Stellar Parameters from LBVs R110 and R40

Quiescent Stage by Fitting FEROS' Spectroscopic Observations with CMFGEN

Athos Silva[1]
Marcelo Borges Fernandes[1]
Elisson de Almeida[2]

[1]Observatório Nacional, Brazil
[2]Universidad de Valparaíso, Chile

POEMS, Rio de Janeiro, June 24th-28th 2024

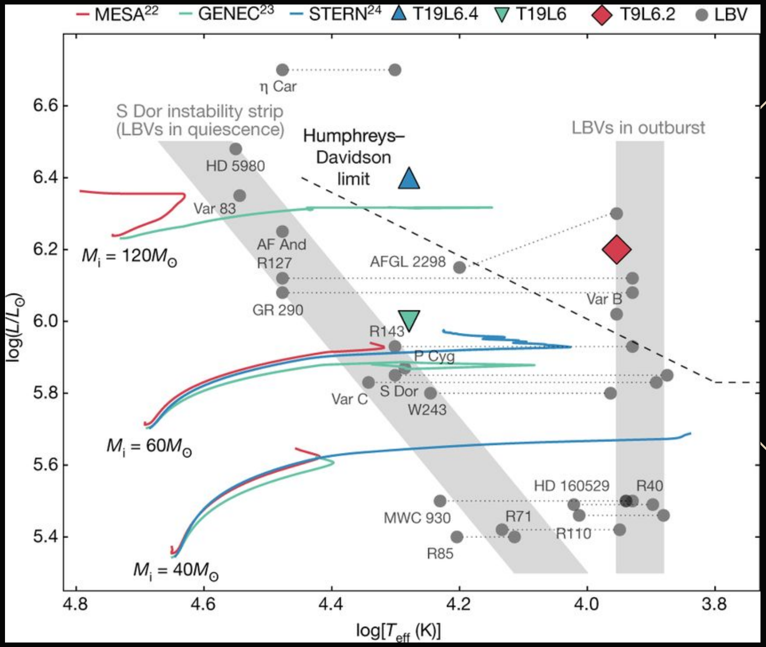
What is a Blue Luminous Variable?

- LBV is an evolutionary stage of massive stars that lasts only ~25000 years.
- Therefore, LBV stars are rare even in the Local Group and their role in the stellar evolution is still very debated.
- For stars with $M_{ZAMS} > 40\ M_{\odot}$, they are expected to be observed between the transition from main sequence to Wolf-Rayet.
- For $20\ M_{\odot} < M_{ZAMS} < 25\ M_{\odot}$, LBVs should occur with the He burning at the core, around post-RSG (red supergiant) and pre-SN (supernova).
- Stars with $M_{ZAMS} < 20\ M_{\odot}$ are not observed in the LBV phase.

AG Car (Hubble Space Telescope)

What is a Blue Luminous Variable?

- They are characterized by episodes of strong mass ejection (eruption):
  - High mass loss rate: $10^{-7} < \dot{M} < 10^{-3}\ M_{\odot}\ yr^{-1}$;
  - High luminosity: $\log L/L_{\odot} > 5.5$;
  - High effective temperature: 8000 K to 30000 K;
  - Slow winds: v_{∞} from 50 to few 100 km/s.
- The eruption can last from weeks to years, and are followed by a period of stillness (quiescence).
- Both phases are represented by a different region in the HR diagram.



Y.-F. Jiang et al., "Outbursts of luminous blue variable stars from variations in the helium opacity," Nature, vol. 561, 2018.

Targets: R110 & R40

Table 7. Bolometric magnitude (M_{Bol}), effective radius ($R/R_\odot$), and $\log g$ for R 110 in various epochs based on the V magnitude and bolometric corrections (BC) from Humphreys & McElroy (1984).

Year	V	Sp-type	BC	M_{Bol}	$R/R_\odot$	$\log g$
1960 (Q)	10.9	B9Ieq	−0.38	−8.6 ± 0.3	150	1.1
1989 (E)	9.99	F0	−0.1	−9.0 ± 0.3	310	0.45
2005 (Q)	10.9	B9	−0.2	−8.6 ± 0.3	150	1.1
2016 (E)	10.5	A2	0.08	−8.7 ± 0.1	200	0.83

Notes. We assumed $A_V = 0.62 \pm 0.3$ mag for the star and a distance modulus of $DM_{LMC} = 18.50$ mag for the LMC. In the Year column, Q means the quiescence, and E the eruption stage.

Table 6. Bolometric magnitude (M_{Bol}), effective radius ($R/R_\odot$), and $\log g$ for R 40 in different epochs, based on the V magnitude and bolometric corrections (BC) from Humphreys & McElroy (1984).

Year	V	Sp-type	BC	M_{Bol}	$R/R_\odot$	$\log g$
1960 (Q)	10.73	B8Ie	−0.51	−9.0 ± 0.1	160	1.25
1991 (E)	10.15	A4	−0.1	−9.2 ± 0.1	280	0.78
2005 (Q/E)	10.3	A0–A2	−0.2	−9.1 ± 0.1	250	0.85
2016 (E)	9.2	F8Iab	0.08	−9.8 ± 0.1	750	−0.1

Notes. We assumed $A_V = 0.3 \pm 0.1$ mag for R 40 and a distance modulus of $DM_{SMC} = 18.90$ mag for SMC. In the Year column, Q means the quiescence and E the eruption stage.

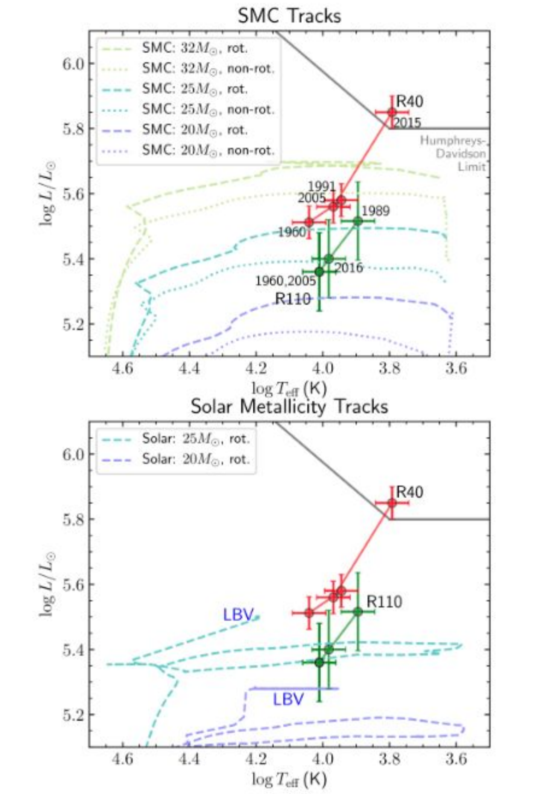
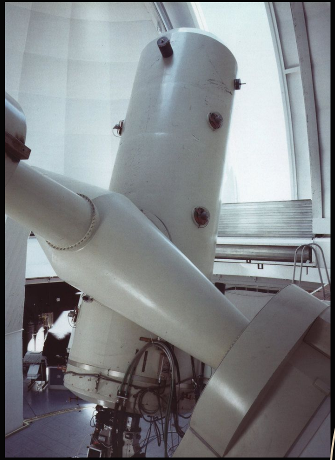


Fig. 5. HR diagram showing the position of R 40 and R 110 in different epochs, based on our estimations. The Humphreys–Davidson limit is shown as a gray line. In addition, evolutionary tracks with rotation of $v_{\mathrm{rot,ZAMS}} = 0.4\,v_{\mathrm{crit}}$ (dashed lines) and without rotation (dotted lines) for SMC metallicity (Georgy et al. 2013, *top panel*) and for solar metallicity (Ekström et al. 2012, *bottom panel*) are also shown. *Bottom panel*: we indicate the regions where LBV phase may occur according to Groh et al. (2013a).

J. C. N. Campagnolo et al., "Detection of new eruptions in the Magellanic Clouds luminous blue variables R 40 and R 110," Astronomy & Astrophysics, vol. 613, article A33, 2018.

The Fiber-fed Extended Range Optical Spectrograph (FEROS)

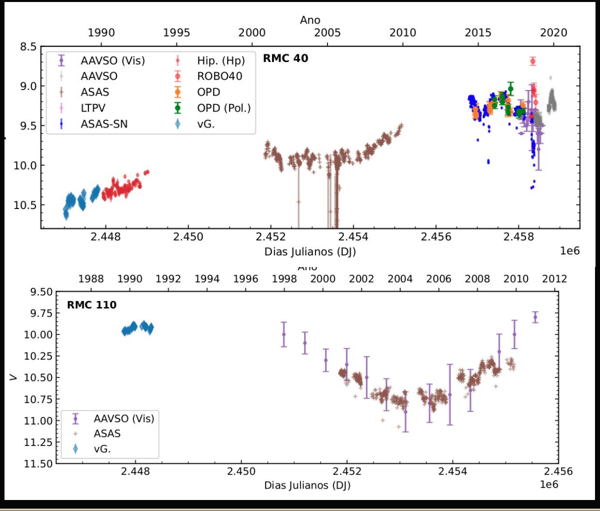


- FEROS is a spectrograph installed at the MPG/ESO 2.2-metre telescope located at ESO's La Silla Observatory:
  - Resolution of 0.03 Å/pixel (R ~ 48000);
  - Spectral range from 3600 to 9200 Å

- The spectra taken in 2005 were reduced using MIDAS routines developed by our group, following standard echelle reduction procedures. The data taken between 2007 and 2016 were reduced by the ESO/FEROS pipeline.

- The signal-to-noise ratio (S/N) is between 60 and 120 around Hα.

- So far, our preliminary work has employed data from 2005 to 2007 of a quiescent phase.



CMFGEN

- CMFGEN is an atmosphere code developed to model the spectra of a variety of objects – O stars, Wolf-Rayet stars, luminous blue variables, A and B stars, central stars of planetary nebula, and supernovae.

- The principal computational aim of CMFGEN is to determine the temperature and ionization structure of the atmosphere, and the atomic level populations.

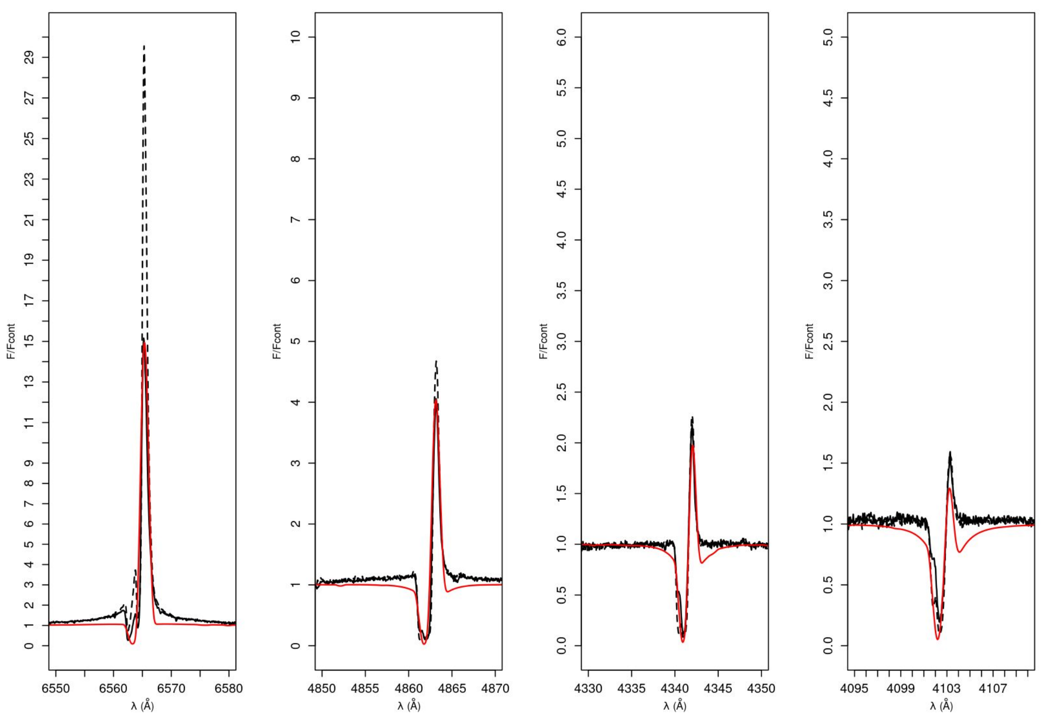
- CMFGEN simultaneously solves the radiative transfer equation (RTE) for spherical geometry in the comoving frame in conjunction with the statistical equilibrium equations (SEEs) and radiative equilibrium equation (REE).

- The auxiliary tool PLT_SPEC allows to generate spectra from our models, which can be compared with the observed ones in order to obtain a best fit of stellar parameters.

Preliminary results: R110

- Best fit for 2007's spectrum:
  - $\dot{M}$ = 5.2 x 10E-6 $M_{\odot}\ yr^{-1}$
  - v_{∞} = 60 km/s
  - β = 1.0
  - T_{eff} = 10000 K
  - log g = 1.2
  - f (clumping) = 0.1
  - R = 48000
  - v sini = 30 km/s
  - X ~ 0.38, Y ~ 0.60 as in Vink & de Koter (2002).

Solid black line: FEROS 2007; Dashed black line: FEROS 2005; Red line: CMFGEN model.



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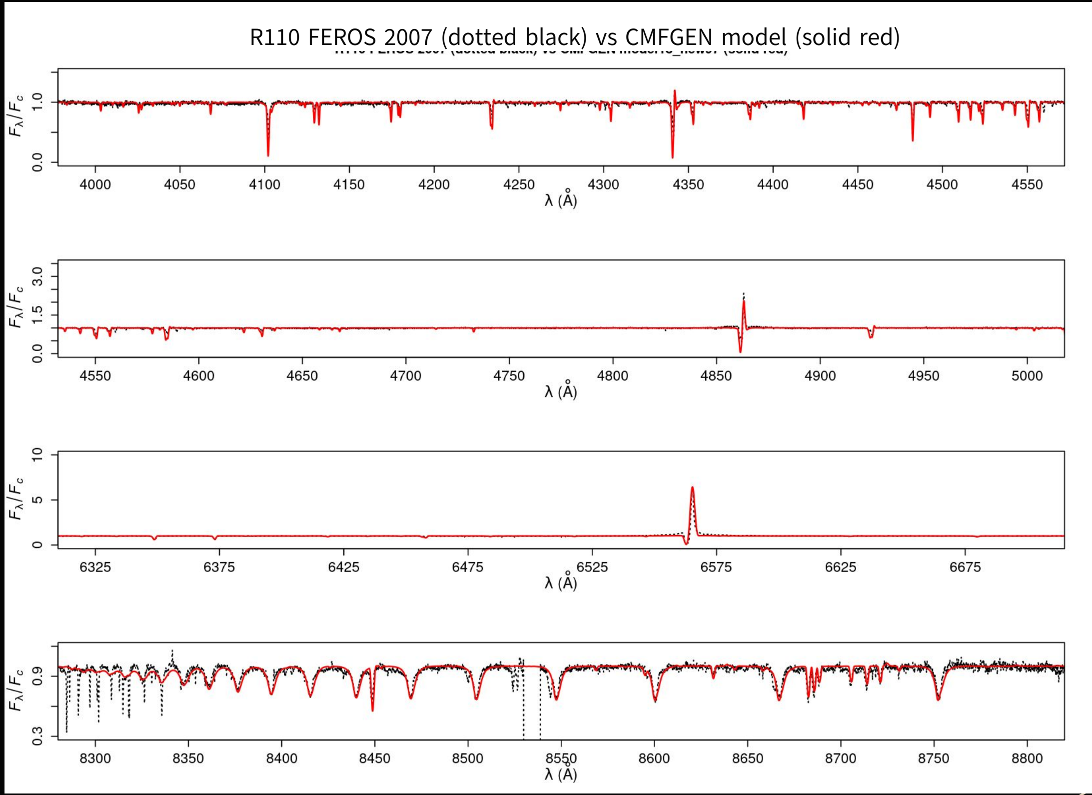
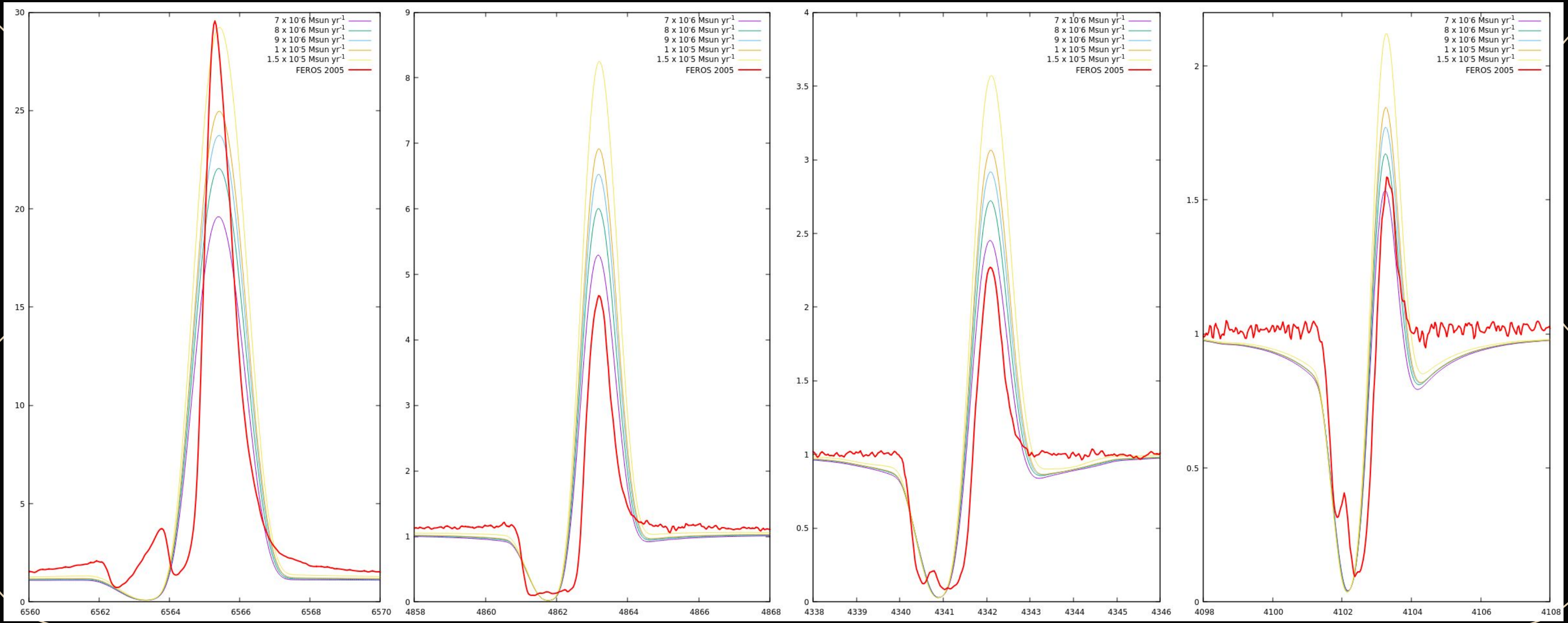


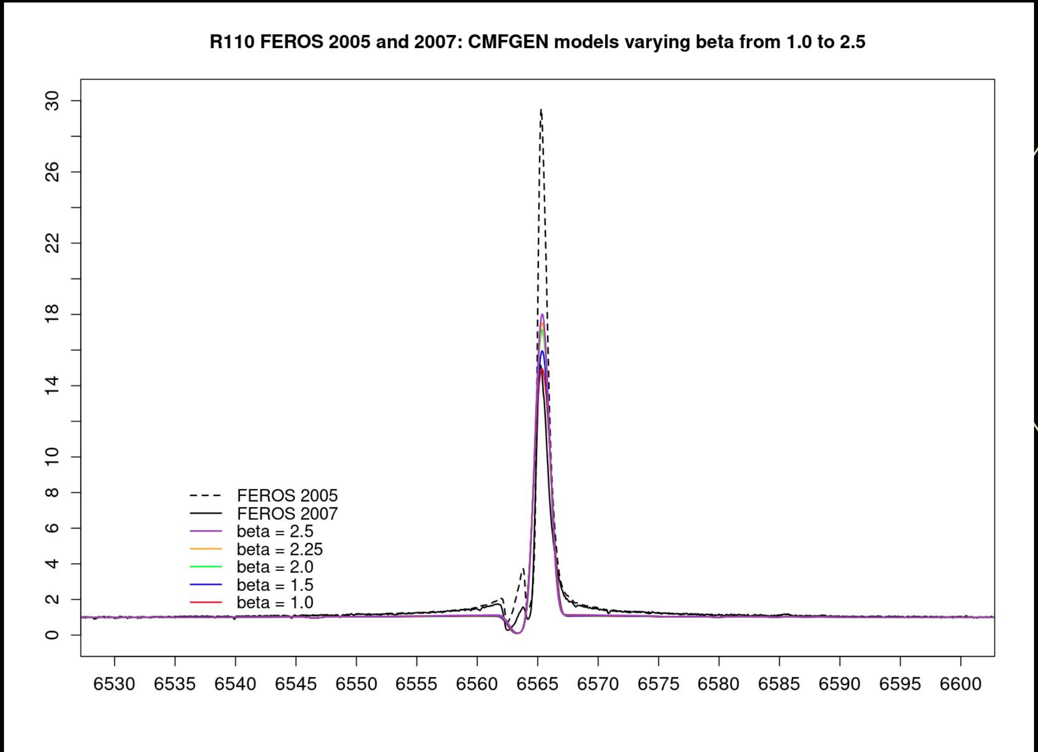
Preliminary results: R110

- Adjusting only the mass loss rate does not yield a better fit for the spectrum observed in 2005.



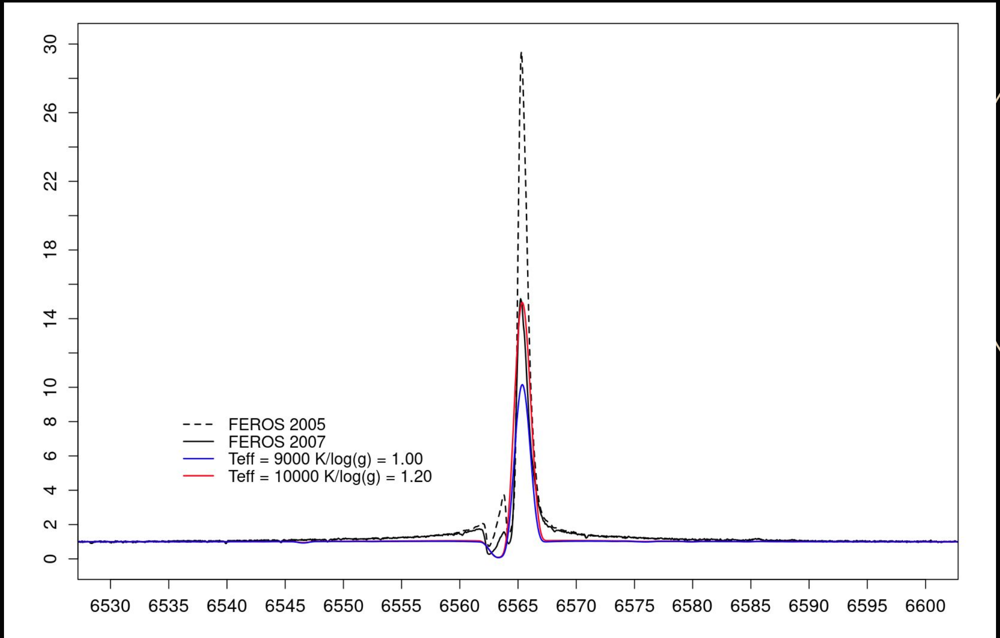
Preliminary results: R110

- Adjusting only for β factor of the empirical velocity law is also not enough to explain 2005's spectrum.



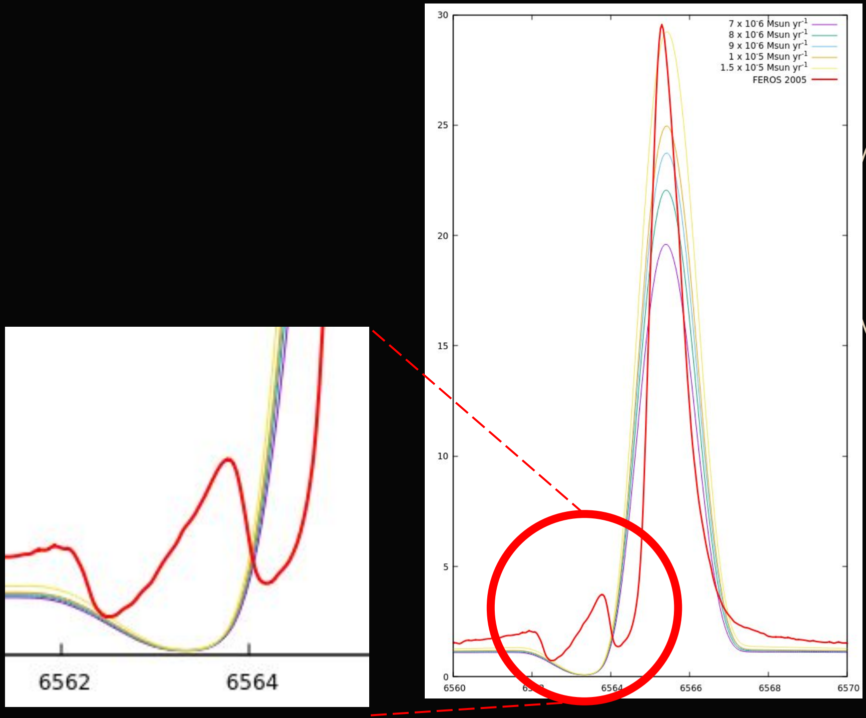
Preliminary results: R110

- In 2007, the light curve shows the beginning of an eruption (increasing L_*).
- We first tested a model with L_* constant and decreased T_{eff} / *log g*. But instead, the emission component from Hα decreased.
- This indicates that higher T_{eff} (along with higher mass loss) could explain the 2005 observed spectrum.



Preliminary results: R110

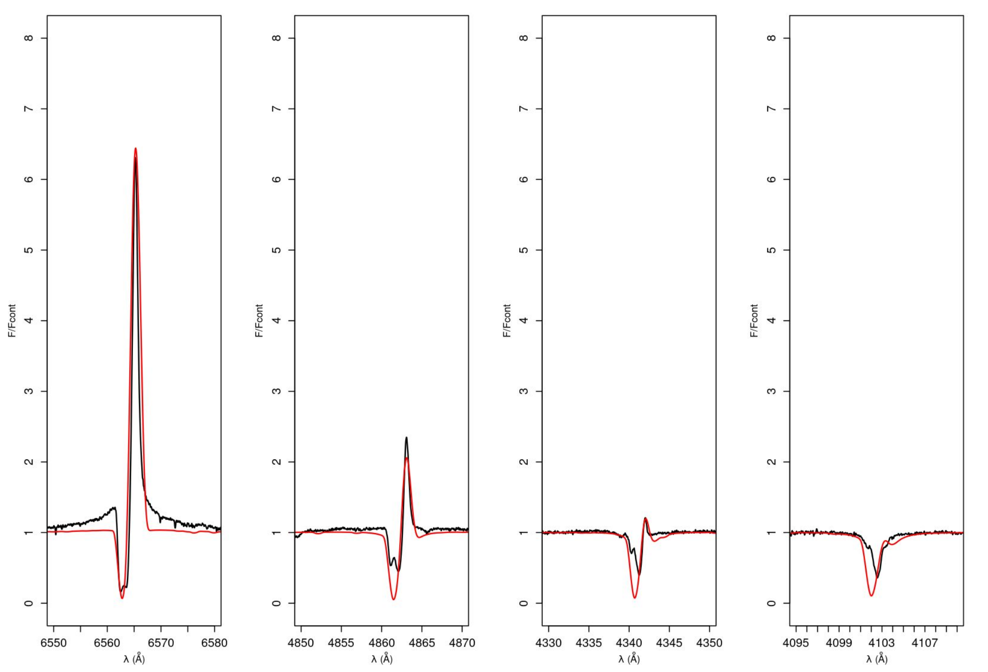
- Strange feature in the absorption component of observed line profile:
    - Possible presence of inhomogeneous layers in the shell?
    - A P Cygni line profile inside itself?



Preliminary results: R40

- Best fit for 2005's spectrum:
  - $\dot{M}$ = 5.8 x 10e-6 $M_{\odot}\ yr^{-1}$
  - v_{∞} = 90 km/s
  - β = 1.0
  - T_{eff} = 8500 K
  - log g = 0.85
  - *f* (clumping) = 0.1
  - R = 48000
  - *v* sini = 30 km/s
  - X ~ 0.38, Y ~ 0.60 as in Vink & de Koter (2002).

Solid black line: FEROS 2005; Red line: CMFGEN model.



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  - *v* sini = 30 km/s
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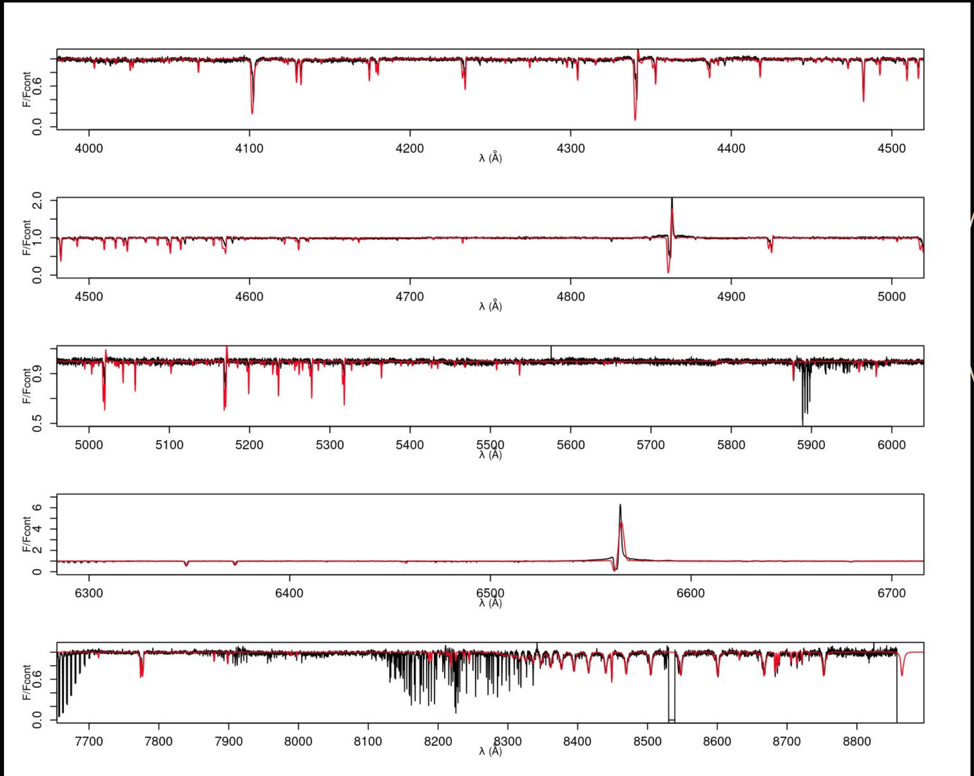
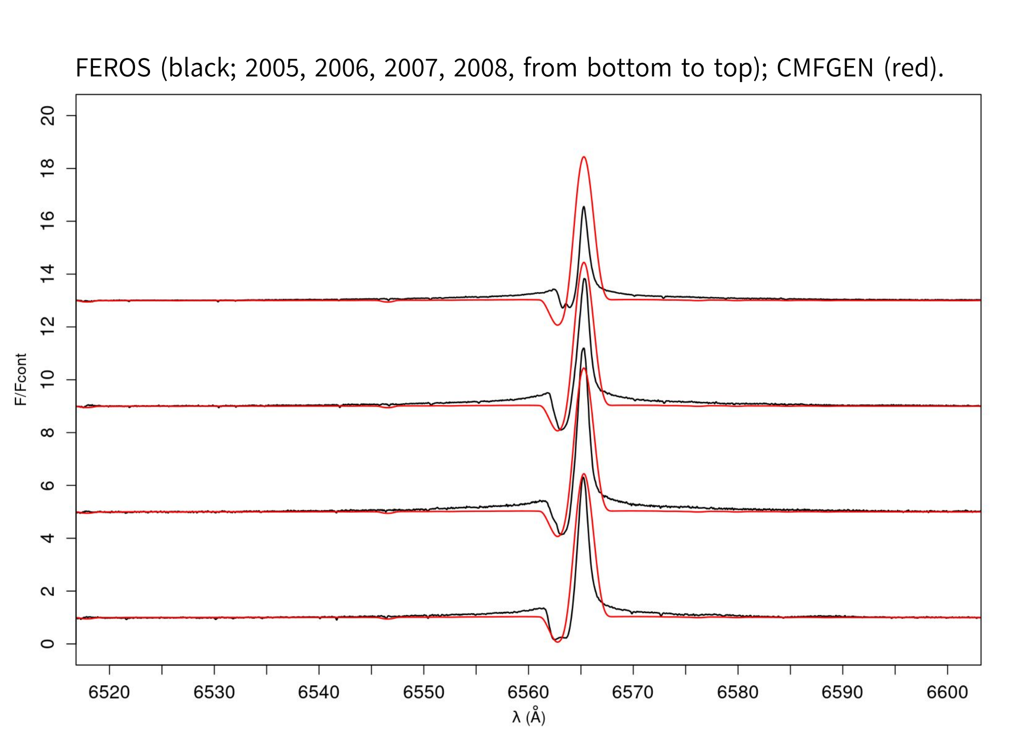


Preliminary results: R40

- 2006's spectrum indicates a slight increment of mass loss, probably due to the eminence of eruption.

- Hα emission component starts to decrease from 2007-2008. We estimate a decrease in T_{eff} with L_* constant (to be verified).



What's next?

- R110: a new model for 2005's spectrum with higher T_{eff} / log g + mass loss rate adjustment.
- R40: a new model for 2006-2008 with increasing mass loss rate and decreasing T_{eff} .
- Start of models for R71.
- Implement a radiative transfer code that works with spherical asymmetry in order to properly fit the absorption profiles.

Thank you!

Muito obrigado!