A look at the wind asymmetries in the S-type symbiotic star EG Andromedae through the spectroscopy from Skalnaté Pleso Observatory

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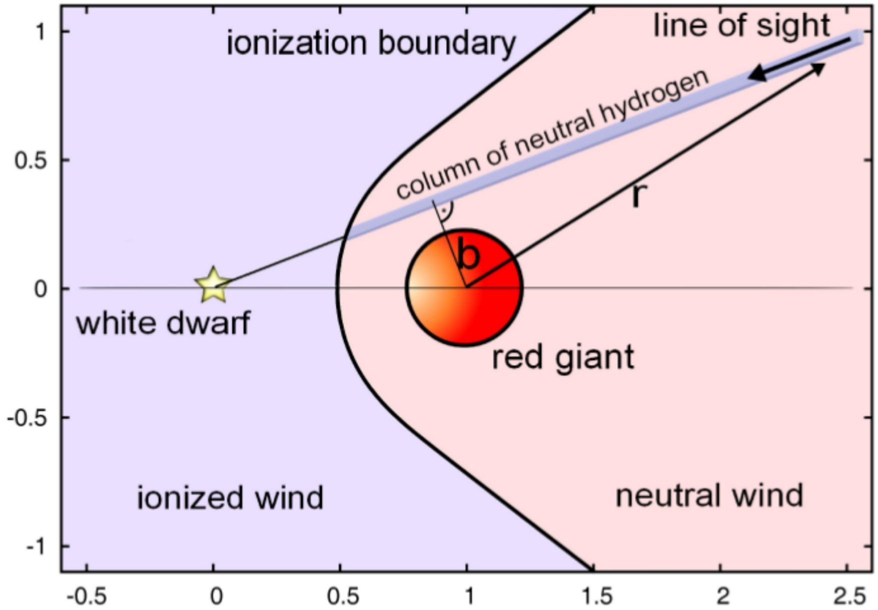
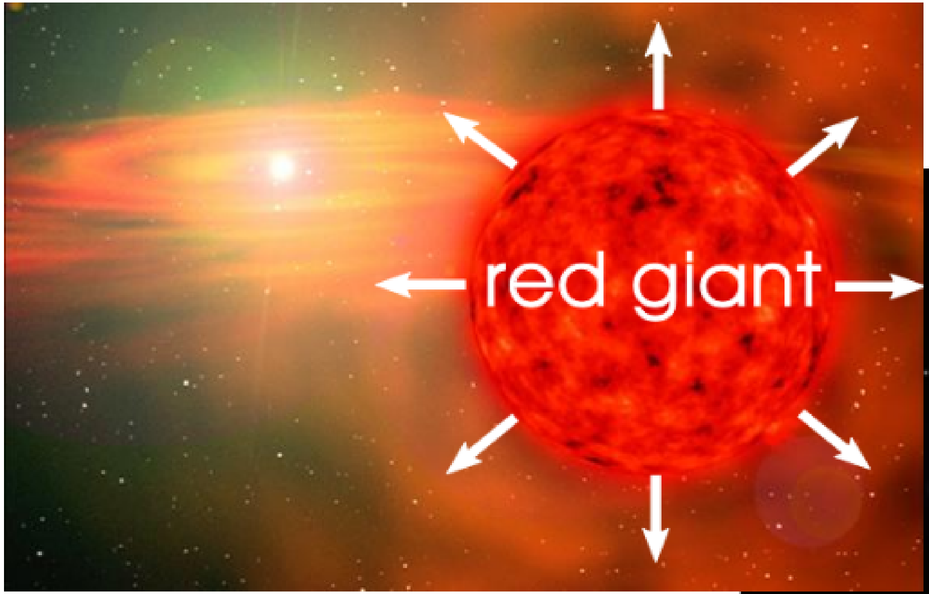
Symbiotic stars

- widest interacting binary stars (P≈few years)
- white dwarf + red giant
- neutral and ionized wind
- quiescent and active phases

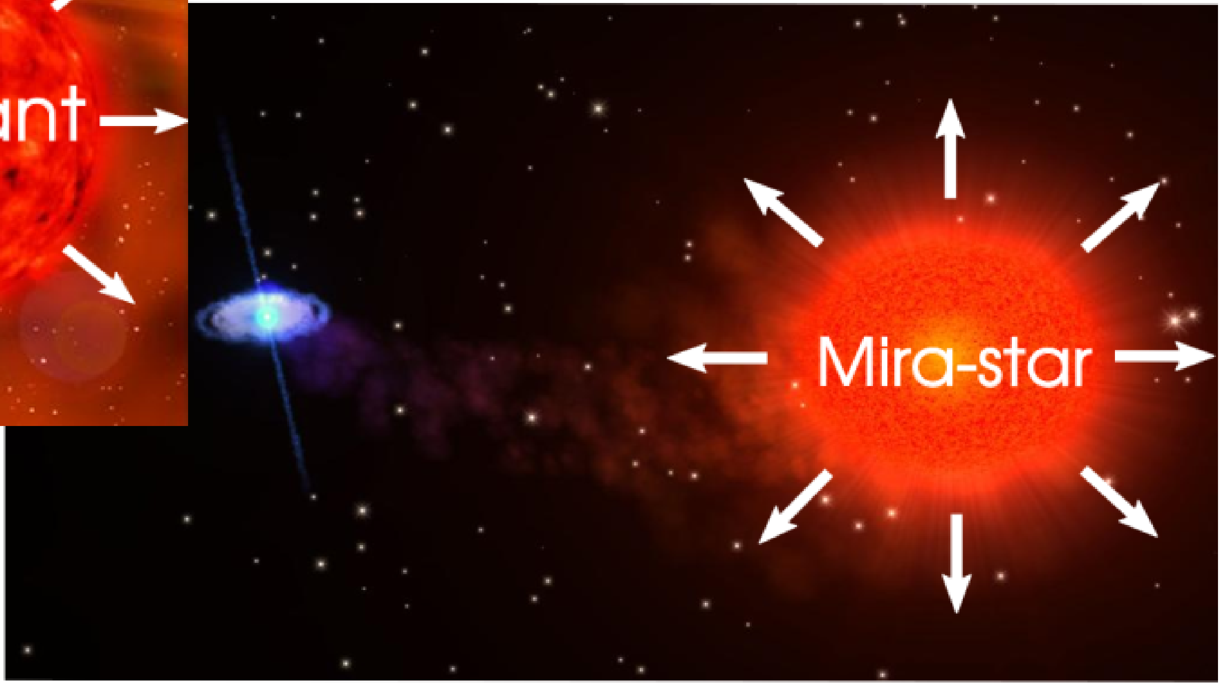


Mechanism of the mass loss from cool companions

S-type systems



D-type systems



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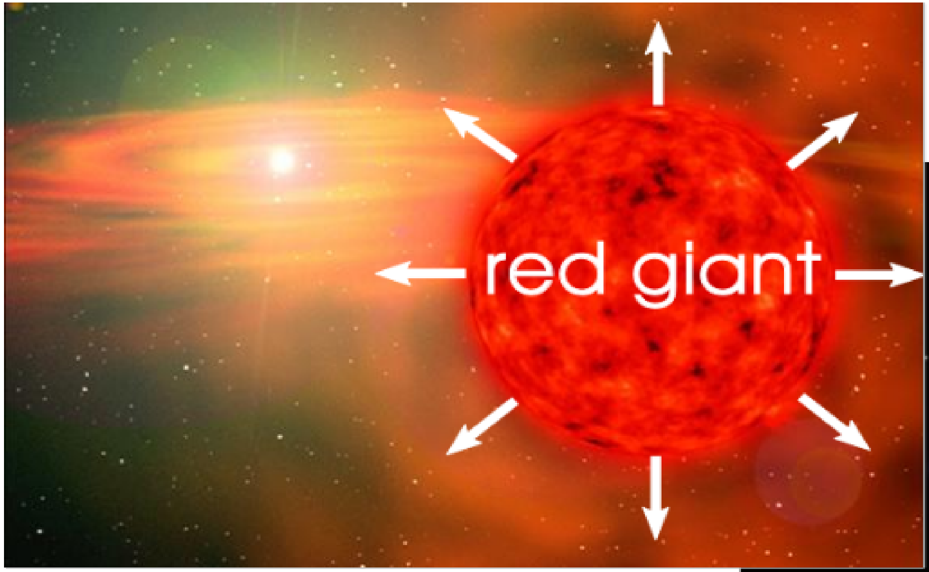
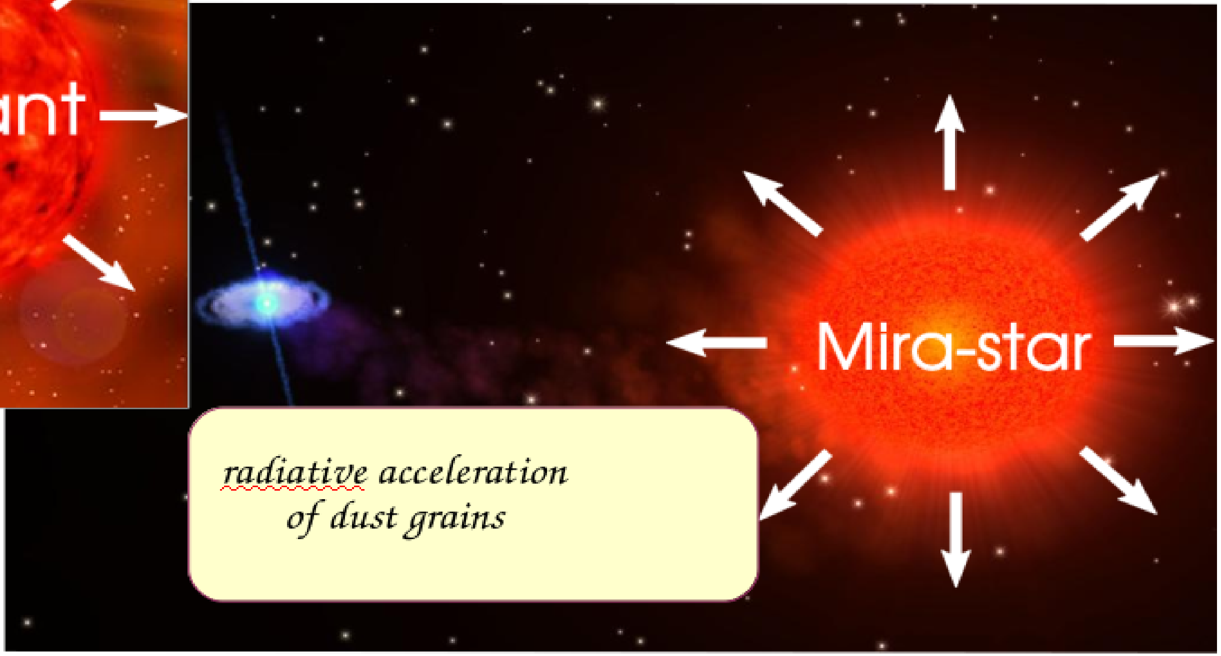


D-type systems



radiative acceleration of dust grains

Höfner 2015, ASP Conf. Ser. 497, 333

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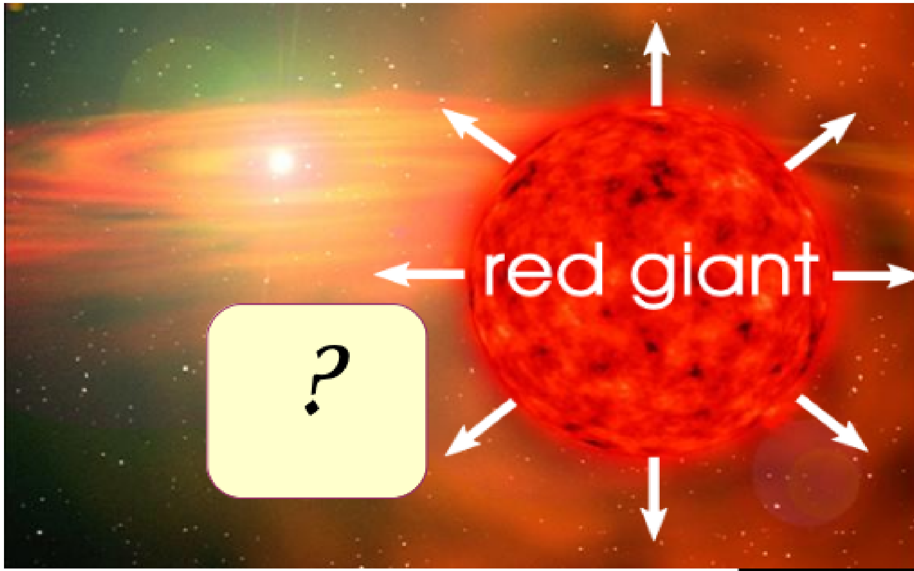
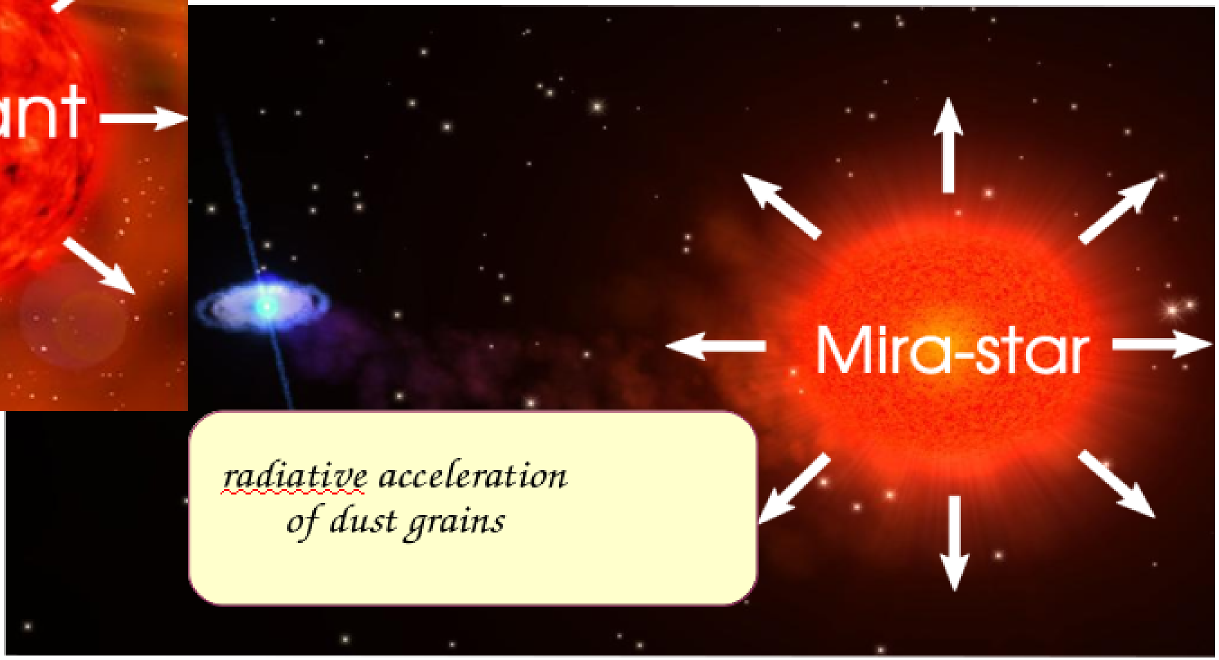


O'Gorman et al. 2013, AJ 146, 98

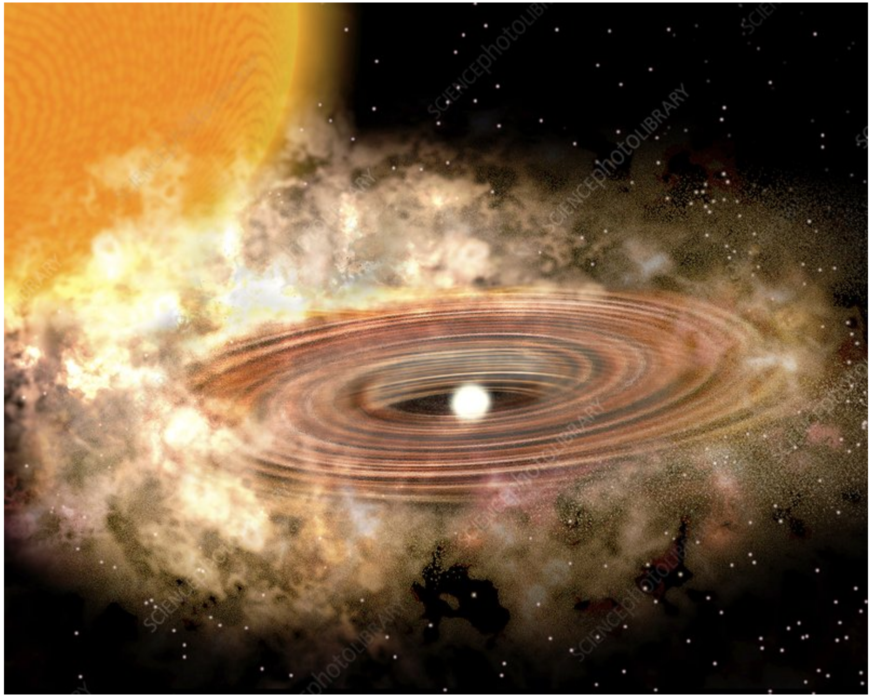
D-type systems



Höfner 2015, ASP Conf. Ser. 497, 333

The luminosity problem

- accretion heats up the white dwarf up to T ~ 100 000 K, L = 10 - 1000 L_{Sun}

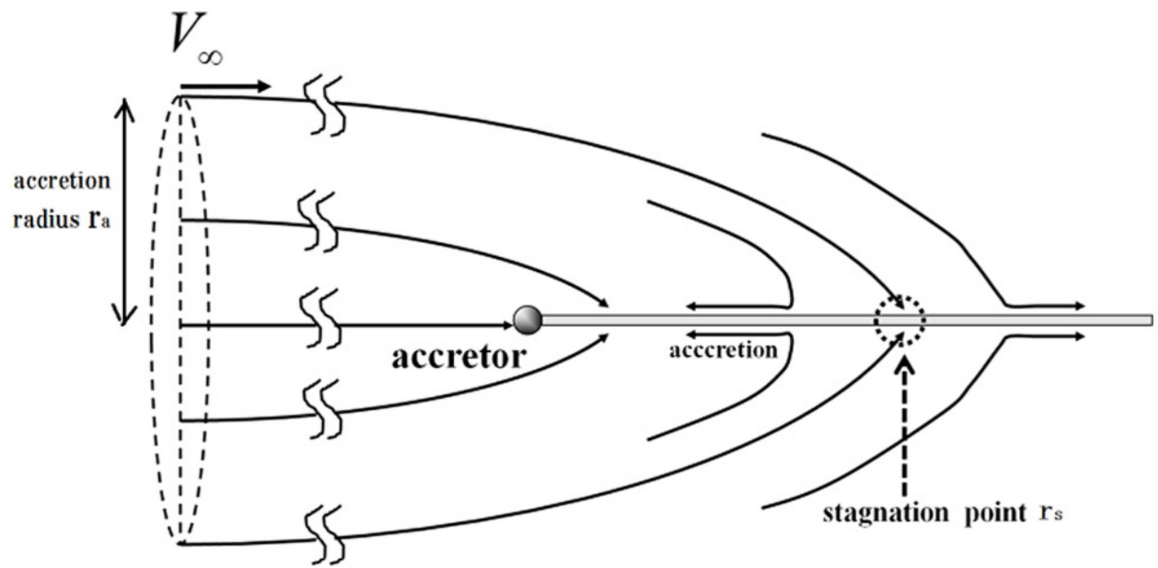


Required **accretion rate** :
10^{-8} – 10^{-7} M_{Sun} / year

Measured **mass-loss rate** :
~ 10^{-7} M_{Sun} / year

Bondi – Hoyle – Lyttleton accretion

- a point star moving through a gas cloud (uniform and free of self-gravity)
- material focused by gravity behind the star and accreted

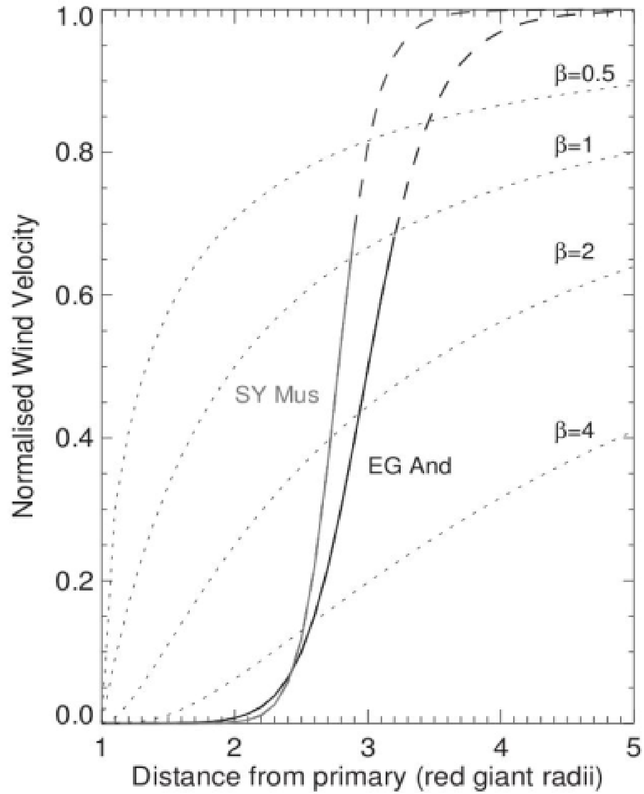


Ohsugi 2018

- binary stars: **mass accretion rate ~ few % of the mass loss rate**

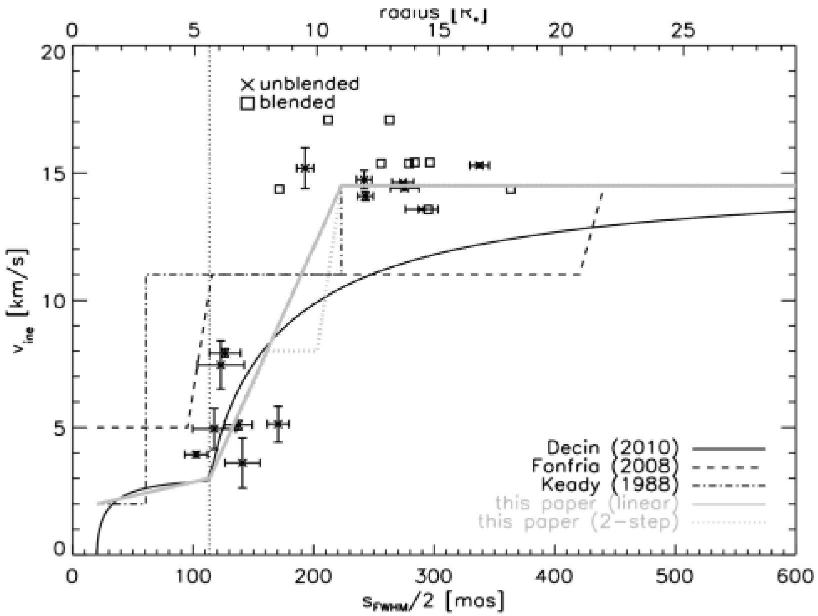
Mechanism of the mass loss from cool companions

- canonical β-*law* $v(r) = v_\infty \left(1 - \frac{R}{r}\right)^\beta$



Crowley & Espey 2010, ASP Conf. Ser. 425, 191

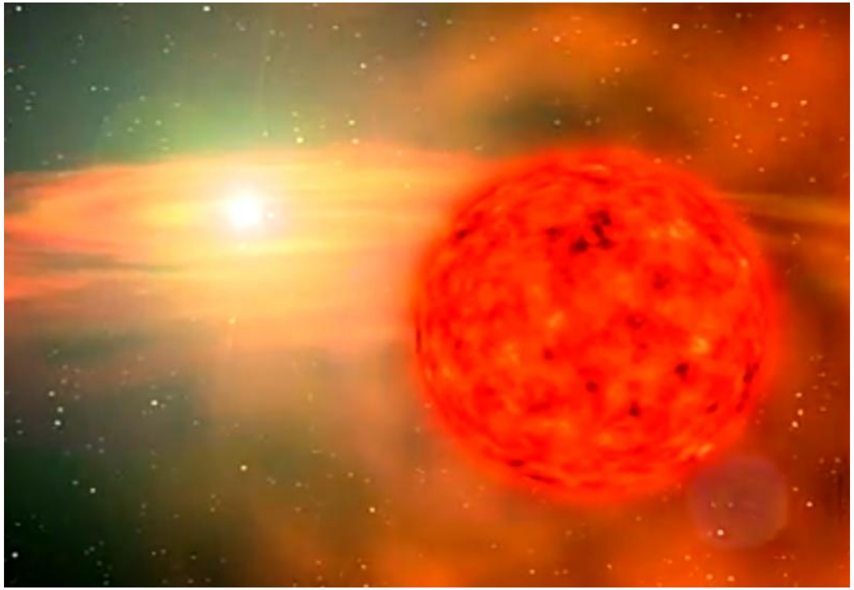
- *steeper v(r) for cooler stars*



Decin et al. 2015, *A&A* 574, A5

EG Andromedae

- quiet symbiotic star (no recorded outburst)
- white dwarf (WD) + red giant (RG)
- P = 483 days, i ≈ 80°
- RG: $R = 75 \pm 10\ R_{Sun}$, $L \approx (1 - 2) \times 10^{3}\ L_{Sun}$
- mass transfer via stellar wind
- RG wind terminal velocity of ~ 30 km/s

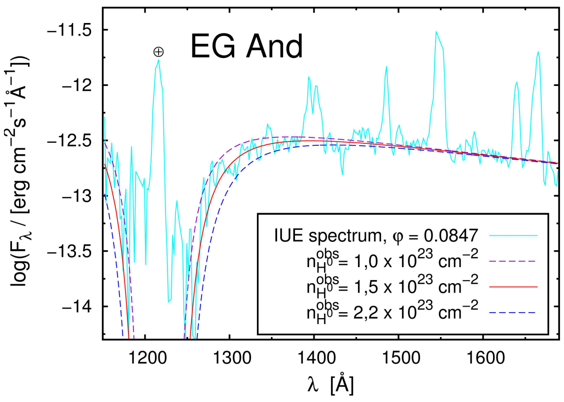


- many absorption lines of molecules and atoms originating in the cool giant's wind

H^0 column densities from Rayleigh scattering

- for **EG And** and **SY Mus**
- *IUE* and *HST* spectra

  + adopted values from literature



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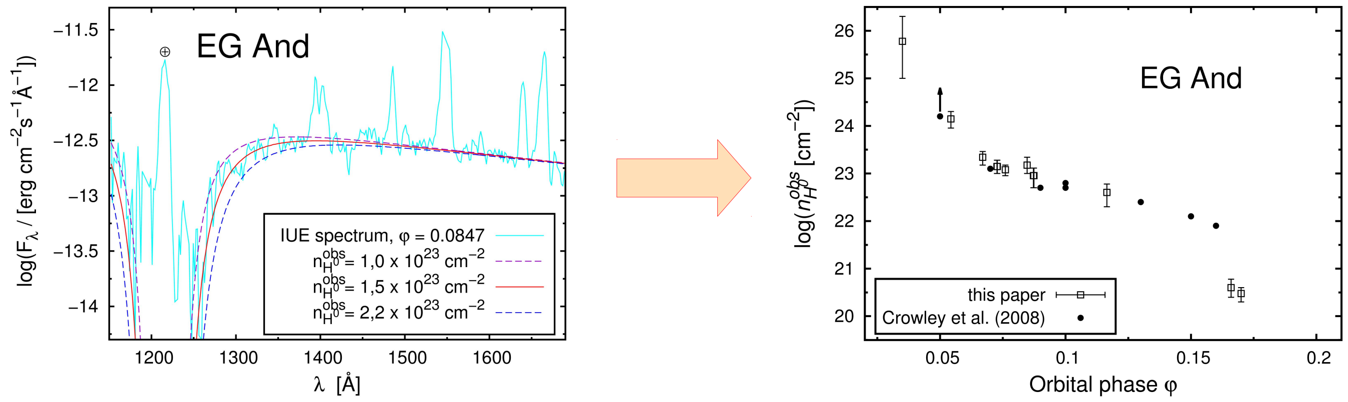

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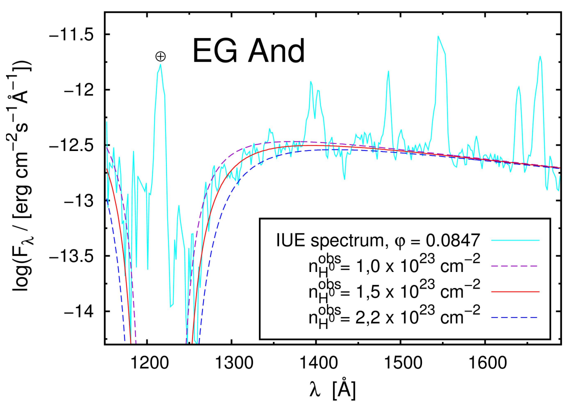

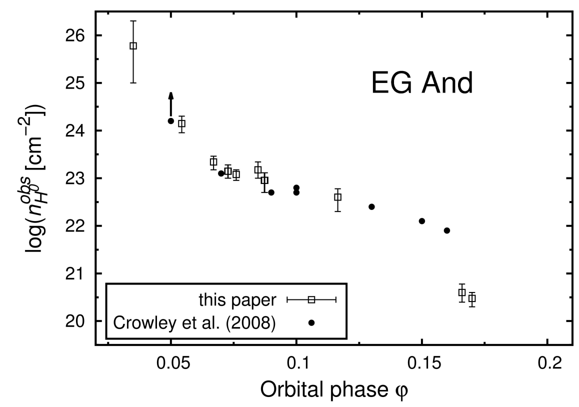

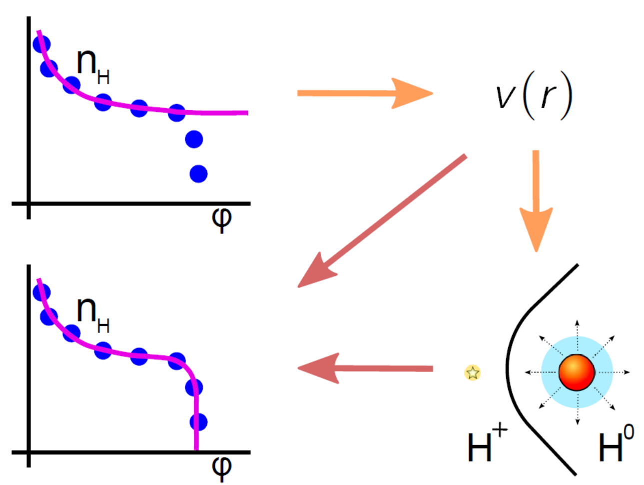

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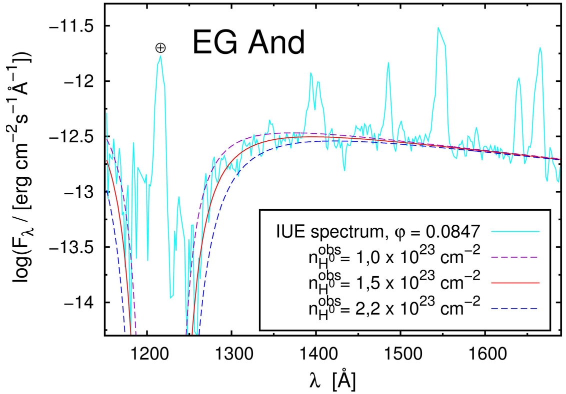
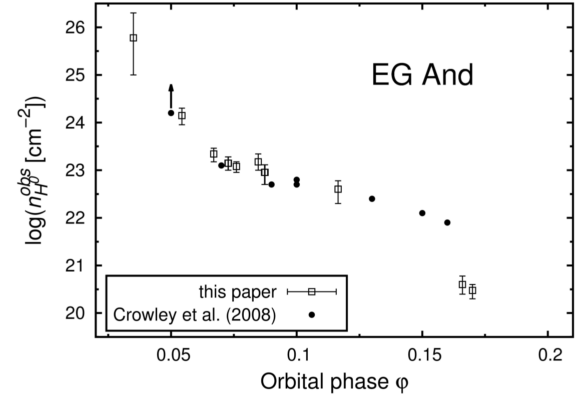
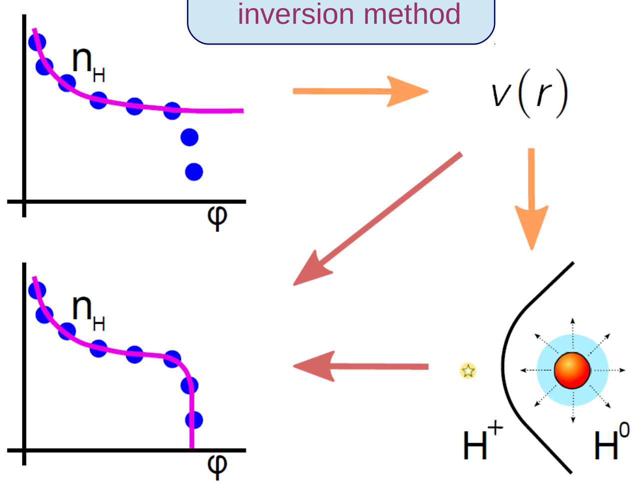




Knill et al. (1993)
A&A 274, 1002
inversion method



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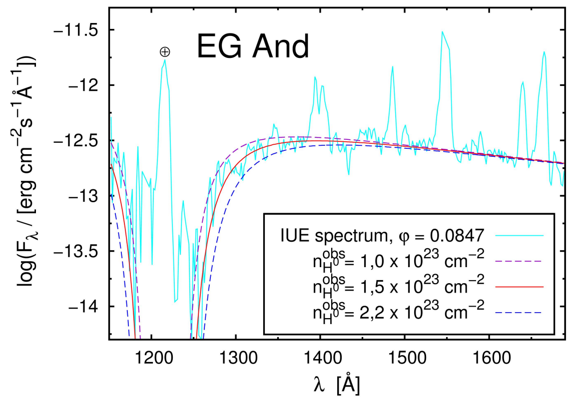
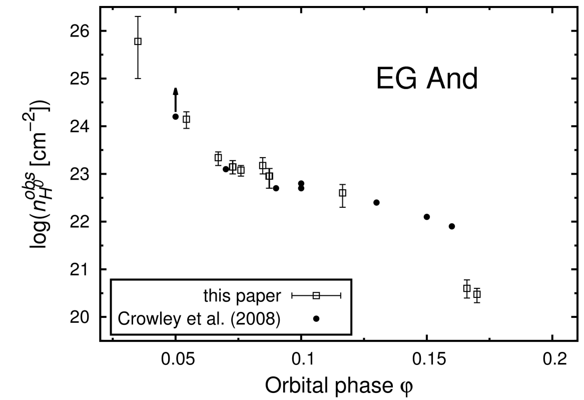
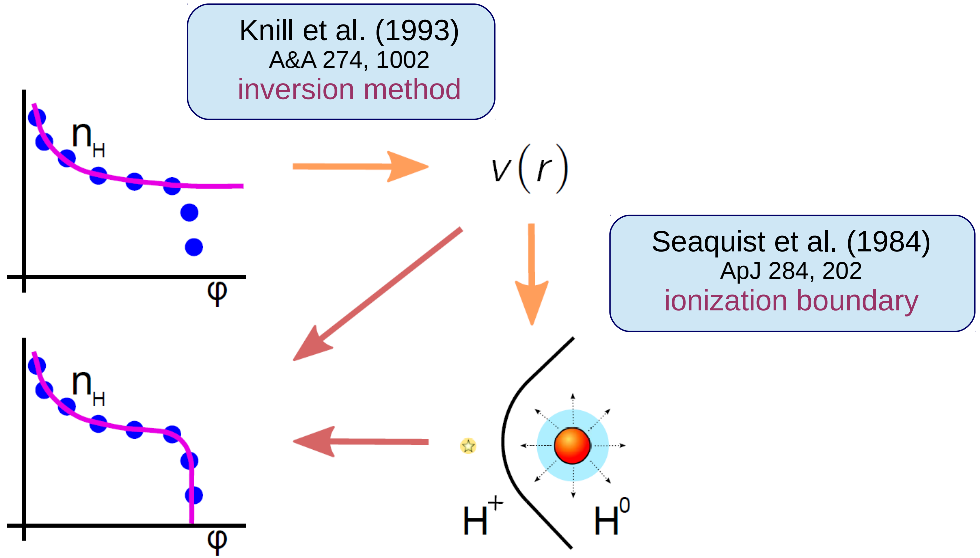
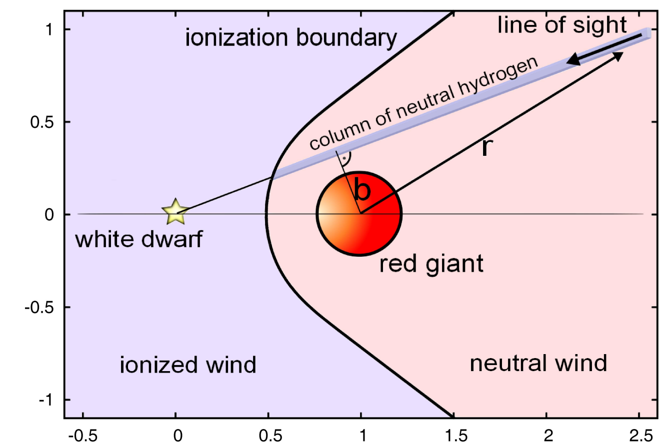


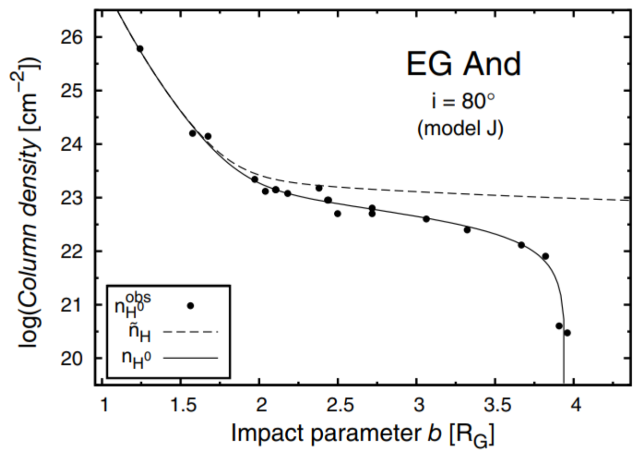


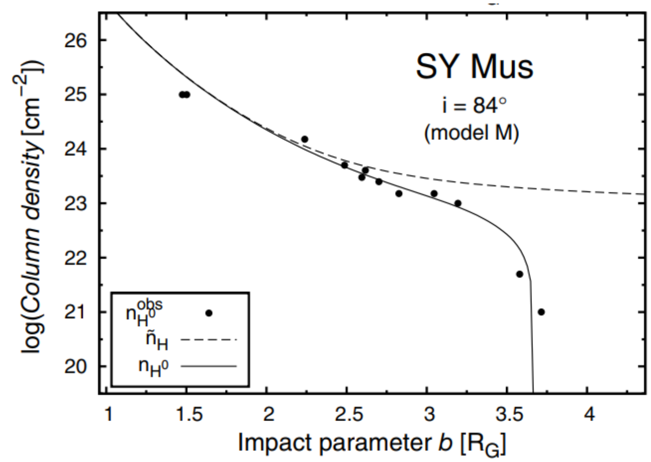


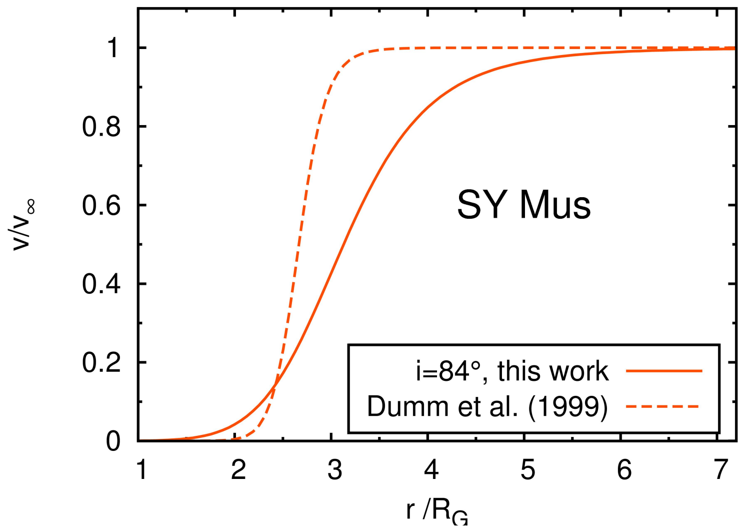
- including **ionization** of the wind



Velocity profile







- simple analytic formula:

$$v(r) = \frac{v_\infty}{1 + \xi r^{1-K}},$$

Wind enhancement in the orbital-plane area

Object	i	$\dot{M}_{sp}$ [$M_\odot$ yr^{-1}]	model
EG And	70°	1.06×10^{-6}	I
	80°	9.00×10^{-7}	J
	90°	7.91×10^{-7}	K
SY Mus	80°	2.13×10^{-6}	L
	84°	1.65×10^{-6}	M
	90°	1.62×10^{-6}	N
	84°	6.51×10^{-7}	O

Shagatova et al. 2016, A&A 588, A83

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Mass-loss rate for giants in S-type symbiotic systems from line-of-sight independent methods ≈ **10^{-7}** $M_\odot$/year

Seaquist et al. 1993, ApJ 410, 260
Mikołajewska et al. 2002, Adv. Space Res. 30, 2045
Skopal 2005, A&A 440, 995

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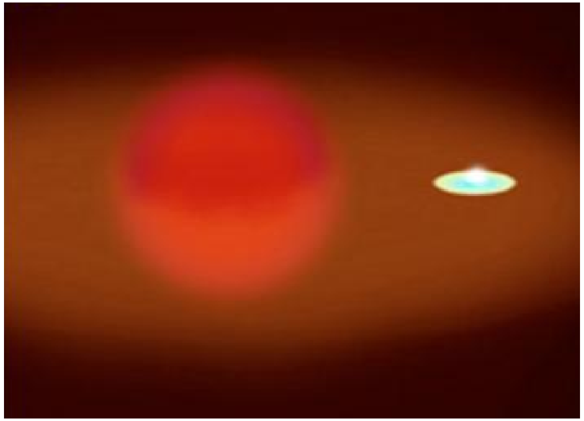
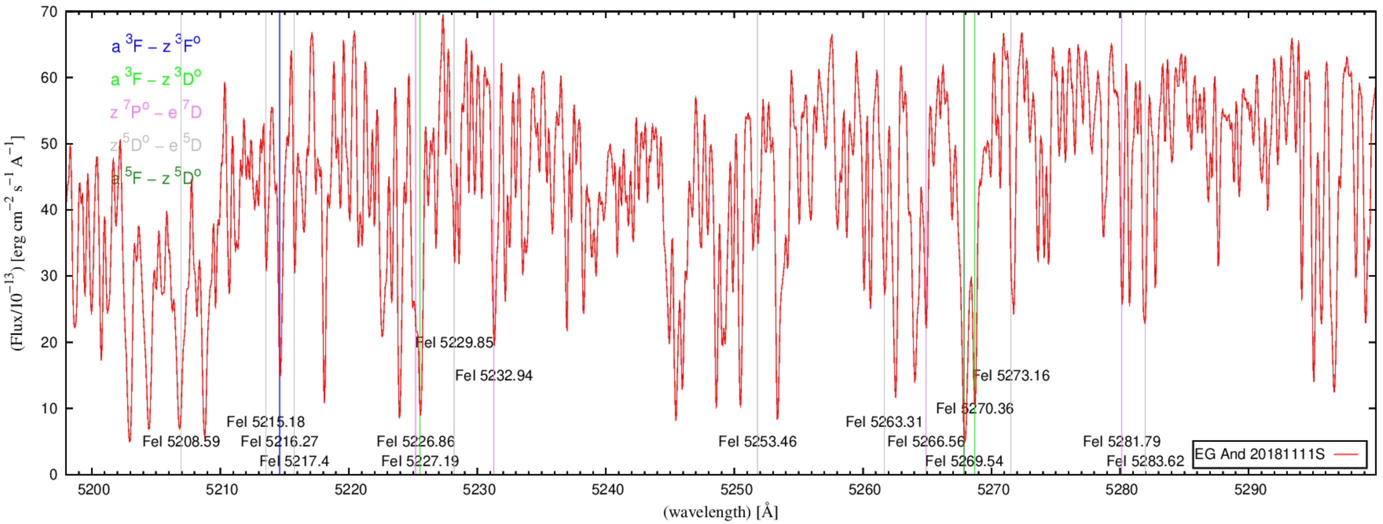


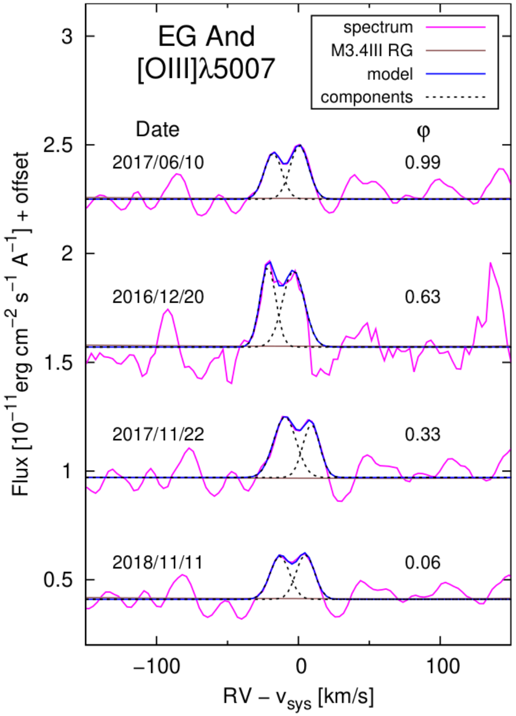
Inconsistent with spherically symmetric wind.

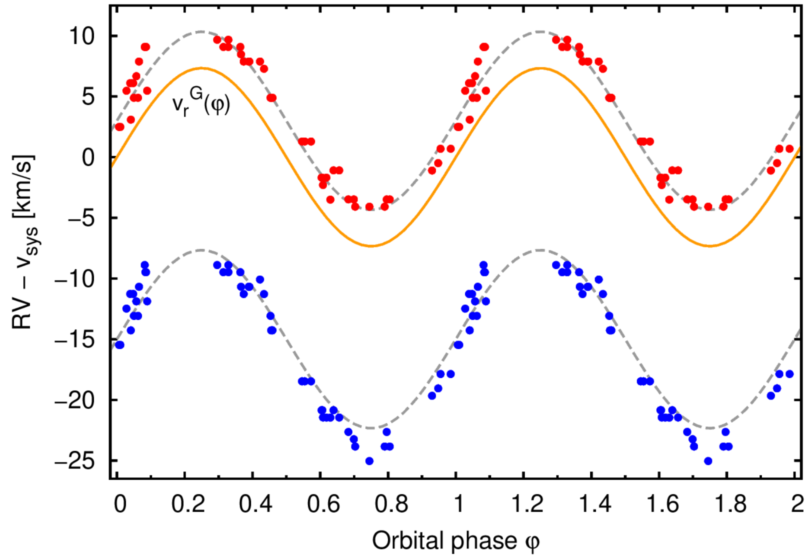
Spectral analysis in the optical - observations

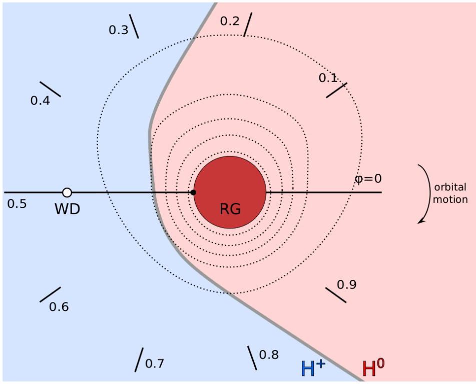
- optical spectra from years 2016 - 2023
- 1.3m telescope at Skalnaté Pleso, R = 30000, λ = 4200 – 7300 Å
- $UBVR_C$ photometry for flux calibration (Sekeráš et al. 2019, G2, AAVSO)
- typical systematic error of radial velocity 0,2 – 0,6 km/s



Location of [OIII] λ5007 line regions







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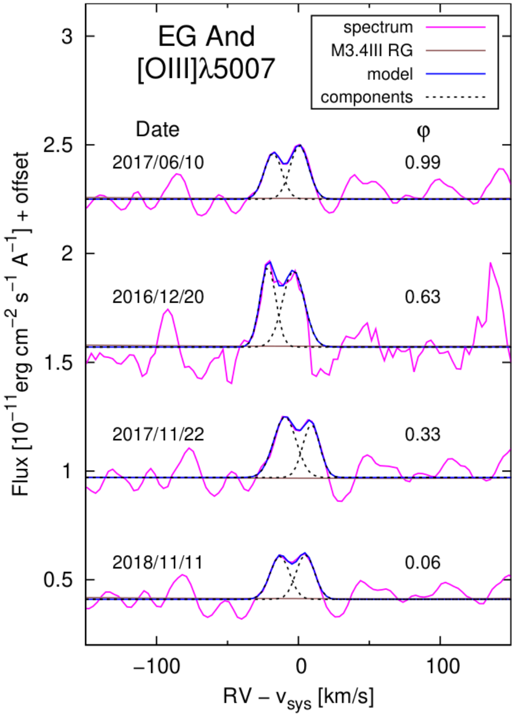
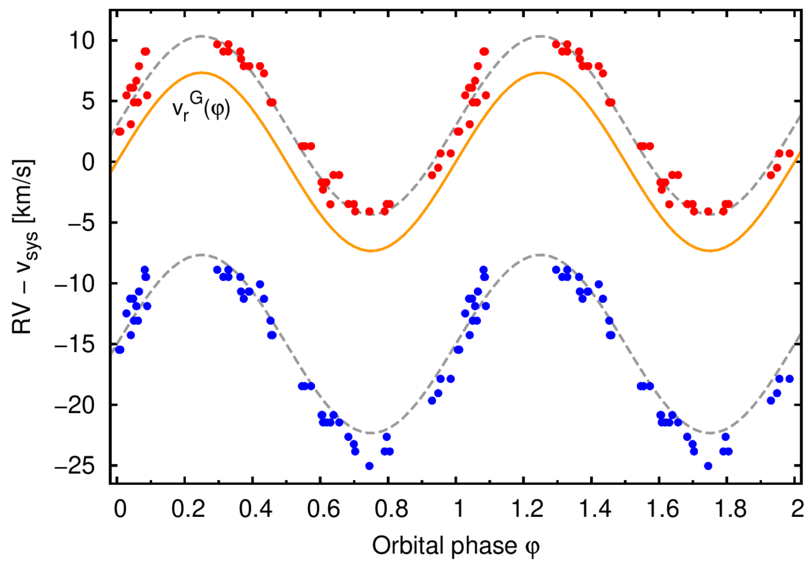
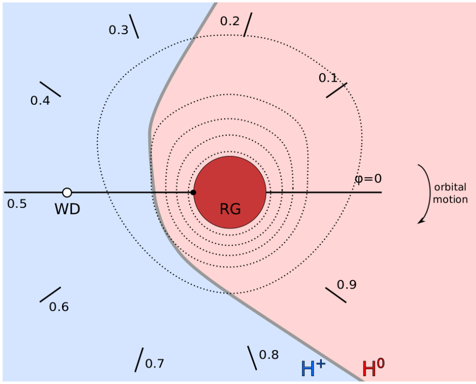
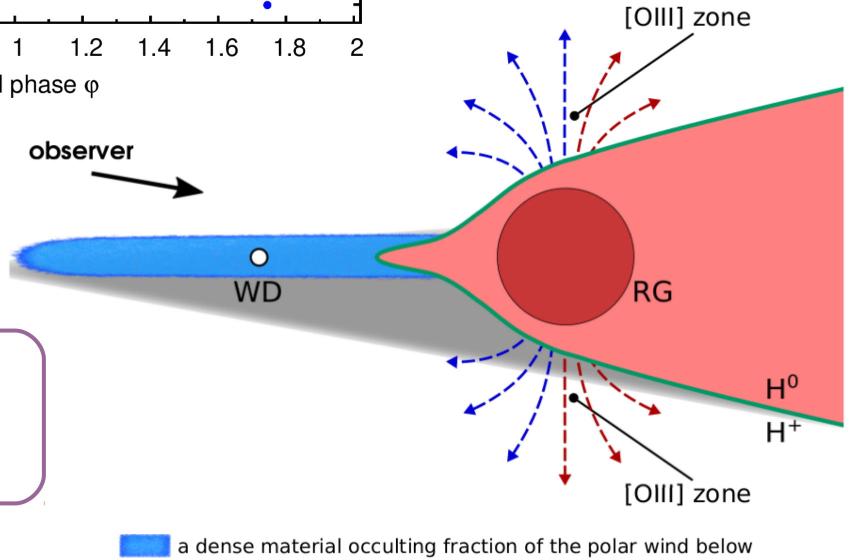








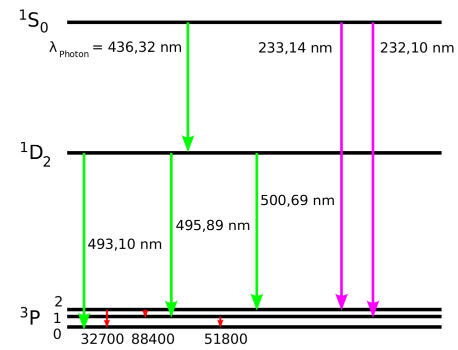
--> ionized regions close to the red giant

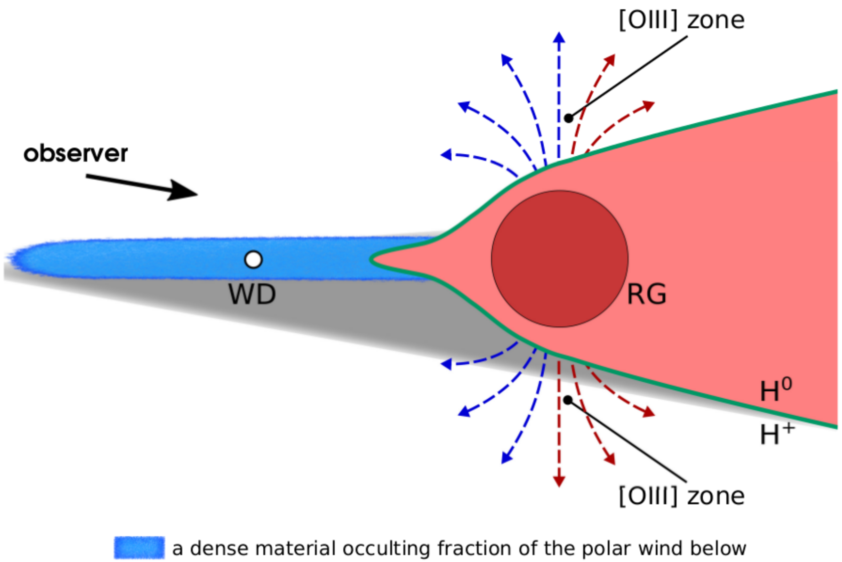
Density in the [OIII] λ5007 line regions

- [OIII] nebular lines are **weakened at higher densities** due to the presence of free electrons

- they originate in regions with **n_e ~ 3 x 10^7 cm^{-3}**, with upper limit of ~ 7 x 10^7 cm^{-3}
  (AX Per, Skopal et al. 2001)

- the limiting mass-loss rate: **~ 10^{-8} M_{Sun} / year** for the density ~ 10^7 cm^{-3} in the vicinity of red giant (1-2 R_g from its surface)





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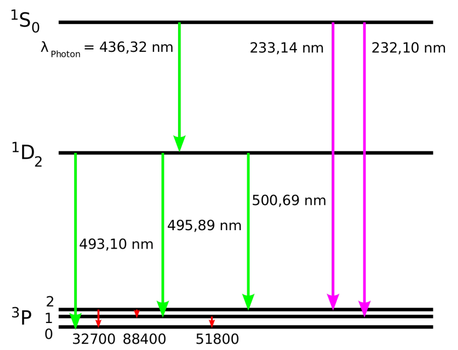

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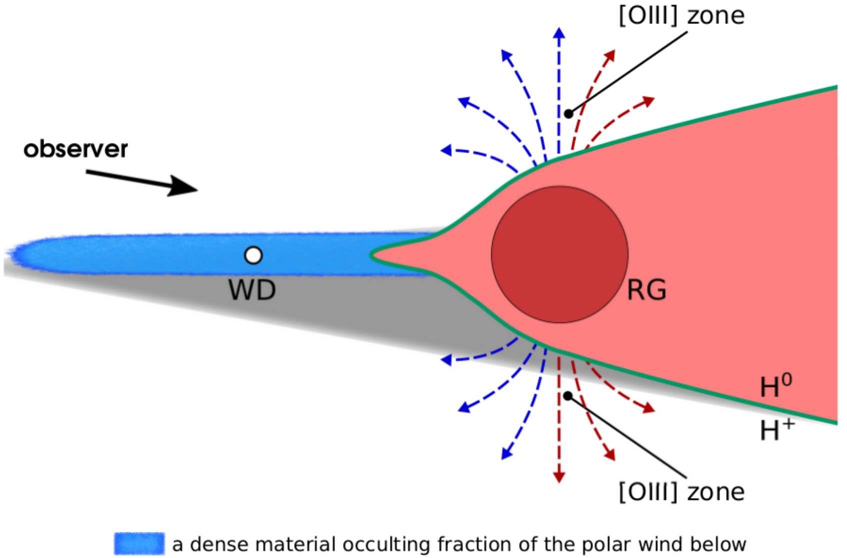
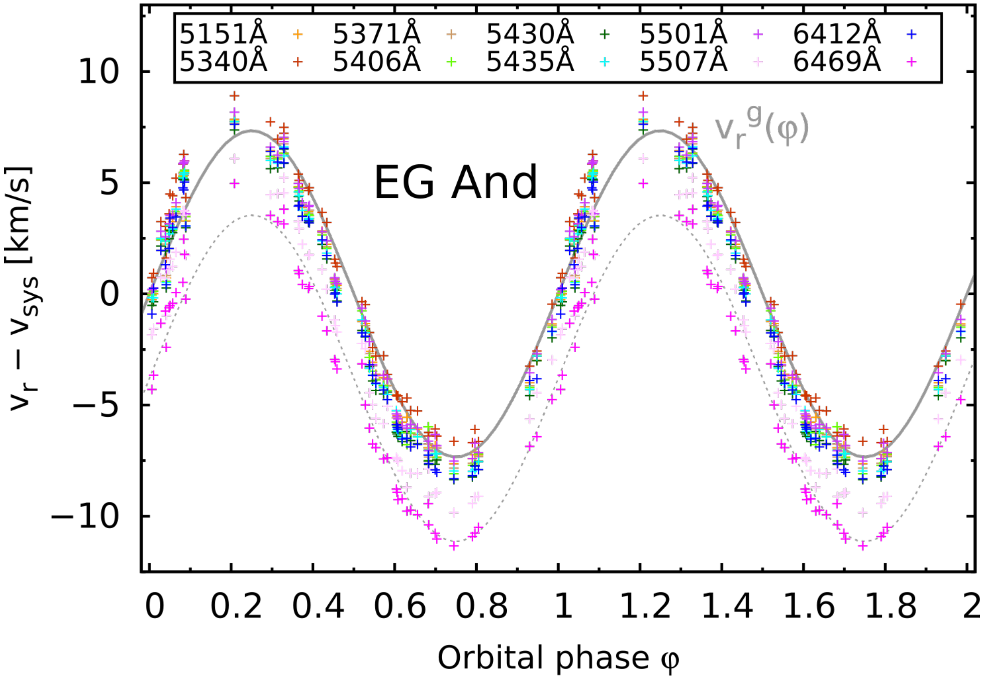
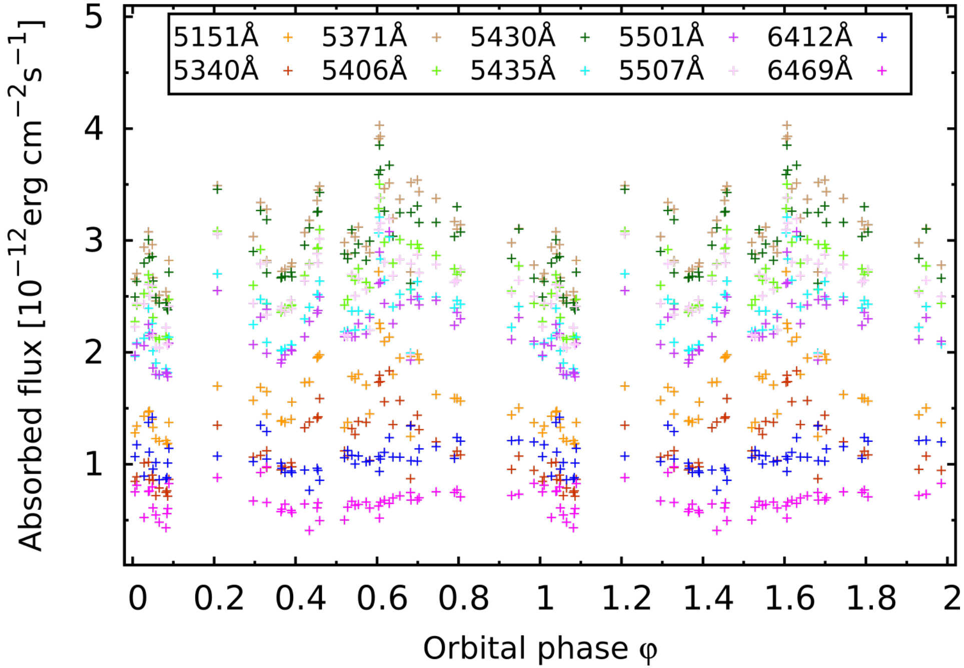


--→ **diluted wind** close to the **red giant poles**

Orbital variability of the Fe I absorption lines





- **slow outflow** up to -5 km/s
- **inflow** values around φ = 0.1

- absorbed fluxes: maxima at φ ~ **0.6**

--> asymmetry of the circumstellar matter distribution

$v_r^G(\varphi)$ – radial velocity of the red giant

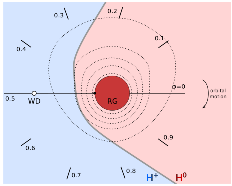
v_{sys} = -94.88 kms^{-1} (Kenyon & Garcia 2016)

- Gaussian fits using Fityk (Wojdyr 2010)

Model atmosphere

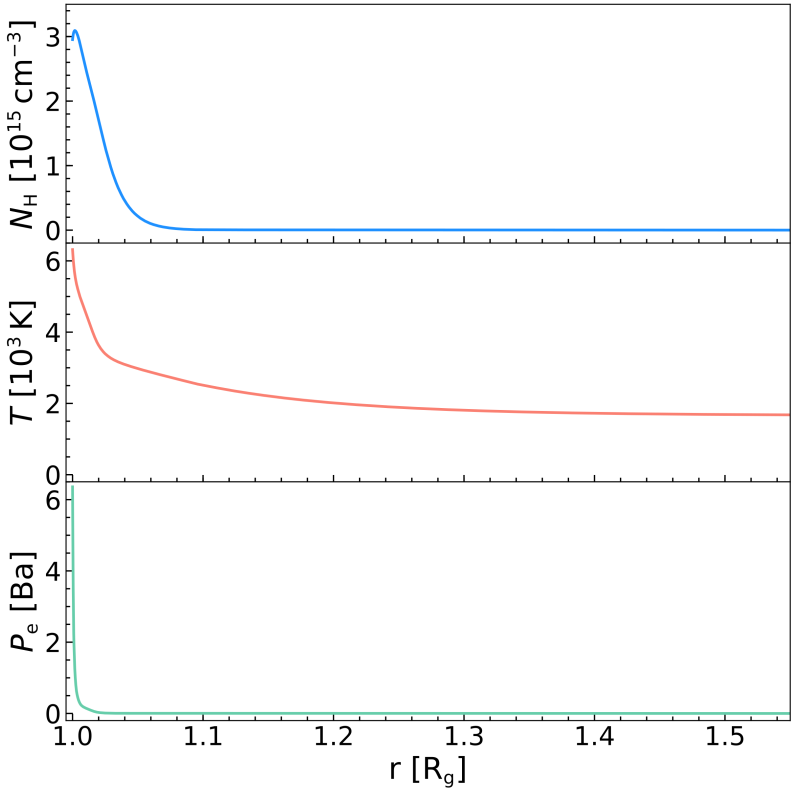
- to model spectral profiles:
  - 10 Fe I absorption lines (5151 – 6469 Å)
  - 10 orbital phases

- MARCS model (1 – 1.1 R_g):



  - Gustafsson et al. 2008
  - spherical geometry, T_{eff} = 3700 K, M = 1.0 M_{Sun}, [Fe/H] = 0

- simplified extension (1.1 – 150 R_g):
  - N_H and T at 150 R_g estimated from hydrodynamical simulation of M-giant wind (Wood et al. 2016)
  - asymmetric conical shape of the neutral zone taken into account



$$N_H(r) = \frac{n_1}{2\lambda_1 R_g} \frac{1 + \xi r^{1-K}}{r^2}$$

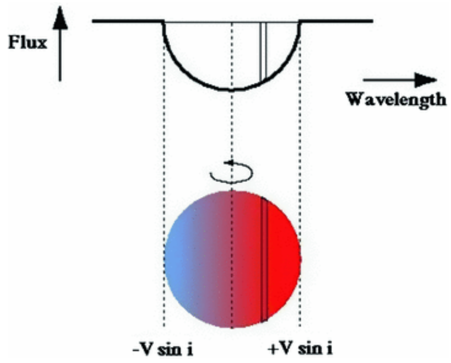
r [R_g]	1 - 1.1	1.1 - 150	150
N_H	MARCS	interpolation by function from Shagatova et al. (2016) [a]	10^4 cm^{-3} (Wood et al. 2016)
T	MARCS	interpolation by exponential + linear function	30 K (Wood et al. 2016)
P_e	MARCS	interpolation by exponential function	10^{-17} dyne/cm^2 (dense ISM clouds) [b]

Line profile of Fe I absorption lines

- atmosphere layer / **distance from center** and **radial velocity** as free parameters
- <u>several broadening mechanisms included</u>:

- natural, pressure, thermal and microturbulence
- Gray 2005, Halenka & Madej (2002), NIST and VALD databases
- **pressure** broadening was treated as originating **from the collisions with neutral hydrogen**

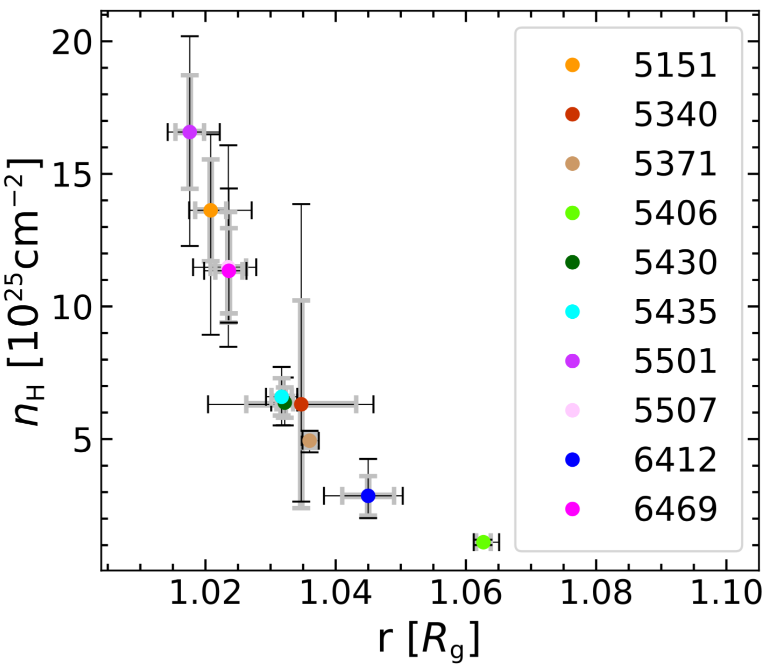
- rotational
- $\boldsymbol{v_{rot}}$**sin(i)** as a free parameter
- Python function *rotBroad* (PyAstronomy.pyasl library)

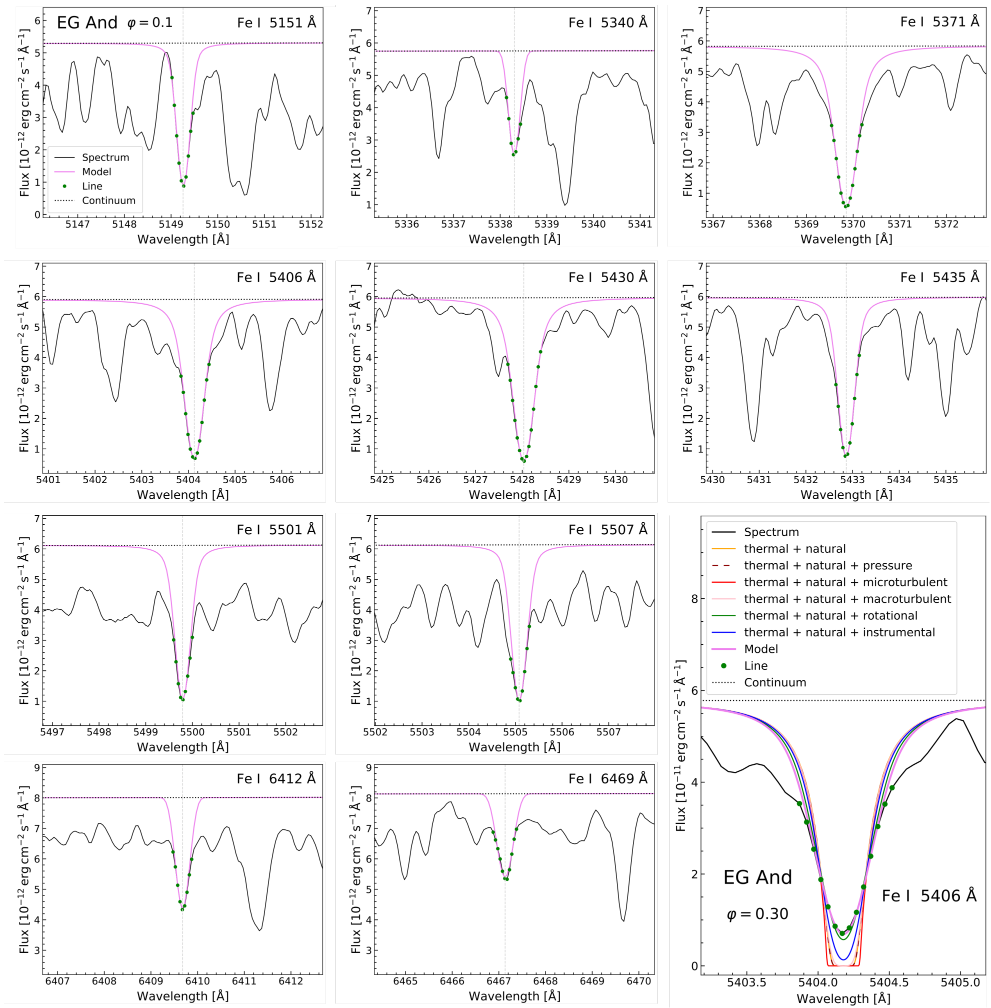


- macroturbulence
- typical value for RGs is v_{mac} = 3 km/s
- to obtain lower and upper limits of v_{rot}sin(i) – two isotropic Gaussian macroturbulence models with $\boldsymbol{v_{mac}}$ **= 0 and 3 km/s**

- instrumental
- *broadGaussFast* function (PyAstronomy.pyasl library)
- at 5151 – 6469 Å, the spectral resolution of our spectra goes from ≈ 39100 to 24000

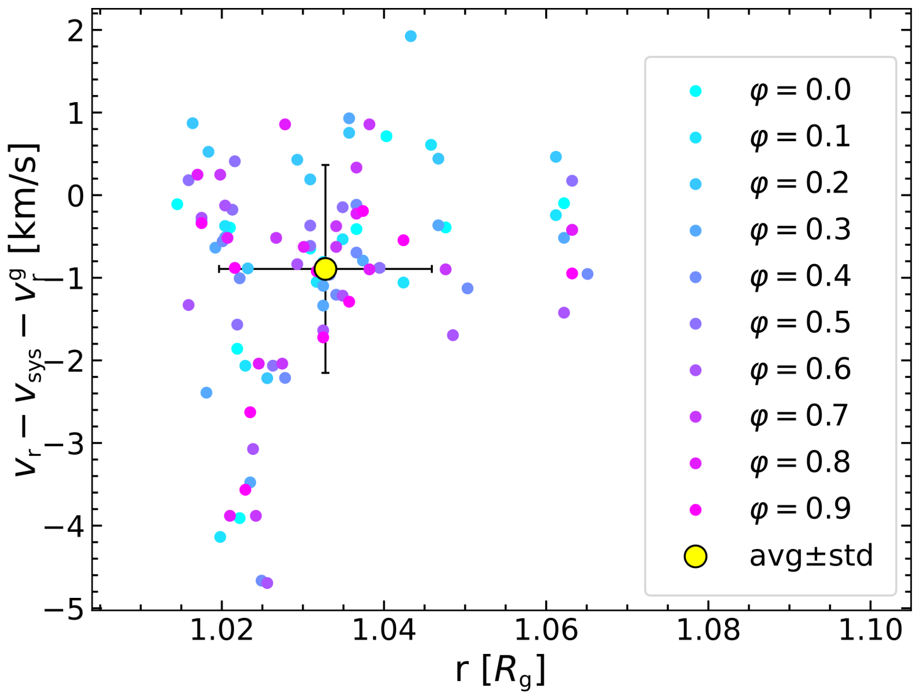
Height in the atmosphere

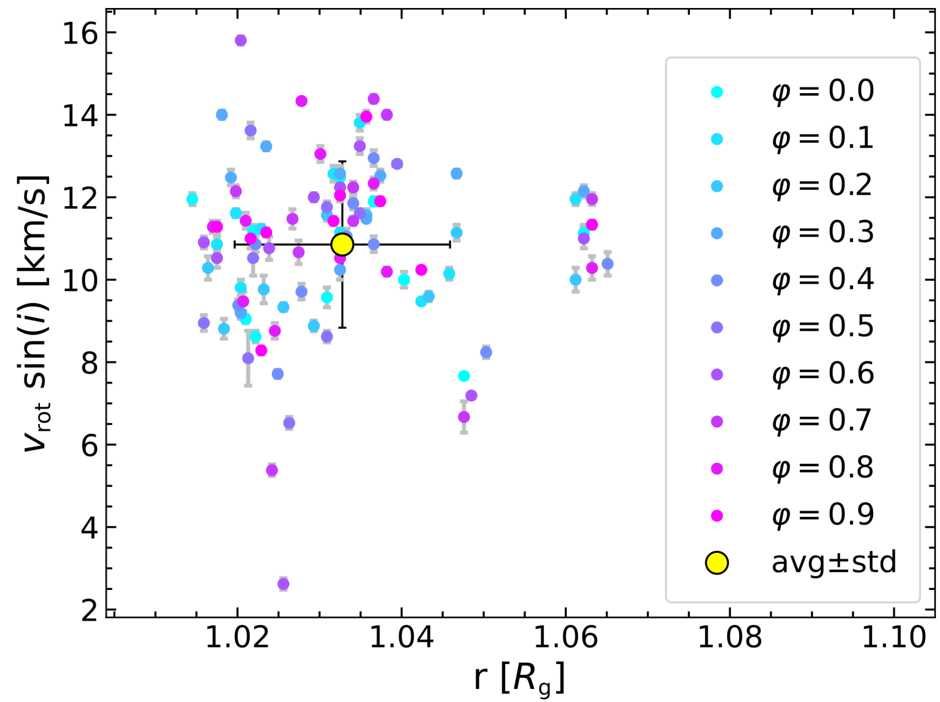




- **r** = deepest layer of origin of the spectral line
- heights within **≈ 0.02 to ≈ 0.06 R_g** above the RG photosphere

Radial and rotational velocities





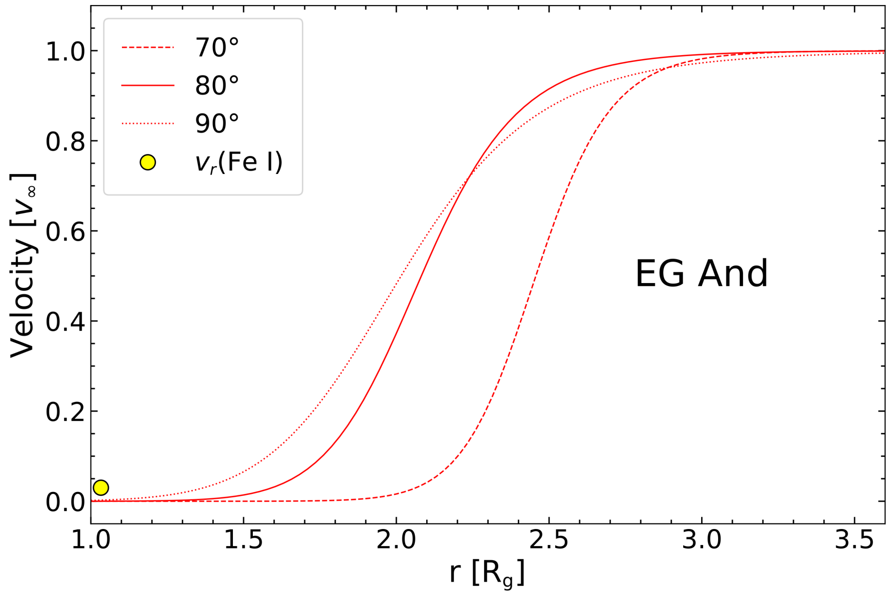
- total averages ± std: v_r = - 0.9 ± 1.3 km/s

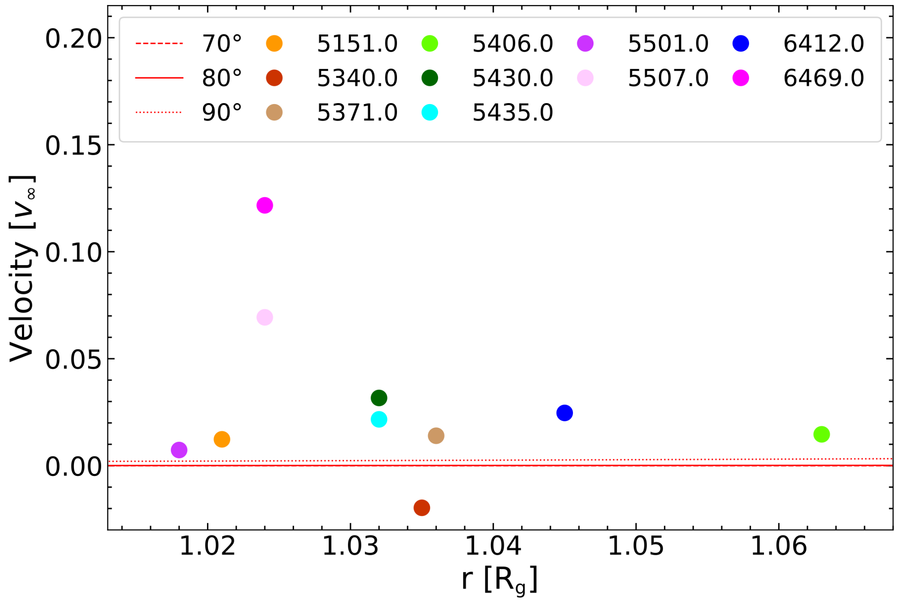
  at r = 1.03 ± 0.01 R_g

  v_{rot}sin(i) = 10.9 ± 2.0 km/s

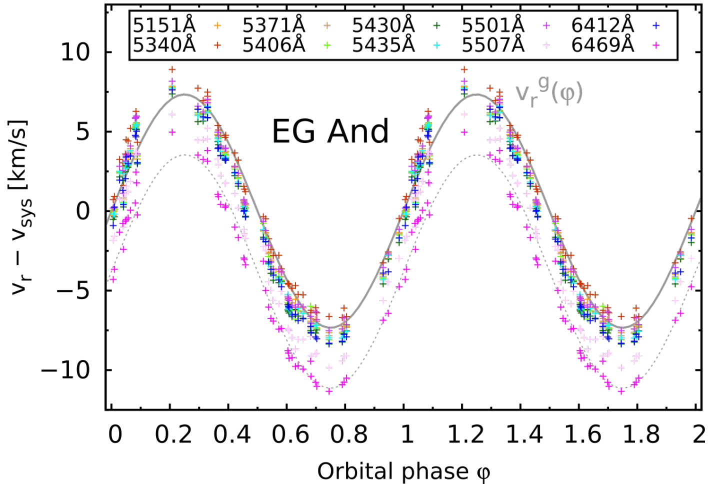
Comparison with velocity profiles

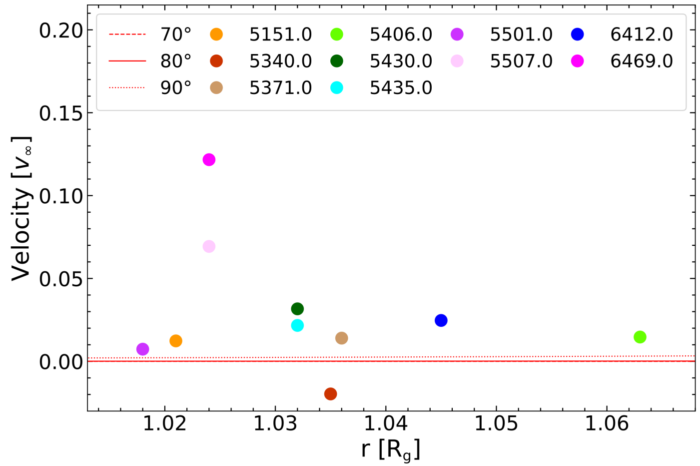
derived from measured near-orbital H^0 column densities

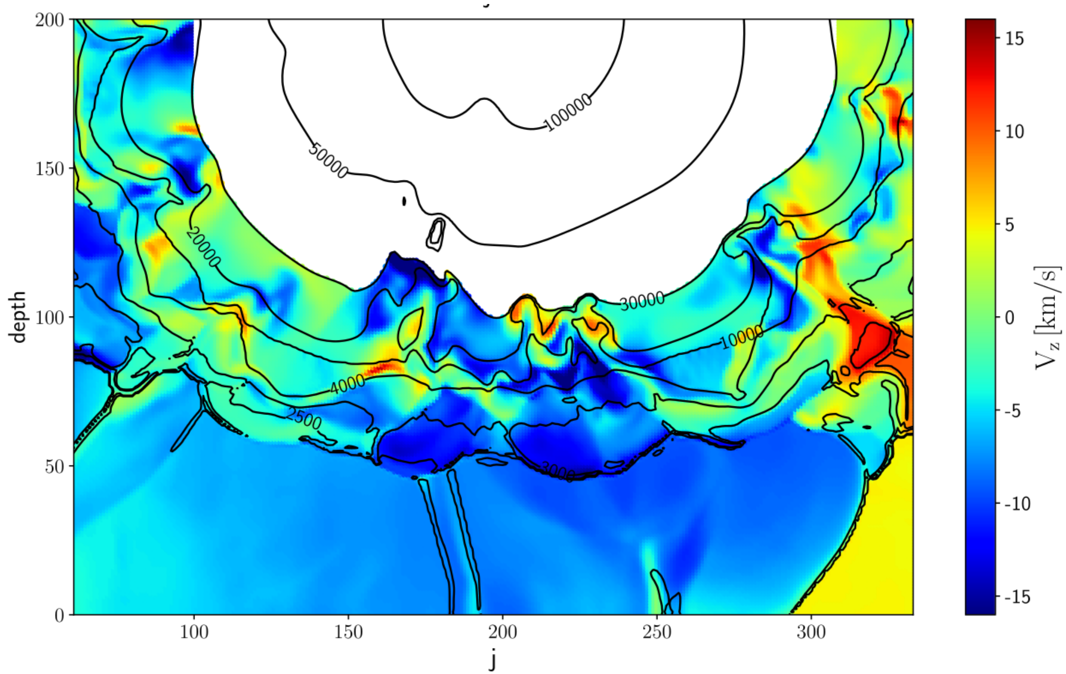




Implications from measured radial velocities

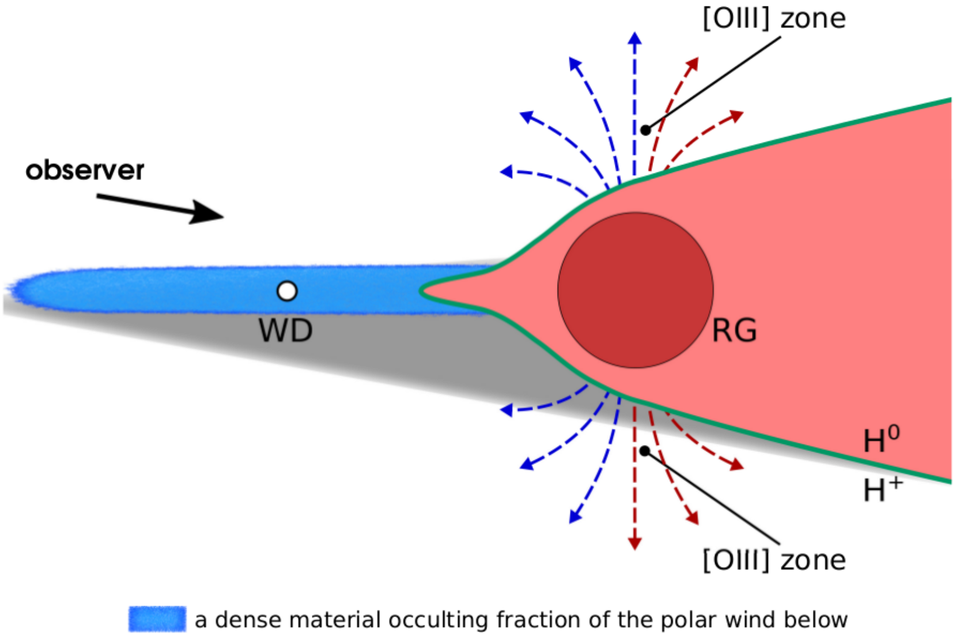






Kravchenko et al. 2018, A&A 610, A29

Implications for wind focusing towards the orbital plane



Seaquist et al. 1993; Shagatova et al. 2016, 2021

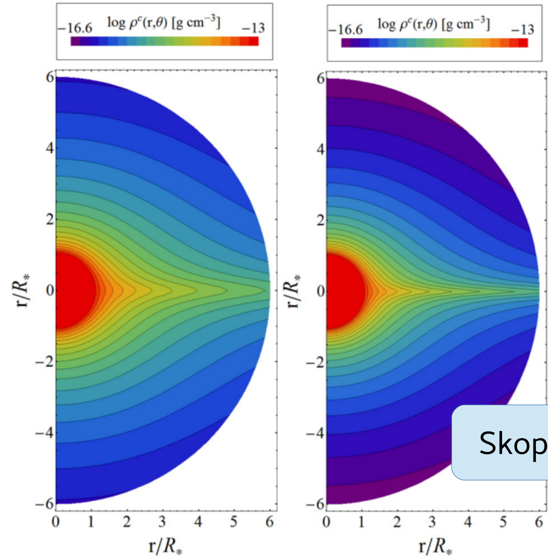
- **focusing by rotation**

- for i = 80° ± 10° :

v_{rot} = **11.1** $_{-2.2/+2.6}$ km/s

Shagatova et al. 2023

S-type systems



Skopal & Cariková 2015

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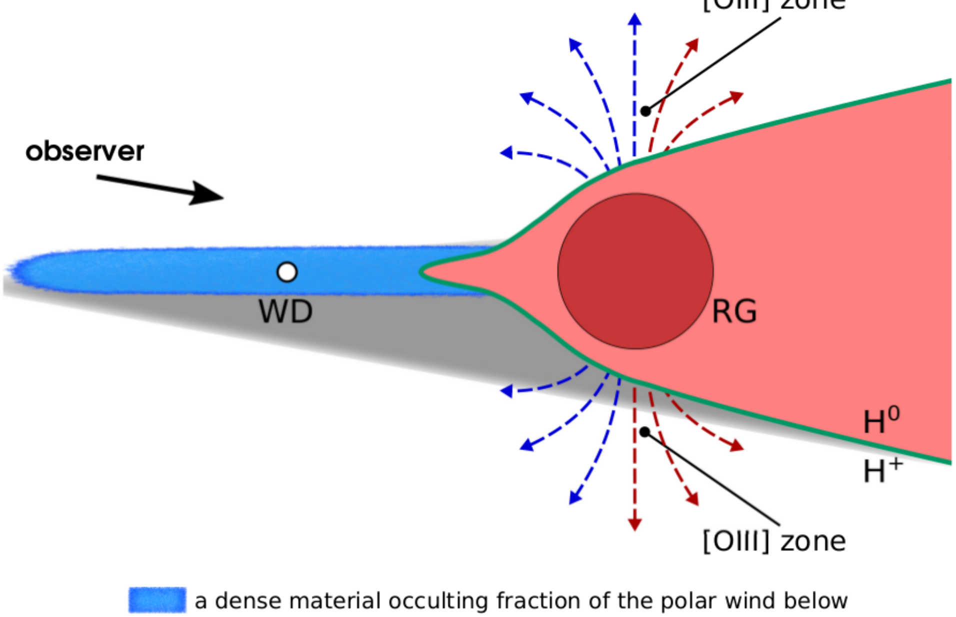
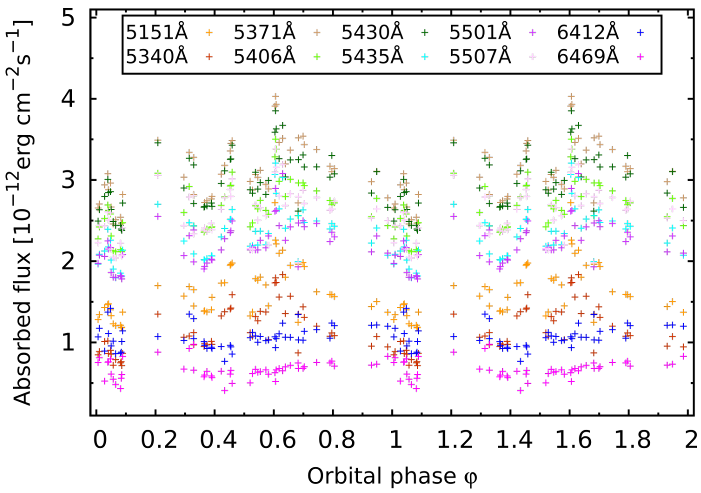
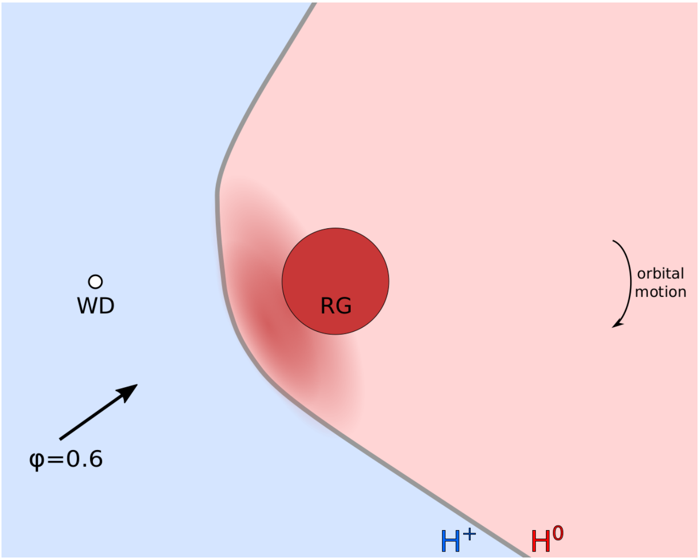
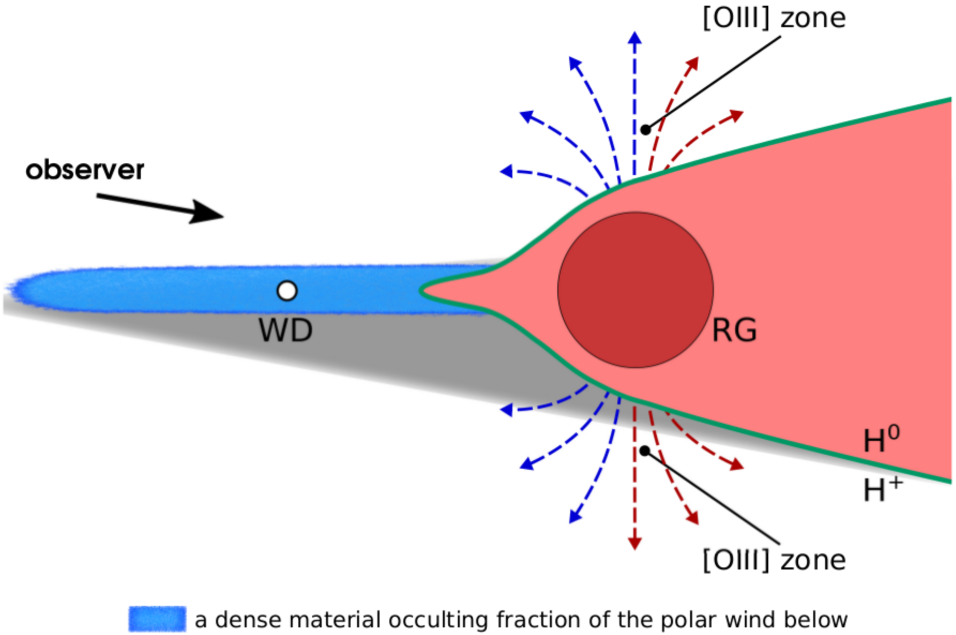


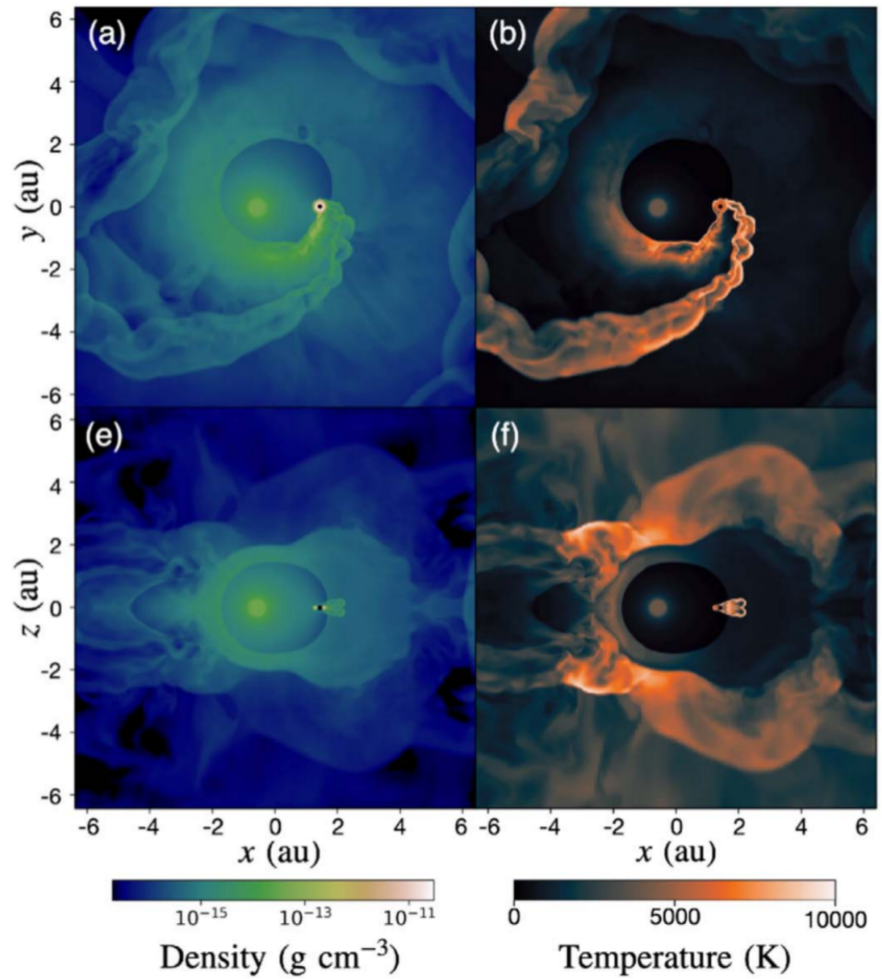




- **gravitational focusing**

Implications for wind focusing towards the orbital plane





- **gravitational focusing**

Lee et al. 2022, ApJ 931, 142

Conclusions

Wind focusing in S-type symbiotic stars

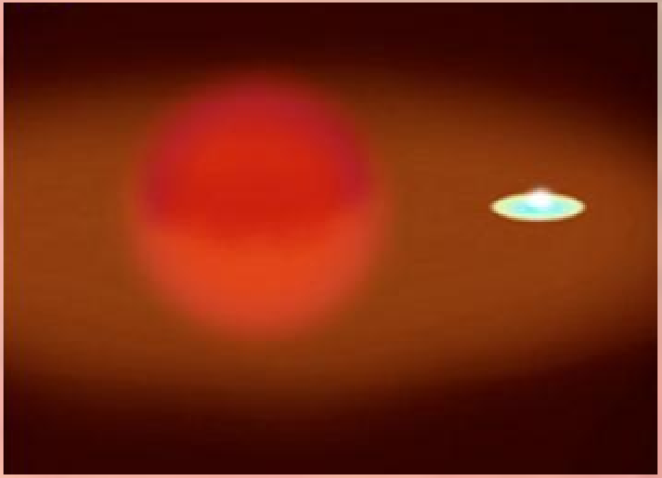
- mass-loss rate from the nebular emission **(independent of the line of sight)**:

  ~ 10^{-7} M_{Sun} / year

- mass-loss rate from the densities near **orbital plane**:

  ~ 10^{-6} M_{Sun} / year

  ---> **enhancement** of the wind



- mass-loss rate from the densities near **RG poles**:

  ~ 10^{-8} M_{Sun} / year

  ---> **dilution** of the wind

- **mechanism** of the wind focusing towards the orbital plane:

  ---> support for both **rotationally and gravitationally induced focusing of the wind** as possible acting mechanism

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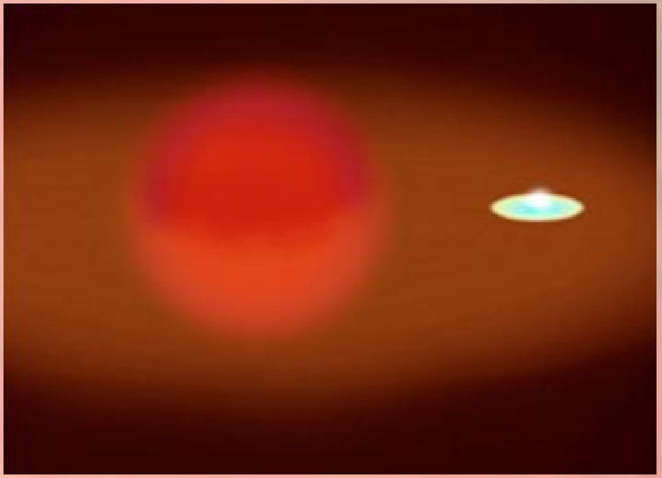

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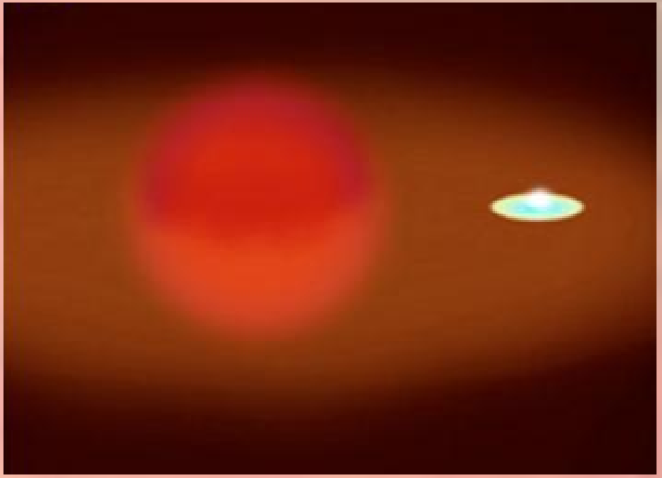

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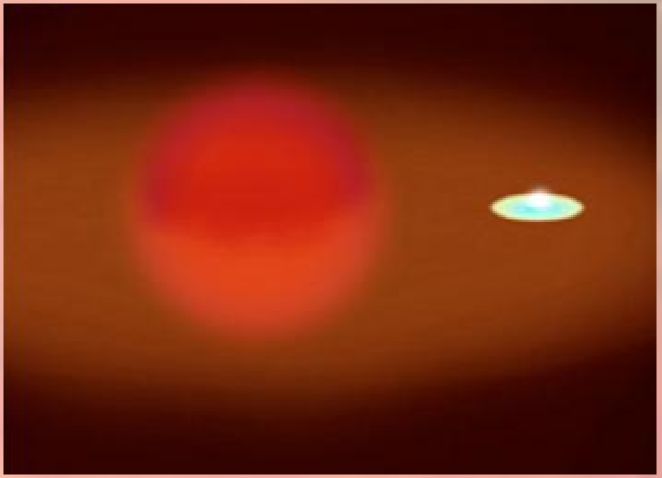

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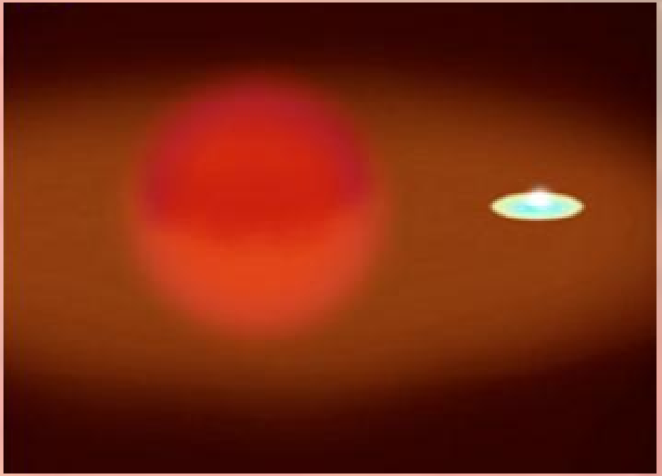

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Thank you for your attention!