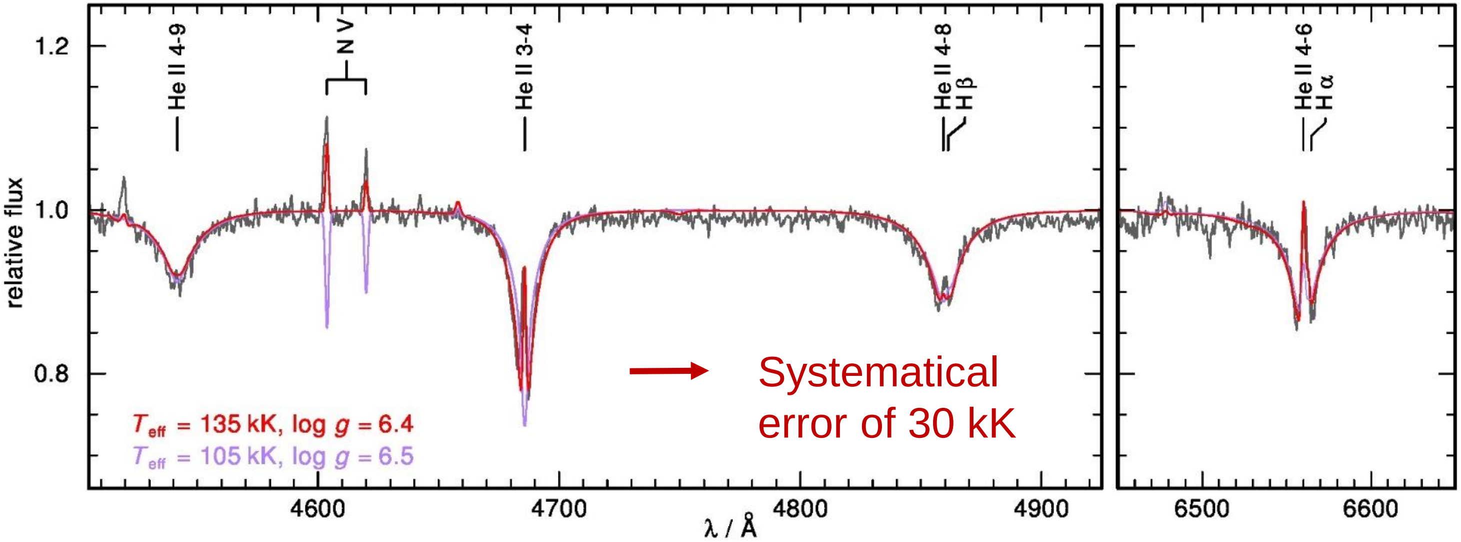

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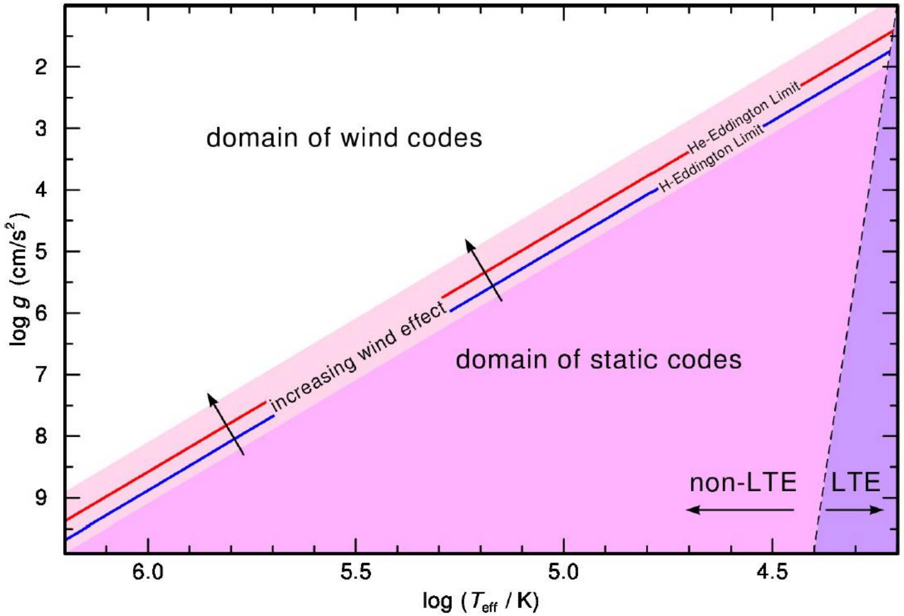
  → high computational times

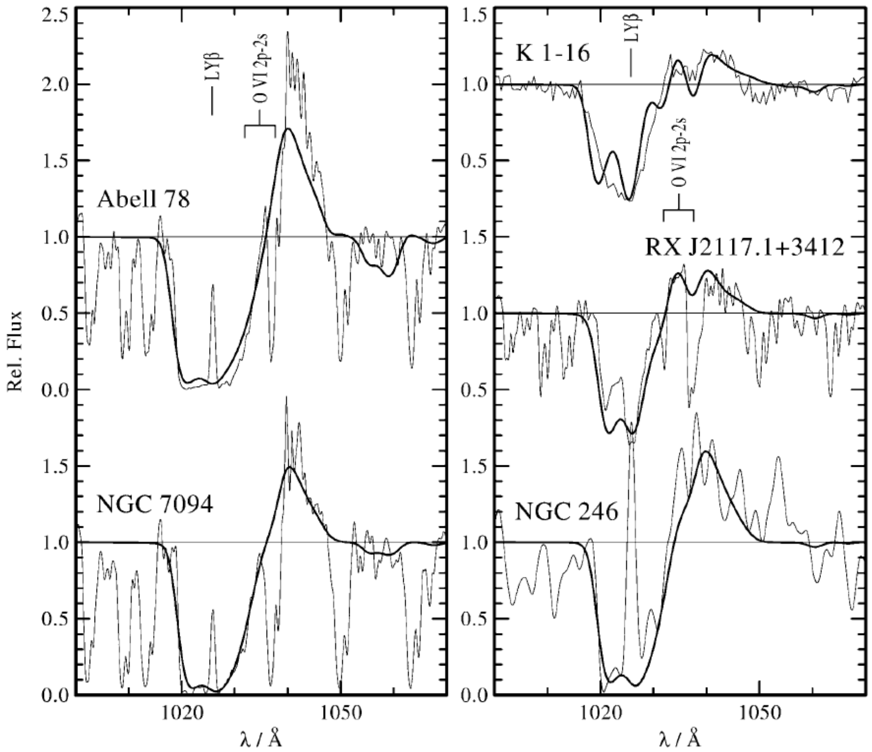
- Stars close to Eddignton limit
  → numerical instabilities



Domains of static LTE and non-LTE codes and domain of wind codes. Figure taken from Rauch (2012) and modied.

Spectral analysis

- Spectral analysis hindered by the occurrence of non-LTE and metal-line blanketing effects
  → high computational times
- Stars close to Eddignton limit
  → numerical instabilities
- Some central stars of PNe still show some residual wind (P-Cygni profiles in UV spectra)
  → Code for an expanding model-atmospheres needed



Profile Fits to the O VI resonance line (Koesterke & Werner 1998)

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PG1159 stars

- 51 PG1159 stars
- 17 CSPN = 33%
- 11 pulsating
- 5 hybrid-type
- Spectral class distinction between O(He)/DOs and PG1159 stars: C/He = 0.02

PG1159 stars

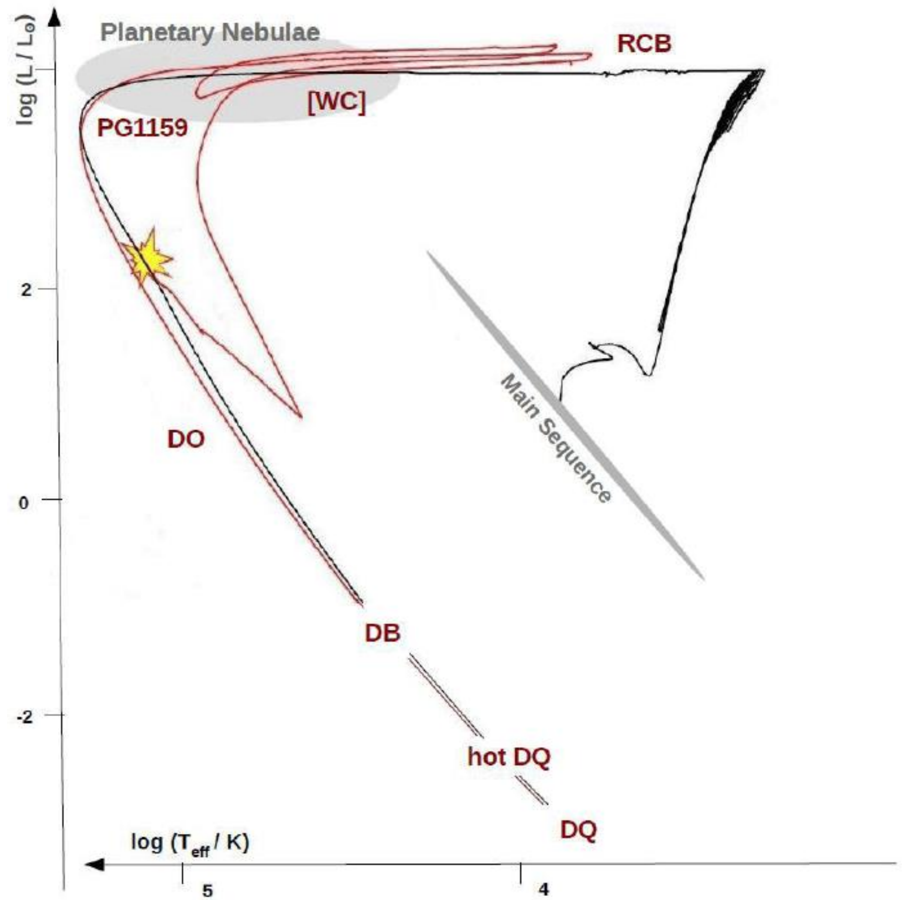
Surface abundaces can be explained by (very) late thermal pulse ((V)LTP) scenarios

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
SAO244567: LTP (still H-rich)

Lo 4 : PG 1159 ⟷ [WC]



VLTP evolution in the HRD.

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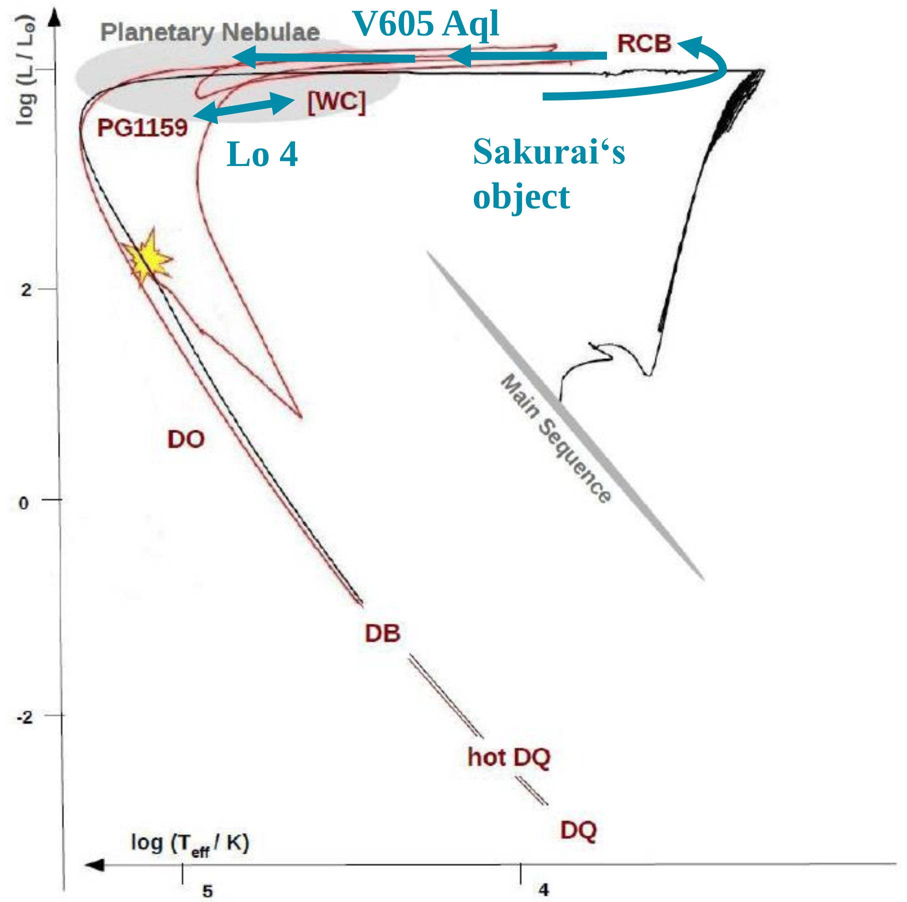

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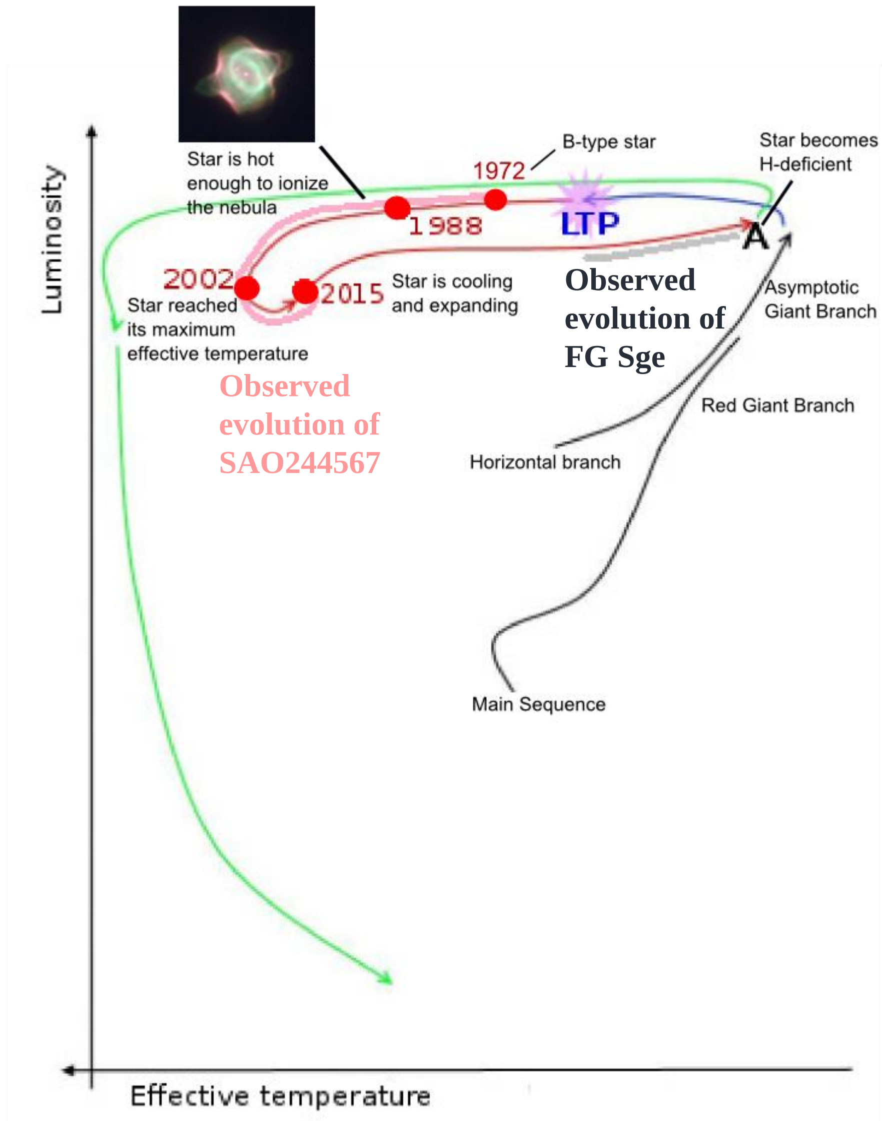
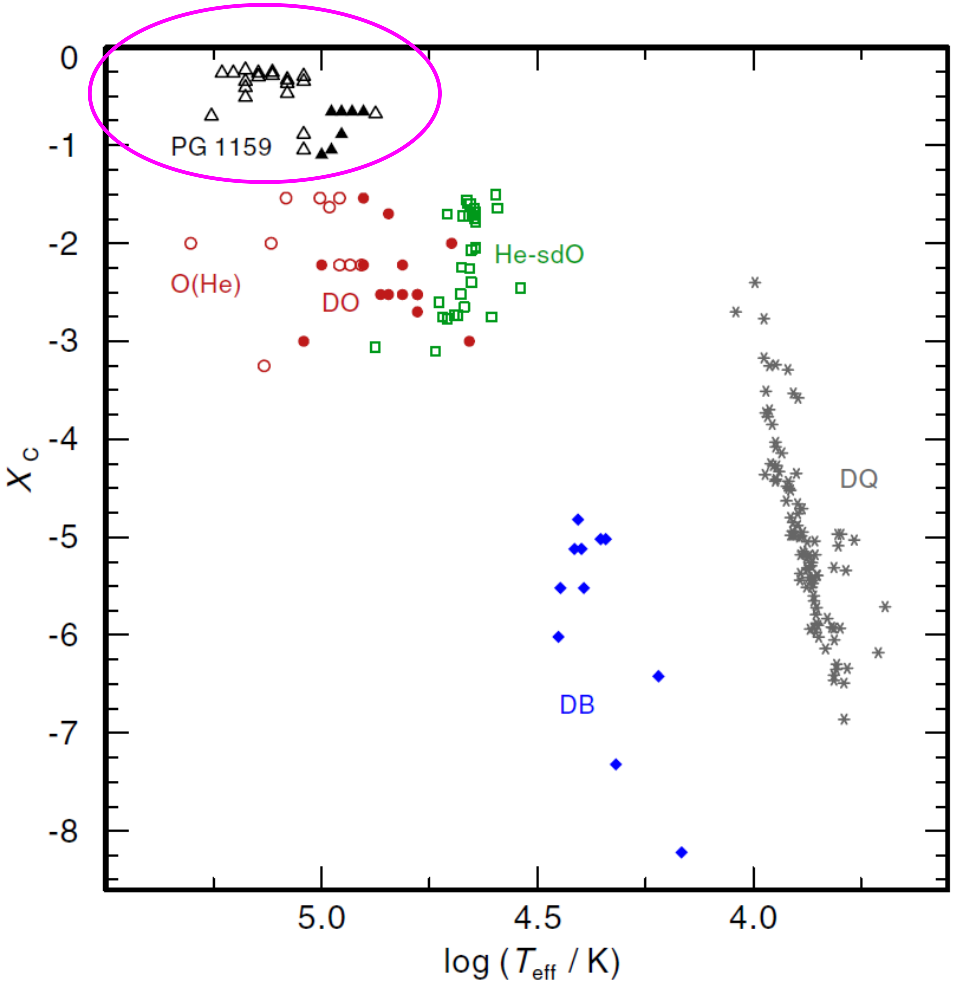


Carbon abundances



Carbon abundances (in logarithmic mass fractions) before and along the non-DA WD cooling track (Reindl+2014).

- Luminous PG 1159 stars:

  C ≈ 0.5

- PG1159 stars close to the wind limit:

  C ⩽ 0.22

→ support for advancing gravitaional settling

Bare C-O core WDs

Analysis of HST/COS spectra of the bare C–O stellar core H1504+65 and a high-velocity twin in the Galactic halo★

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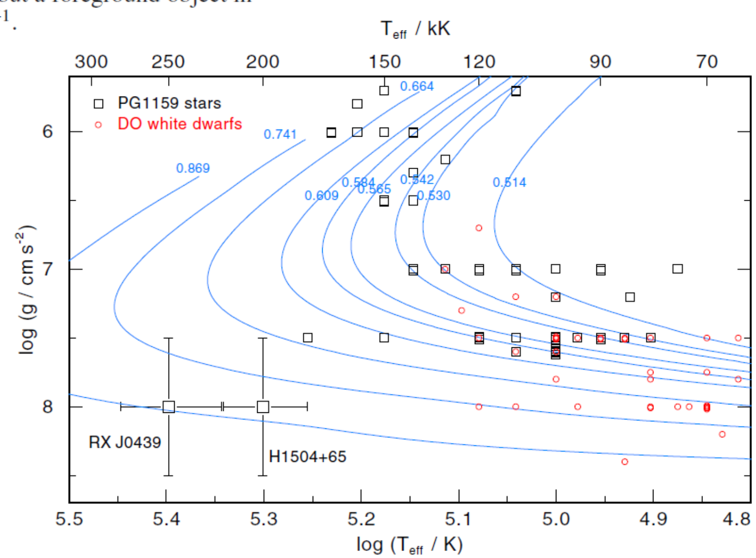
Received 27 August 2015 / Accepted 24 September 2015

ABSTRACT

H1504+65 is an extremely hot white dwarf (effective temperature $T_{\rm eff}$ = 200 000 K) with a carbon-oxygen dominated atmosphere devoid of hydrogen and helium. This atmospheric composition was hitherto unique among hot white dwarfs (WDs), and it could be related to recently detected cooler WDs with C or O dominated spectra. The origin of the H and He deficiency in H1504+65 is unclear. To further assess this problem, we performed ultraviolet spectroscopy with the Cosmic Origins Spectrograph (COS) aboard the *Hubble* Space Telescope (HST). In accordance with previous far-ultraviolet spectroscopy performed with the Far Ultraviolet Spectroscopic Explorer, the most prominent lines stem from C IV, O V–VI, and Ne VI–VIII. Archival HST/COS spectra are utilized to prove that the supersoft X-ray source RX J0439.8−6809 is, considering the exotic composition, a twin of H1504+65 that is even hotter ($T_{\rm eff}$ = 250 000 K). In contrast to earlier claims, we find that the star is not located in the Large Magellanic Cloud but a foreground object in the Galactic halo at a distance of 9.2 kpc, 5.6 kpc below the Galactic plane, receding with $v_{\rm rad}$ = +220 km s^{-1}.



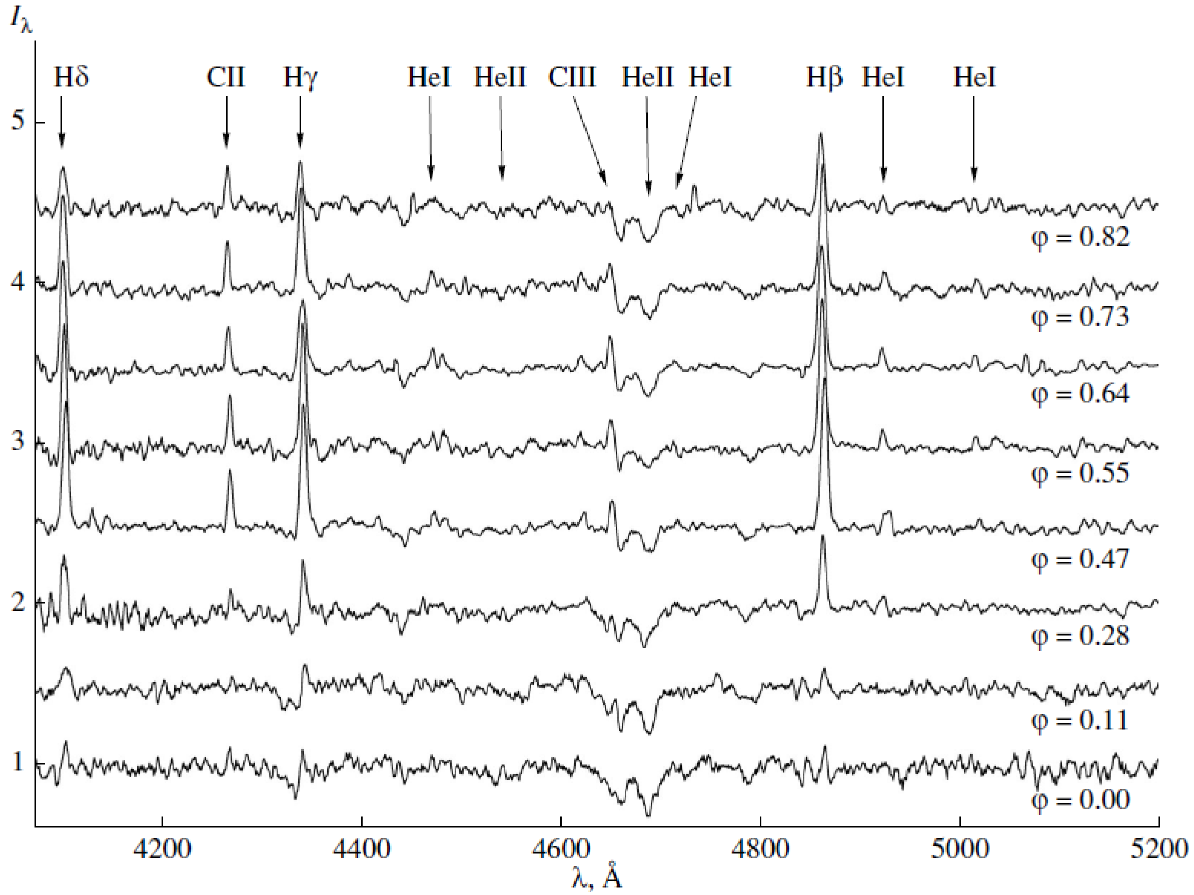
→ High-mass WDs that for an unknown reason were eroded down to their C/O envelope?

→ Merger of two CO WDs?

PG1159 - Binarities

SDSS J212531-010745

Double-lined spectroscopic close binary system discovered by Nagel+2006



Shimansky+2015

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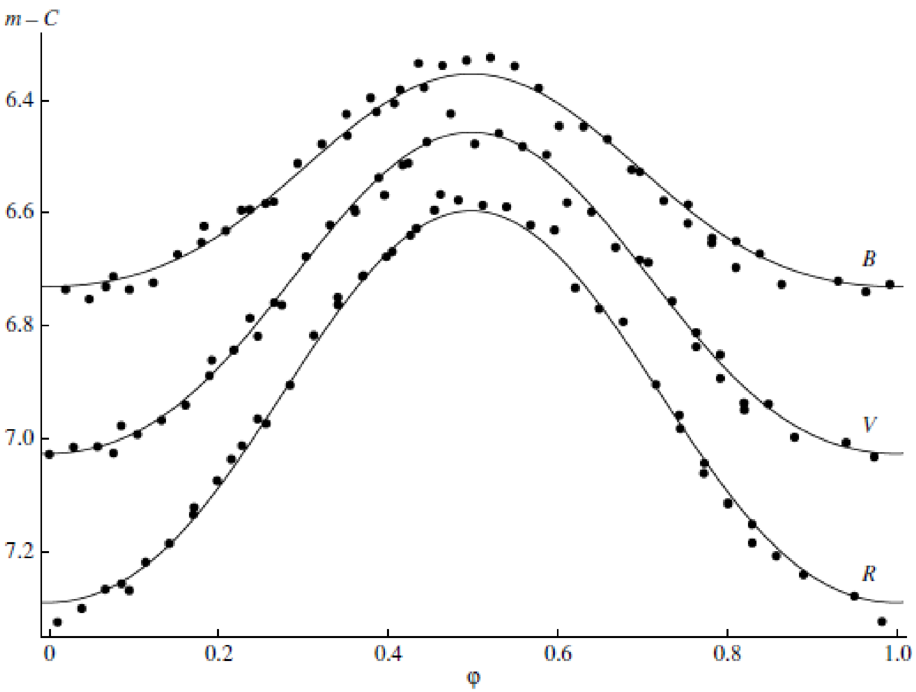


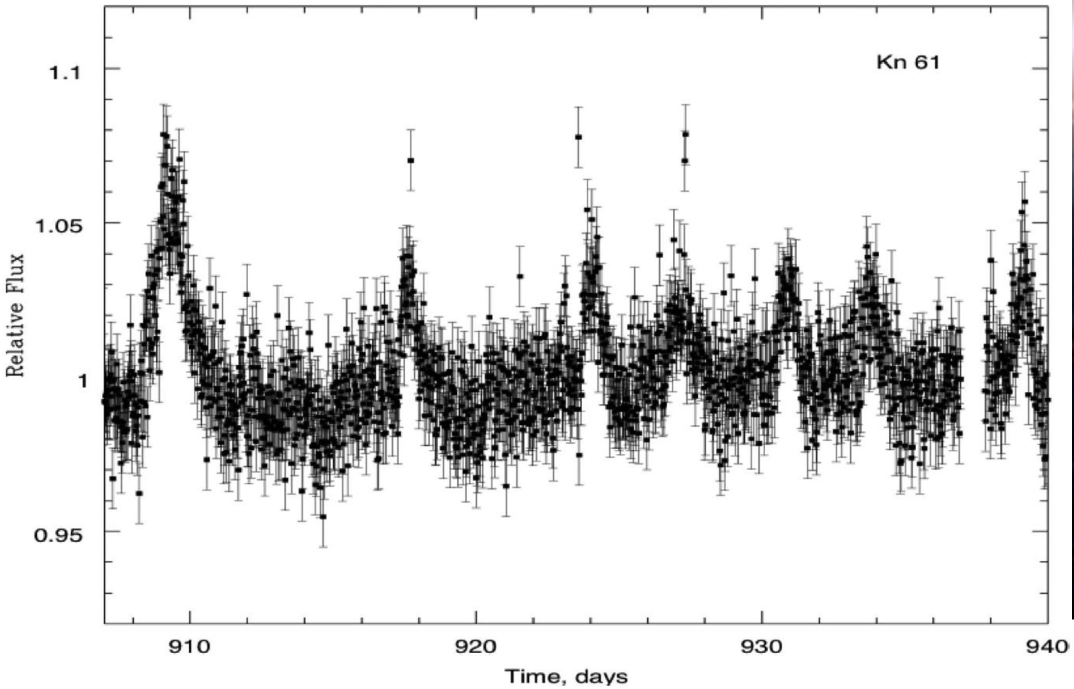
Parameter	Component: primary	Component: secondary
P_{orb}, days	0.289823 ± 0.000002 [20]	
φ_0, JD	2454055.2134 ± 0.0004 [20]	
K, km/s	67.4 ± 10.5	113.0 ± 3.0 [17]
q	0.596 ± 0.093	
T_{eff}, K	$65\,000 \pm 2500$	3700 ± 200
$\log g$	7.2 ± 0.1	5.15 ± 0.15
$M/M_\odot$	0.56 ± 0.06	0.33 ± 0.08
$R/R_\odot$	0.030 ± 0.003	0.25 ± 0.02
$A/R_\odot$	1.77 ± 0.10	
i, deg	35.6 ± 1.3	

Shimansky+2015

PG1159 - Binarities

PN Kn 61

→ Mysterious semi-periodic light variability with peaks that occur with spacings of 2–12 d, A= 80-120mmag) which might be to be related to the interplay of binarity with a stellar wind.



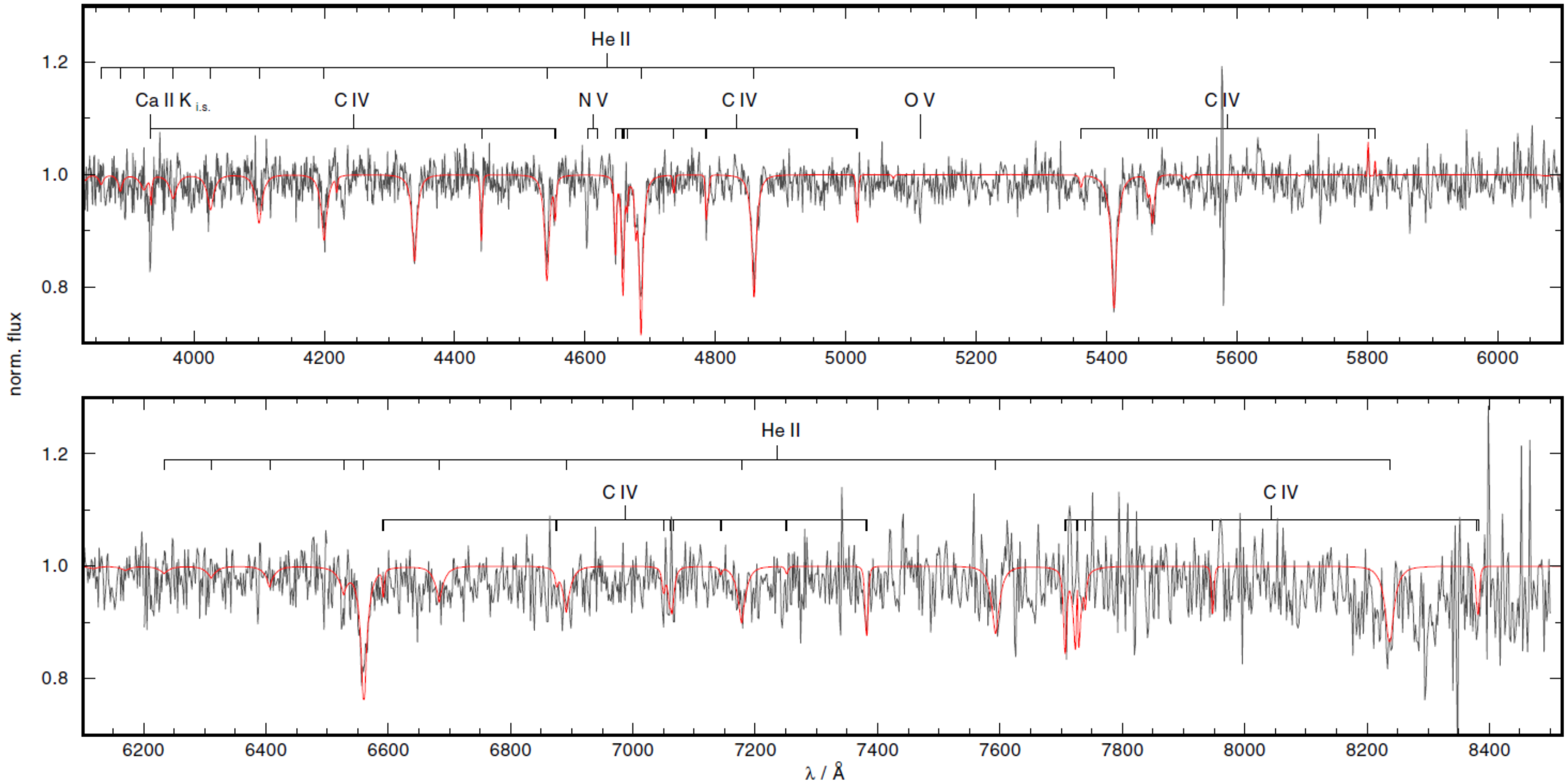
A representative part of the light curve of Kn 61 (De Marco et al. 2015).

Gemini North GMOS, 500 s exposure image of the newly discovered PN Kn 61. [O III] is blue, Hα is red.

PG1159 - Binarities

SDSS J155610.40+254640.3

- RV variable PG1159 star discovered within the MUCHFUSS project
- Maximum RV shift of 116.0 ± 21.0 km/s

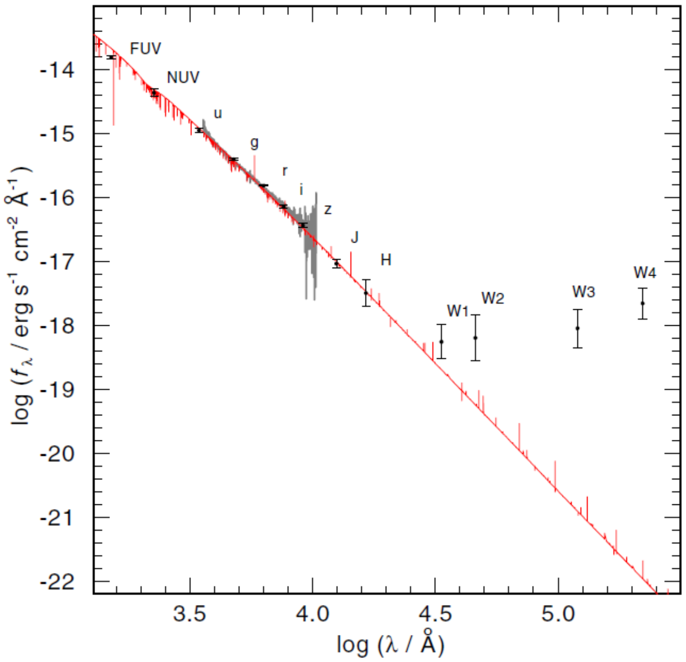


Reindl et al. 2016

PG1159 - Binarities

SDSS J155610.40+254640.3

- ❑ RV variable PG1159 star discovered within the MUCHFUSS project
- ❑ Maximum RV shift of 116.0 ± 21.0 km/s
- ❑ Far-IR excess



Reindl et al. 2016

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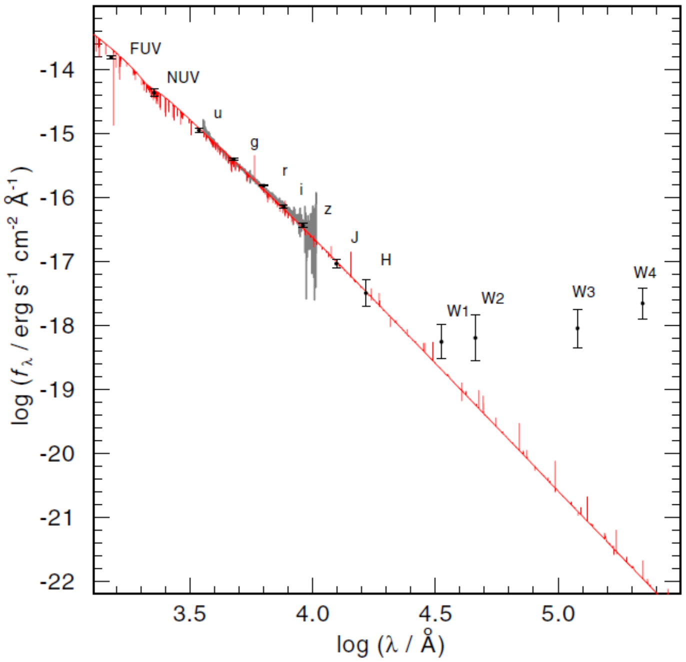
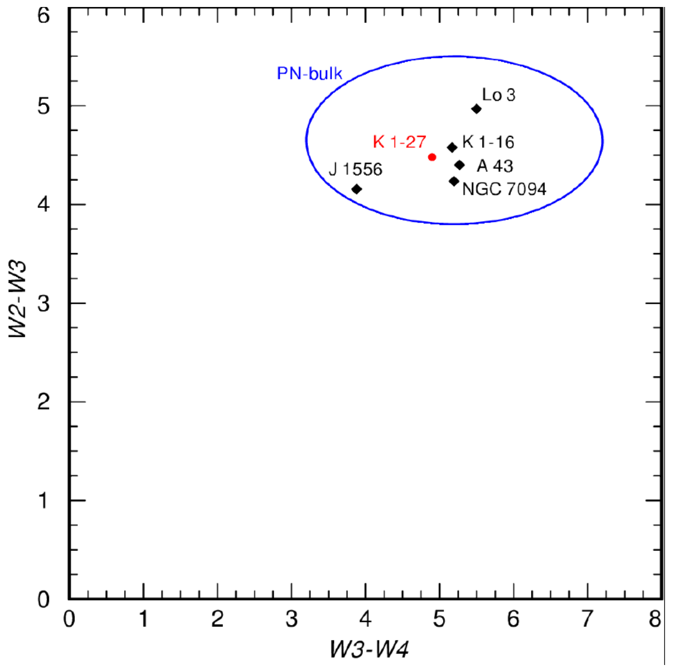


Reindl et al. 2016

No PNe lines!

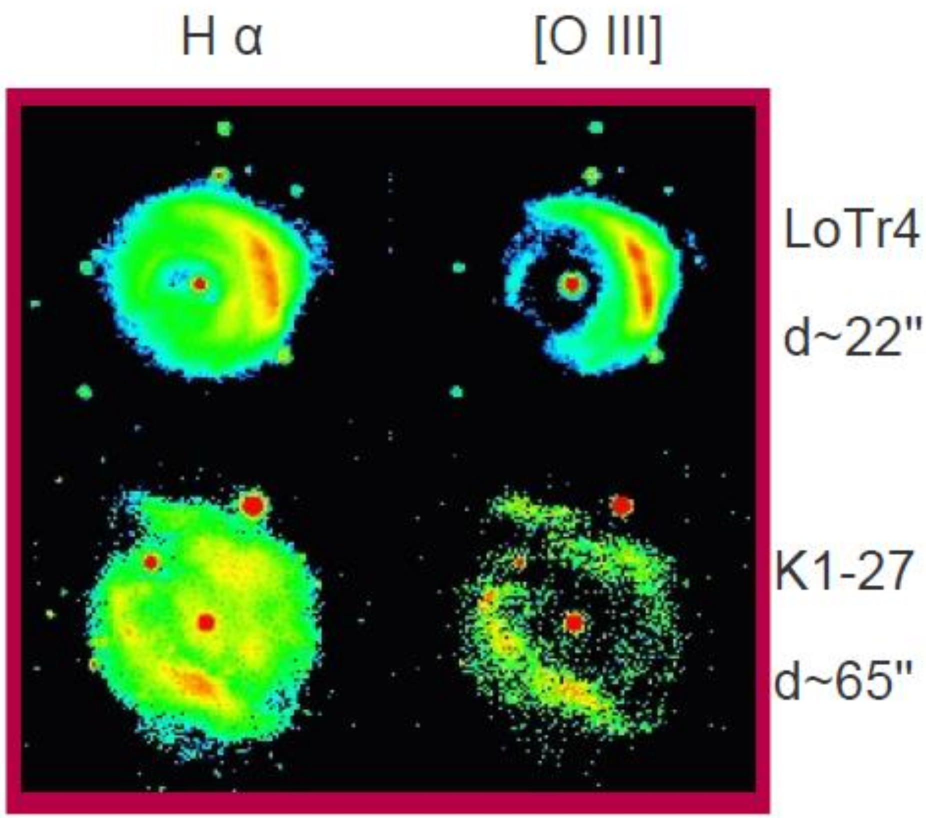
Cool companion

+ dust disk?



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): Re-analysis 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)



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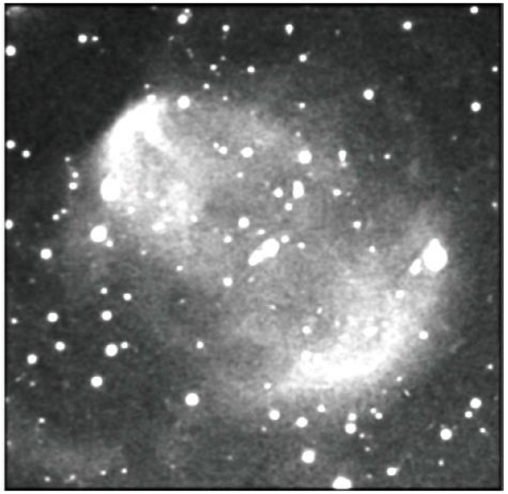
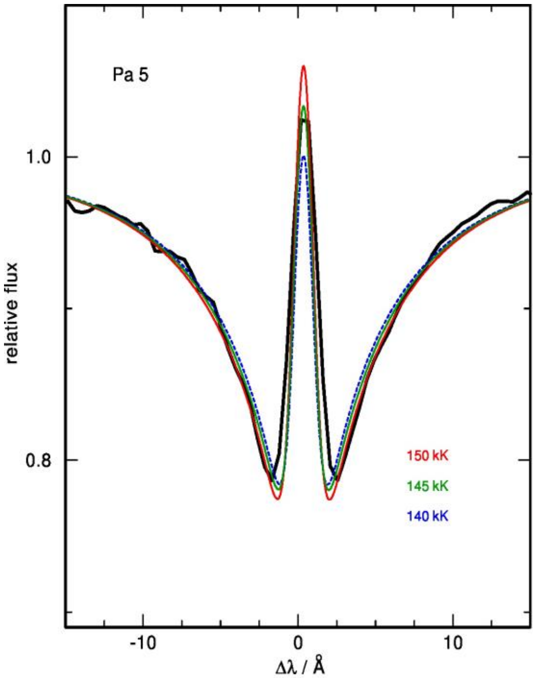
- KPD0005+5106: first classified as a DO white dwarf
  - Werner et al. (2010): T_{eff} = 195 kK, log g = 6.7 → pre-white dwarf
  - 98% He (by mass) → O(He) star
- Werner et al. (2014): Discovery of 4 new O(He) stars in the SDSS DR10: J0757, J1418, J1719, and J1728
  - NLTE analysis with HHeCNOSi models 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



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



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

O(He) stars

A trichotomy exists amongst He-dominated stars

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

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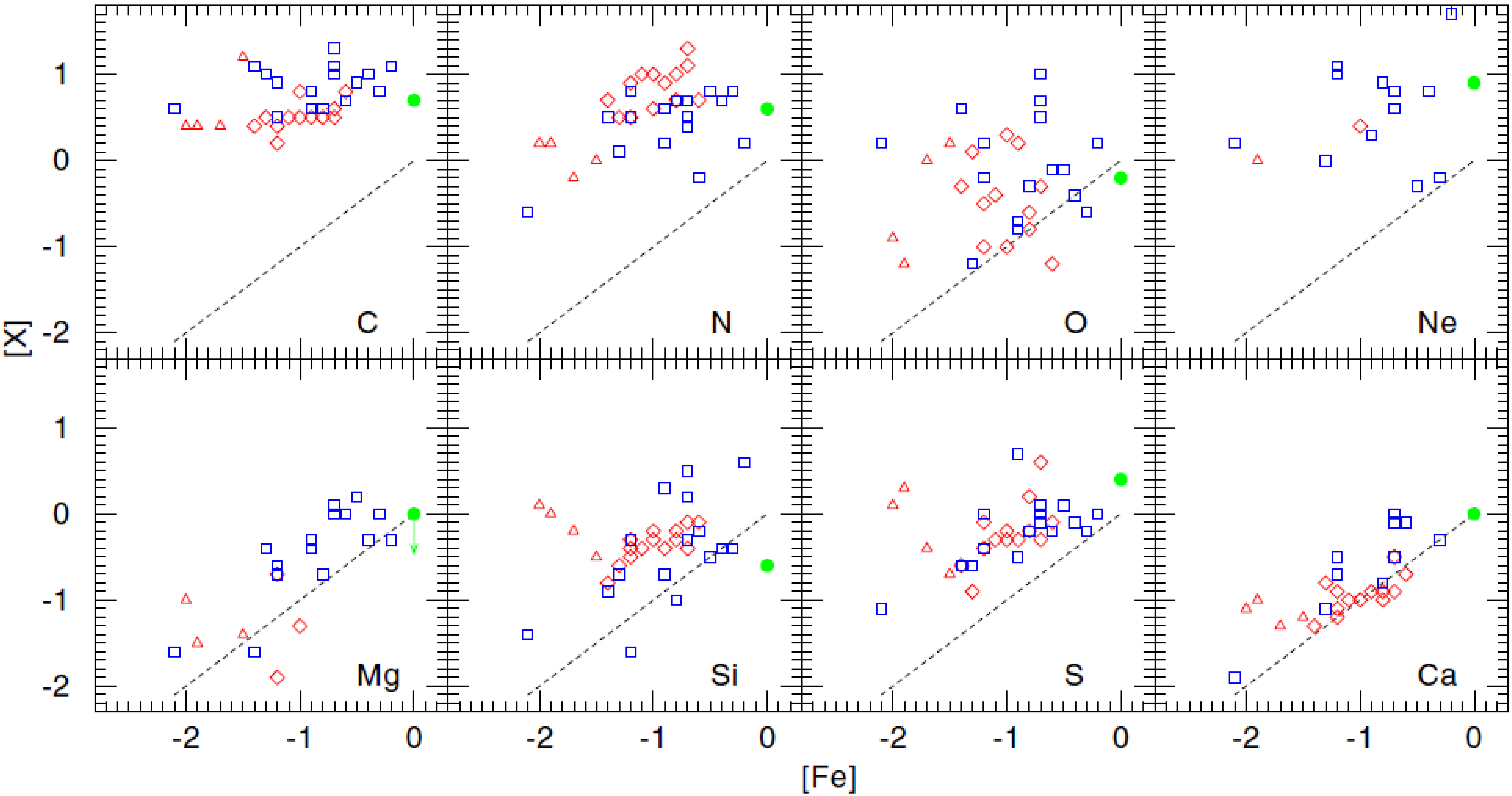
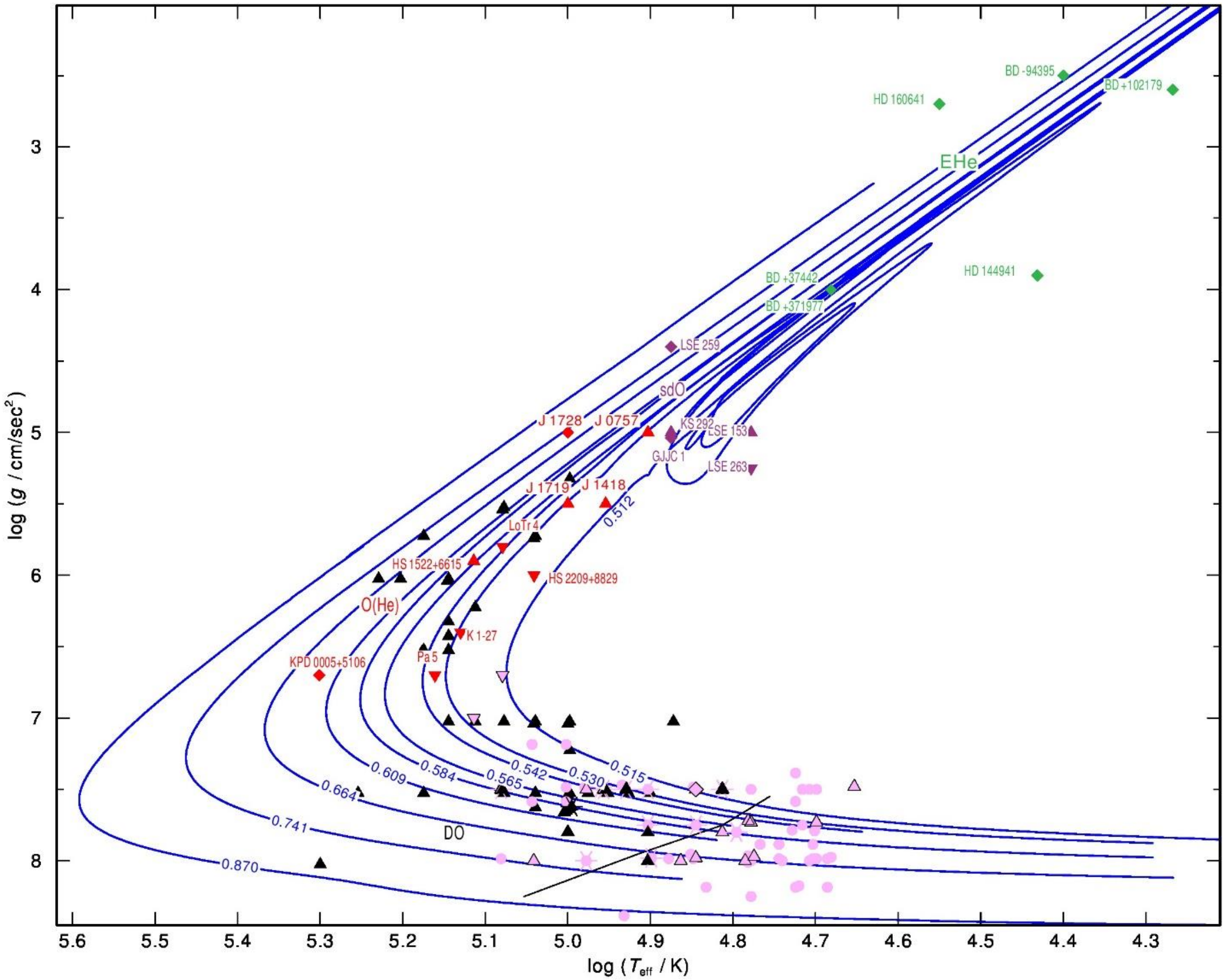
O(He) stars



Abundances of KPD0005+5106 (green) compared to abundances RCB (red) and EHe stars (blue)
The dashed lines indicate the solar composition scaled to iron (Werner et al. 2015).

O(He) stars



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

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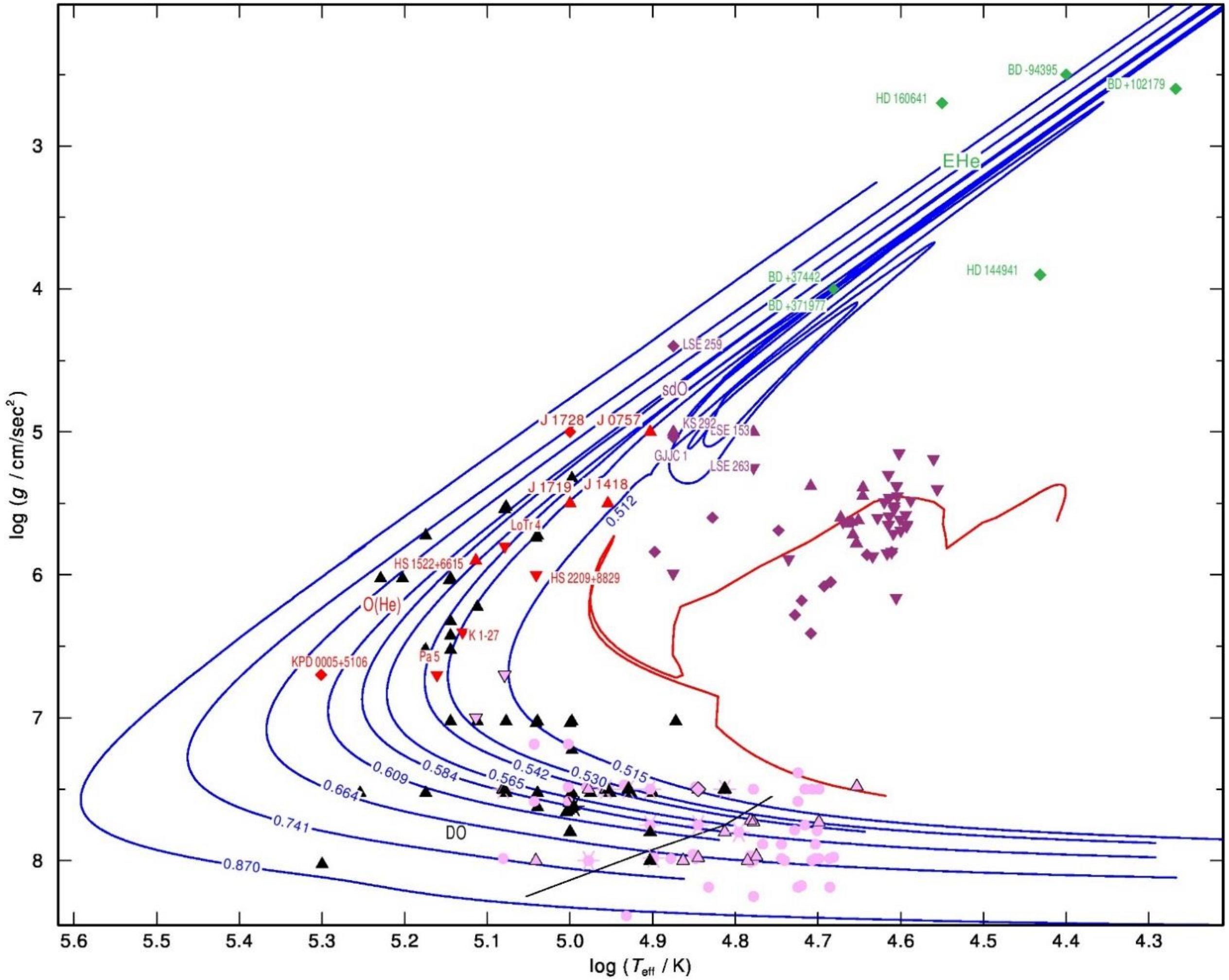
O(He) stars



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- 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

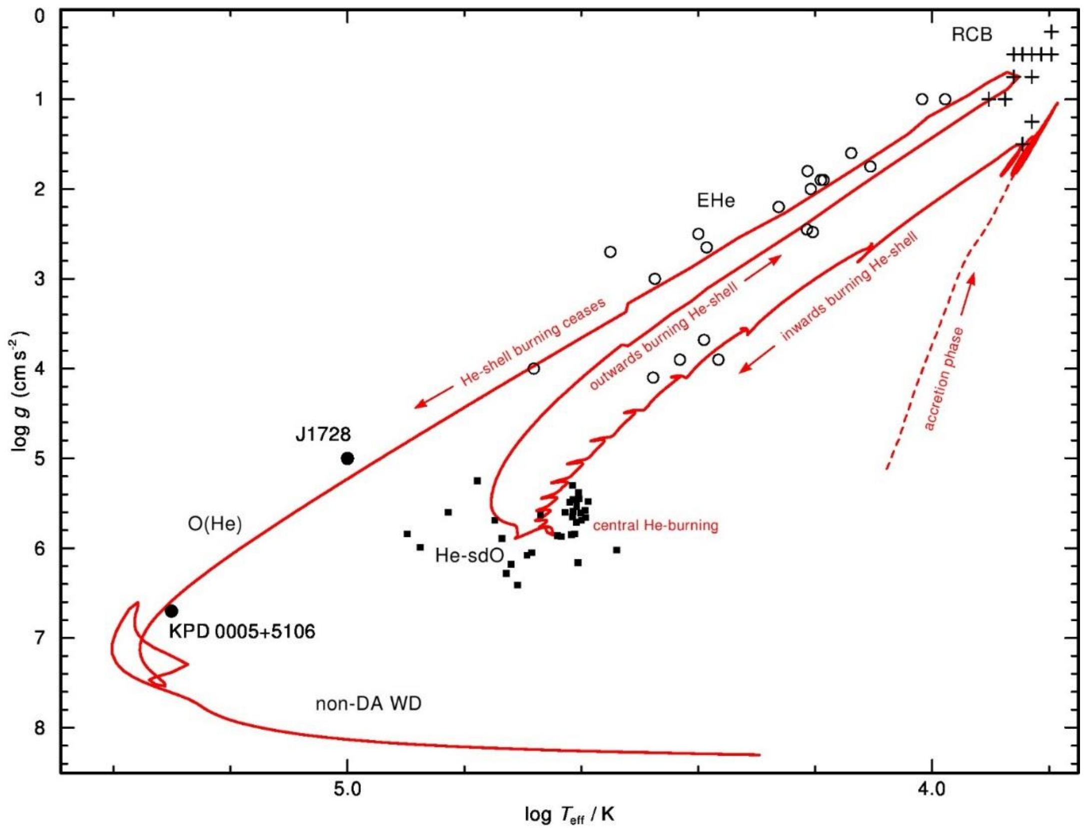
By chance ?

O(He) stars

- Merger of two higher mass (0.4+0.4 $M_{\odot}$) He-WDs (Zhang & Jeffery 2012) 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_{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



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).

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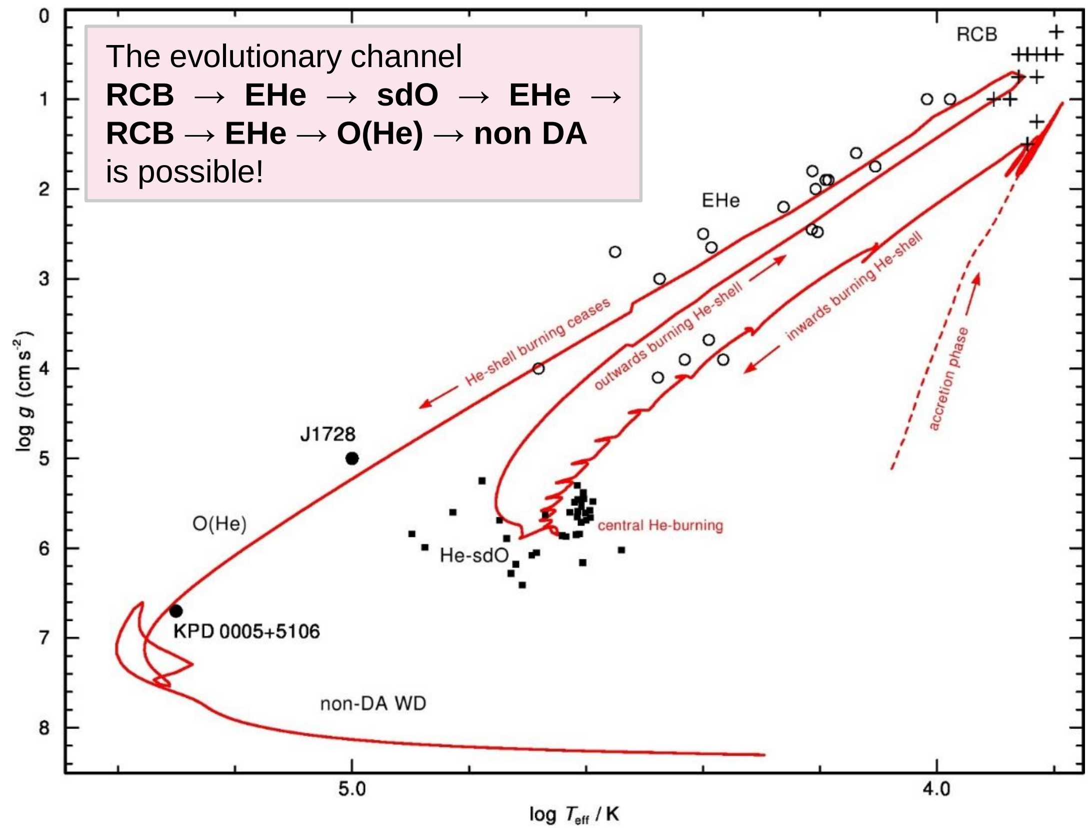

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- ❑ Post-high mass merger produce C&N-rich stars

- ❑ Reindl et al. (2014):
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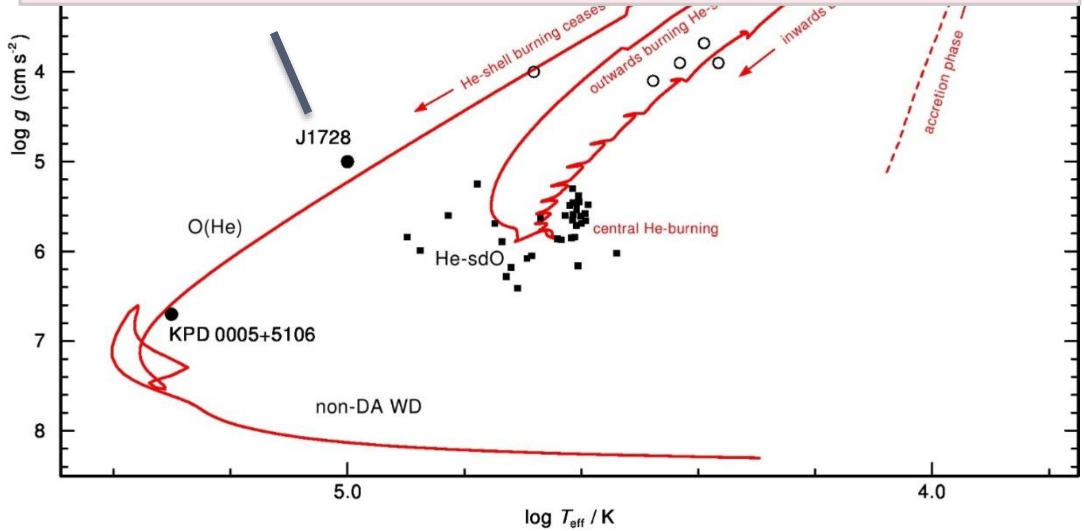
z = 9 kpc, space velocities
⇒ Belongs to the Milky Way halo

↯ Strong contradiction with its high mass $M_{\mathrm{VLTP}} = 0.73\ M_\odot$, $M_{\mathrm{merger}} = 0.9\ M_\odot$

→ Halo currently producing $0.551 \pm 0.005\ M_\odot$ white dwarfs (Kalirai 2012)



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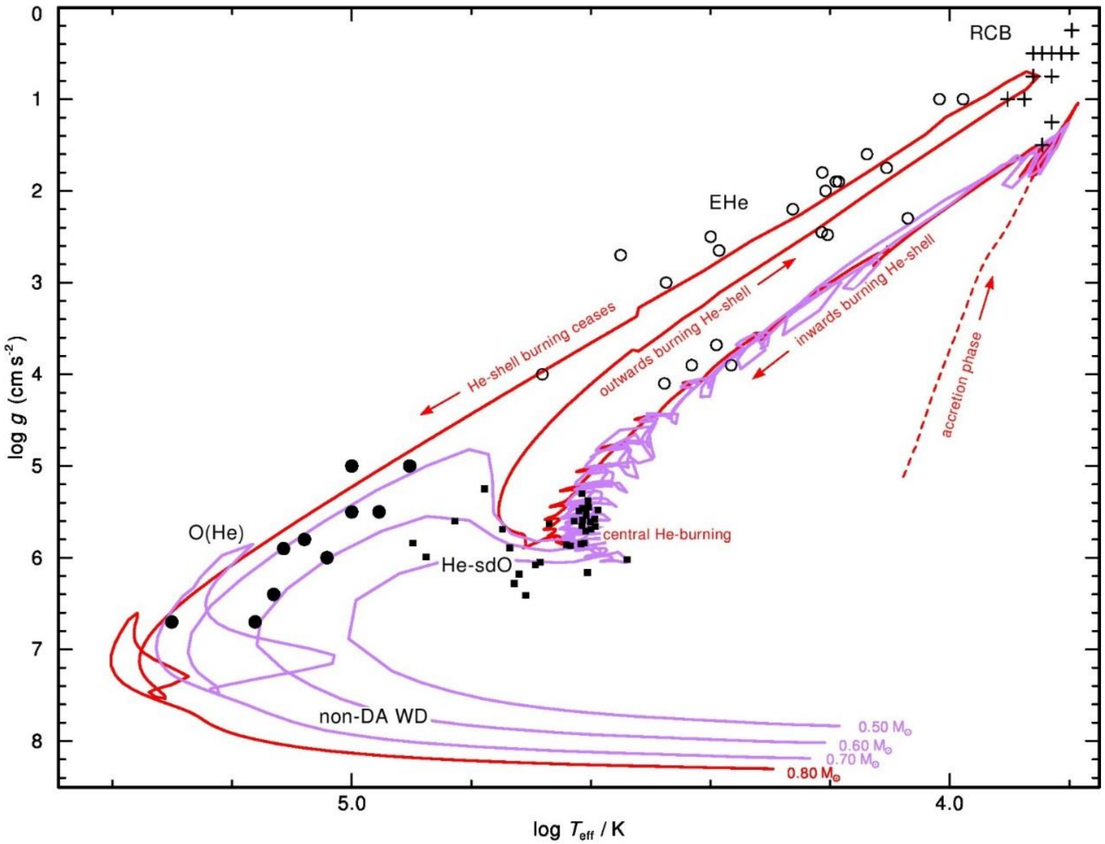
O(He) stars

Reindl et al. (2014): C-rich or N-rich O(He) stars (= low mass O(He) stars) can be reproduced via
RCB → EHe → sdO → O(He) → DO
Composite merger: low mass mergers result in N-rich stars, fast merger: C-rich stars Zhang & Jeffery (2012)

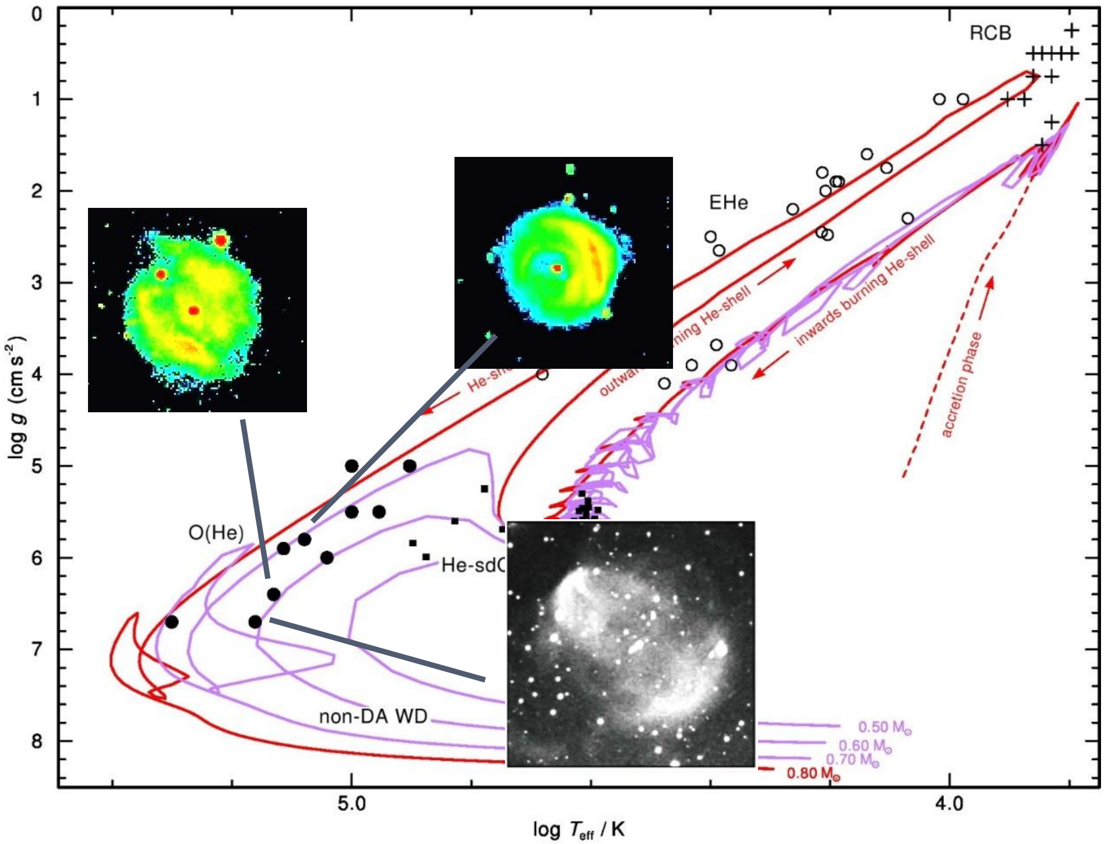


Locations of RCB stars, EHe stars, He-sdO stars, and the two C&N rich O(He) stars compared with He-WD+He-WD merger evolutionary tracks (Zhang & Jeffery 2012a).

O(He) stars

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

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



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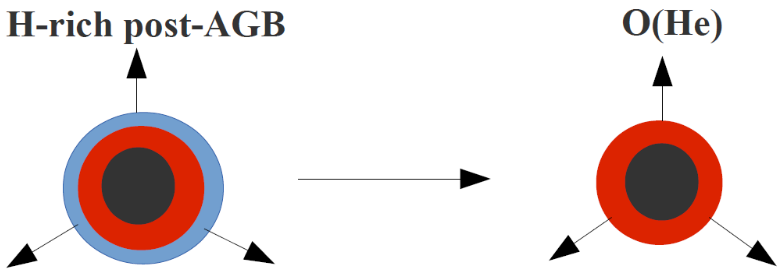
University of Leicester

O(He) stars

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)



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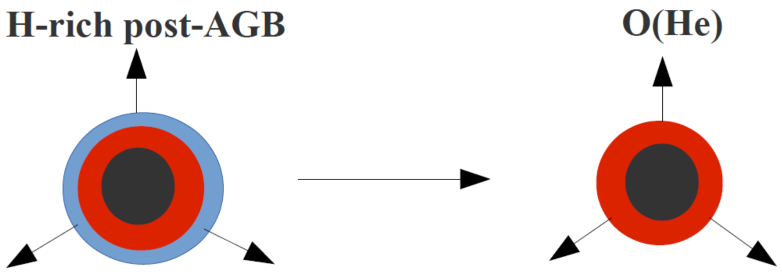

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[WN]-type Central stars

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. 423, 934–947 (2012) doi:10.1111/j.1365-2966.2012.20929.x

IC 4663: the first unambiguous [WN] Wolf–Rayet central star of a planetary nebula★

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Abell 48 – a rare WN-type central star of a planetary nebula★

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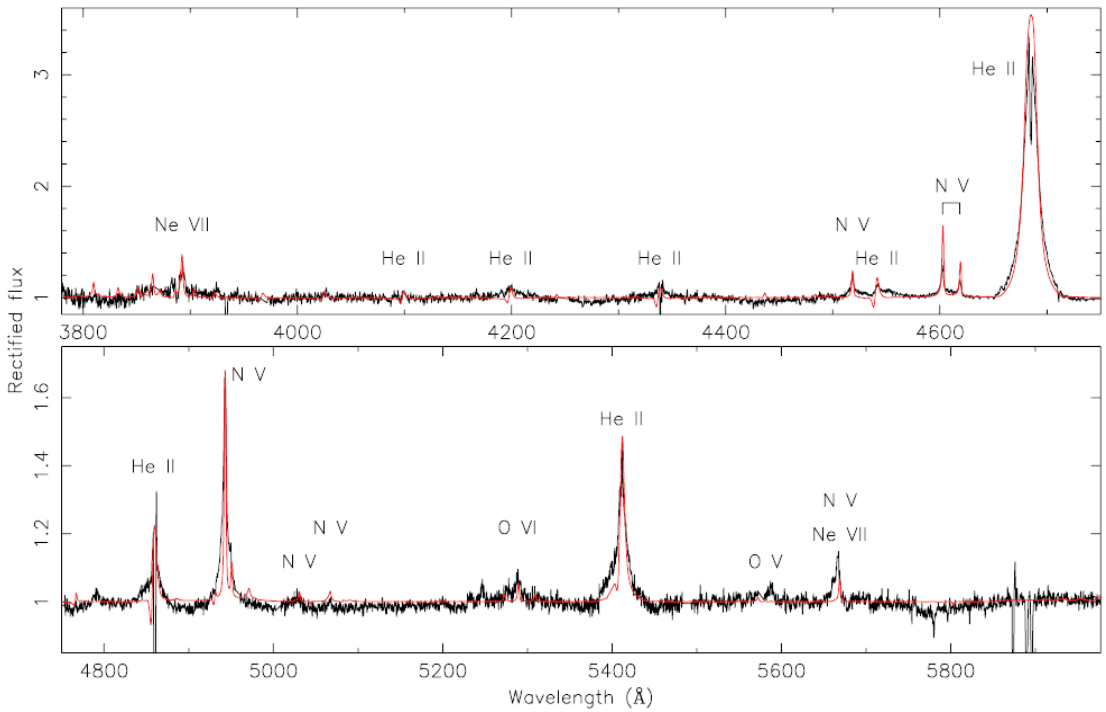
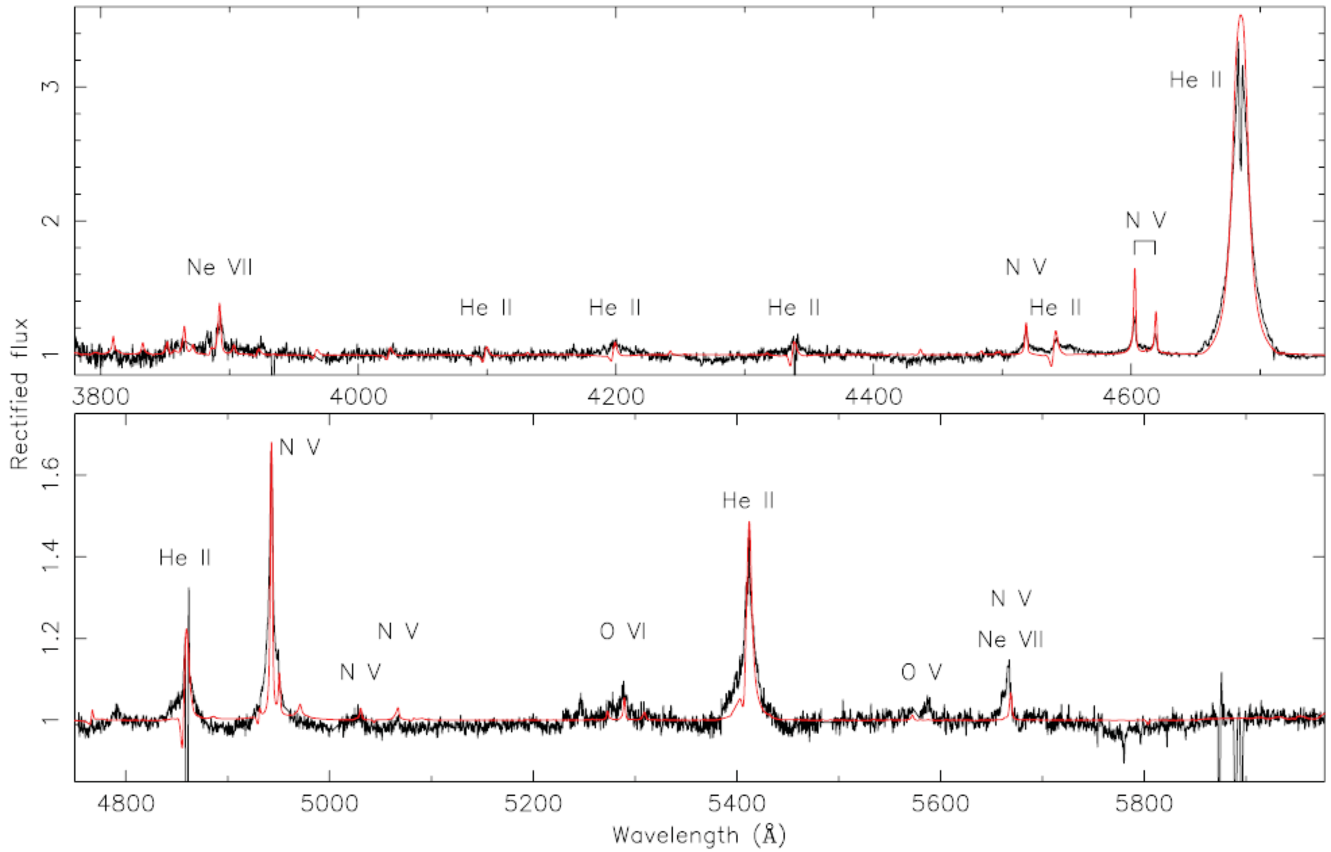
[WN]-type Central stars



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

[WN]-type Central stars



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

Miszalsk+2012: [WN] → O(He)

University of Leicester

O(He) stars

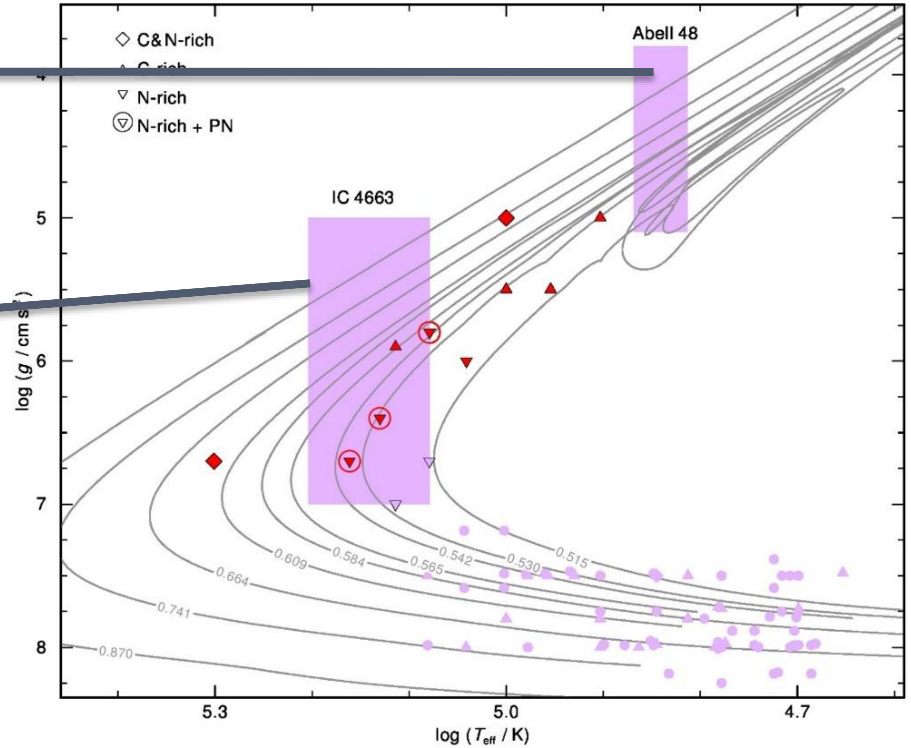
Are O(He) stars really the successors of [WN] type central stars?

✓ 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 $T_{\rm eff}$ – log g plane compared with VLTP evolutionary tracks of Miller Bertolami & Althaus (2006).

Possible solution:

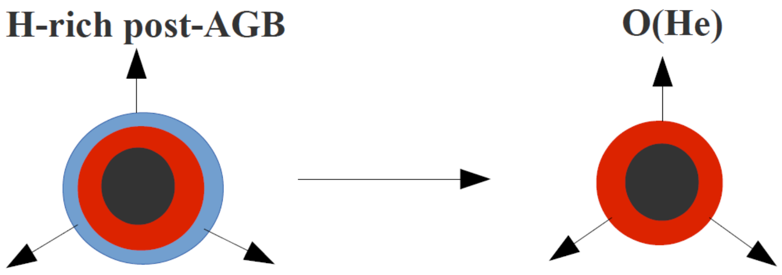
[WN] stars have **higher masses** than O(He) stars

→ 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.

O(He) stars

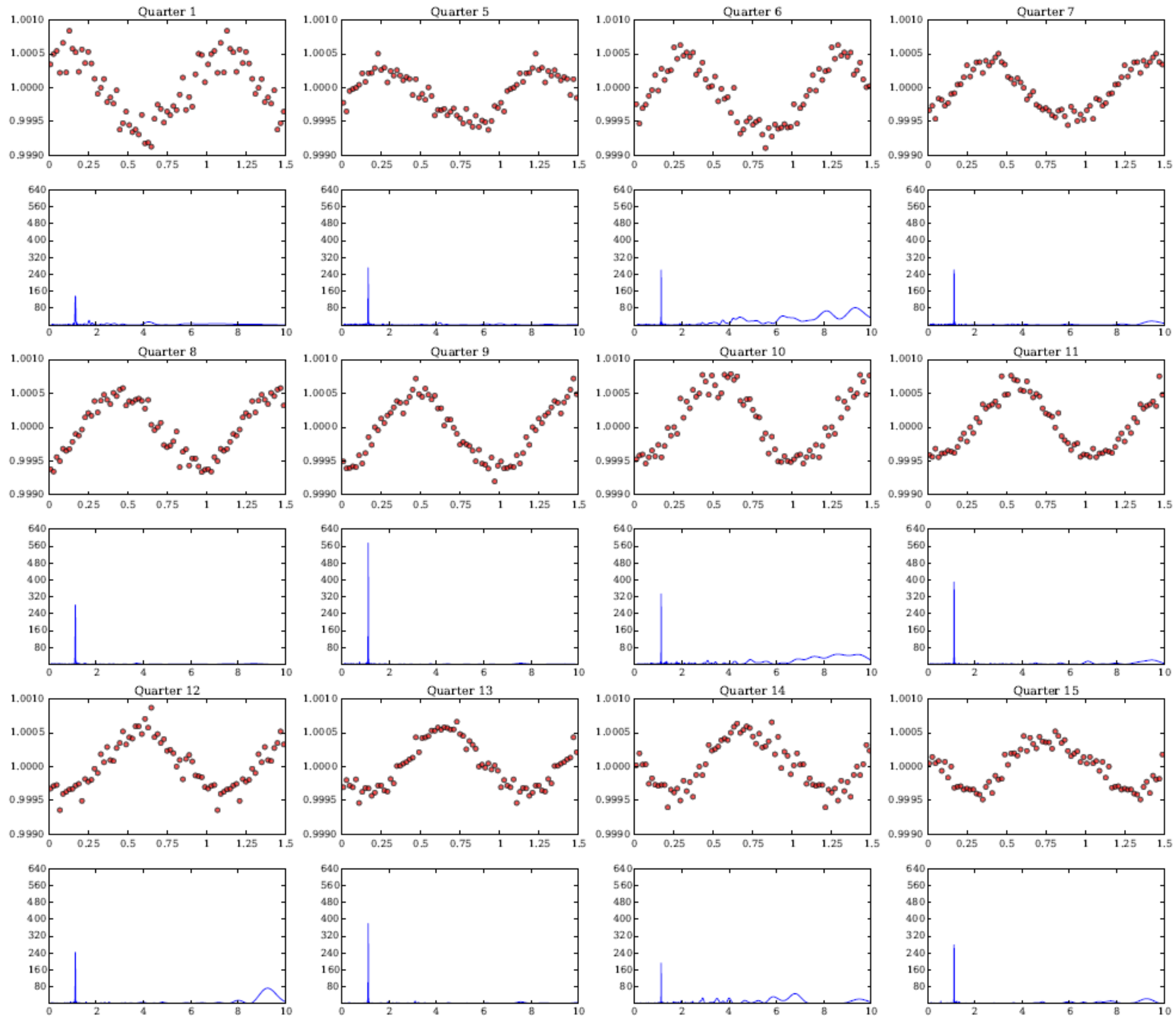
Different evolutionary channel for (N-rich) O(He) type CSPNe?

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)



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

O(He) stars



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

→ **Kepler light curve of Pa 5: P=1.12 d with an amplitude of 0.5mmag (De Marco+2015)**

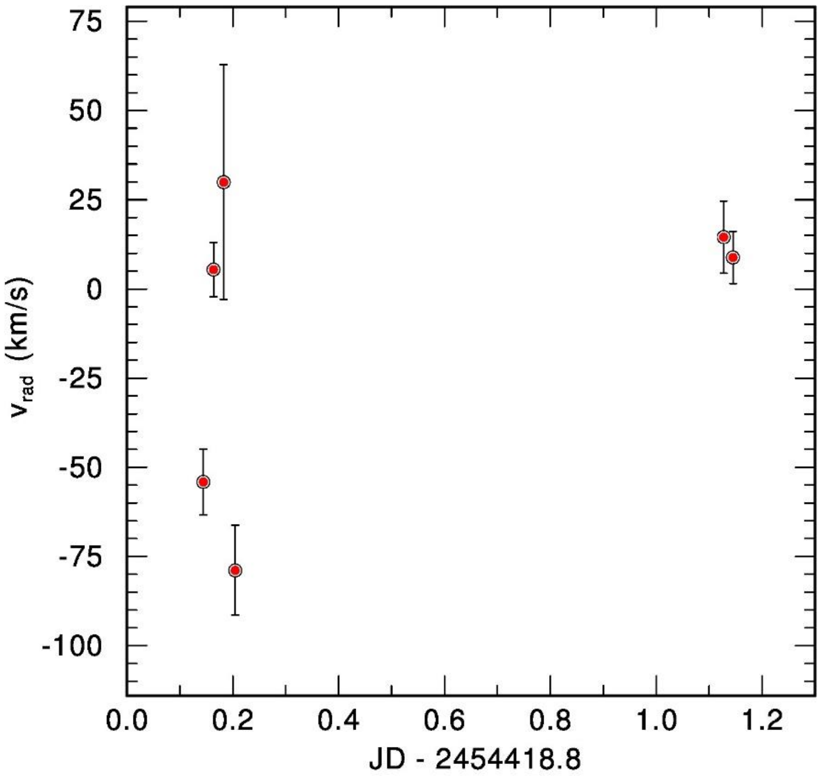
- However, no RV variability < 5km/s
- Planetary mass companion?
  - have been announced around post-giant stars (e.g., Silvotti et al. 2014)
  - doubtful that a planet can survive common envelope evolution
- Variability caused by a magnetic spot?
- Pa 5 has an evolved companion in a nearly pole-on orbit (i < 2.5°).

O(He) stars

- 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?
- Currently ≈ 50 H-rich central stars, one PG1159 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.

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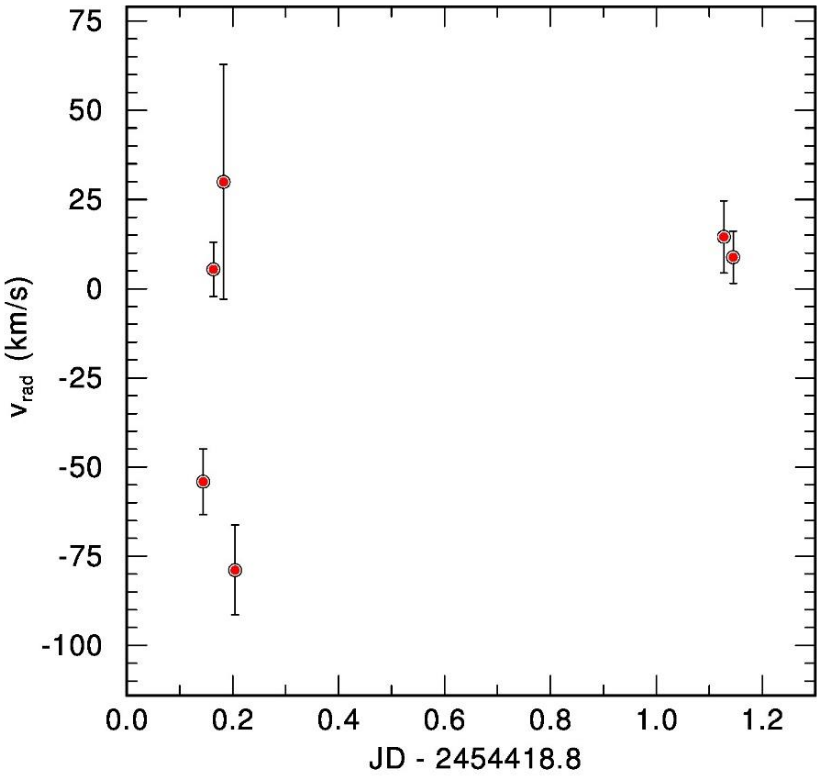

Radial velocities of J0757 measured from six SDSS spectra.

UNIVERSITY OF LEICESTER

Evolutionary status

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PLANETARY NEBULAE IN 2014: A REVIEW OF RESEARCH

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RESUMEN

The mysterious O(He) central stars (H-poor, ~~O~~- N rich) were investigated by Reindl et al. (2014b) who manage to both confirm and deny a merger origin. A future in politics beckons. Refreshingly honest (which may argue against their political future), they conclude that these stars exist and therefore do form, but it is not clear how. Frew et al. (2014c) argue against a relation to the [WN] stars, and propose 'exotic channels', leaving the evolution even more in darkness.

Evolutionary status

Evolutionary status of O(He) 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: 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

Conclusions

- Second H- and He-deficient white dwarf found
- Number of O(He) stars has doubled since 2014
- Trichotomy exists amongst He-dominated stars: C-rich / N-rich / C&N-rich
- C-dominated and He-dominated channel may contribute in an equal extend to the formation of H-deficient white dwarfs
- First hints for close binary systems found in 2out of 10 O(He) stars and 2 more further close binary candidates amongst the 51 PG1159 stars
- Double WD merger can explain some of the He-dominated stars but other formation scenarios must exist as well

How to move forward?

Wishlist:

- Large spectroscopic sky surveys of blue stars to increase the statistics
- Systematic search for spectroscopic and photometric variability to constrain the impact of binary evolution
- High resolution, high S/N spectra optical and UV spectra
  -> Next genaration telescopes (ELT, HDST)
- Model grids