Multiwavelength monitoring of the high-mass X-ray binary Cygnus X-1

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Astronomical Institute of the Czech Academy of Sciences

Credit ESA/NASA

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The target: Cygnus X-1

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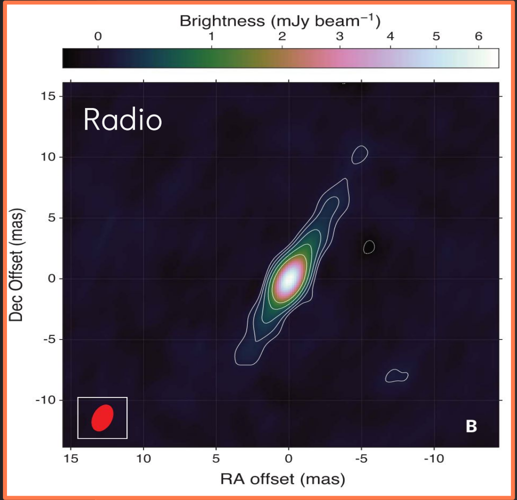
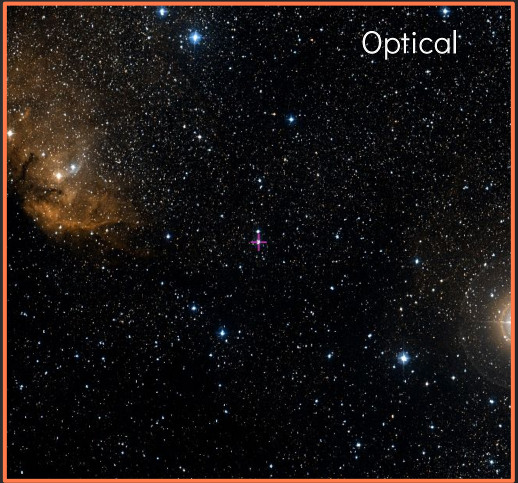
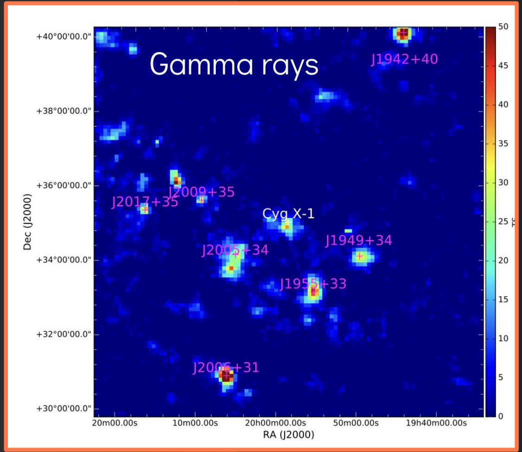





Chandra X-ray Observatory, NASA/CXC/SAO, August 27 2009



❑ High Mass X-ray Binary (HMXB)

$d = 2.22 \pm 0.18$ kpc

$P \simeq 5.6$d

$i = 27.51 \pm 0.7$ °

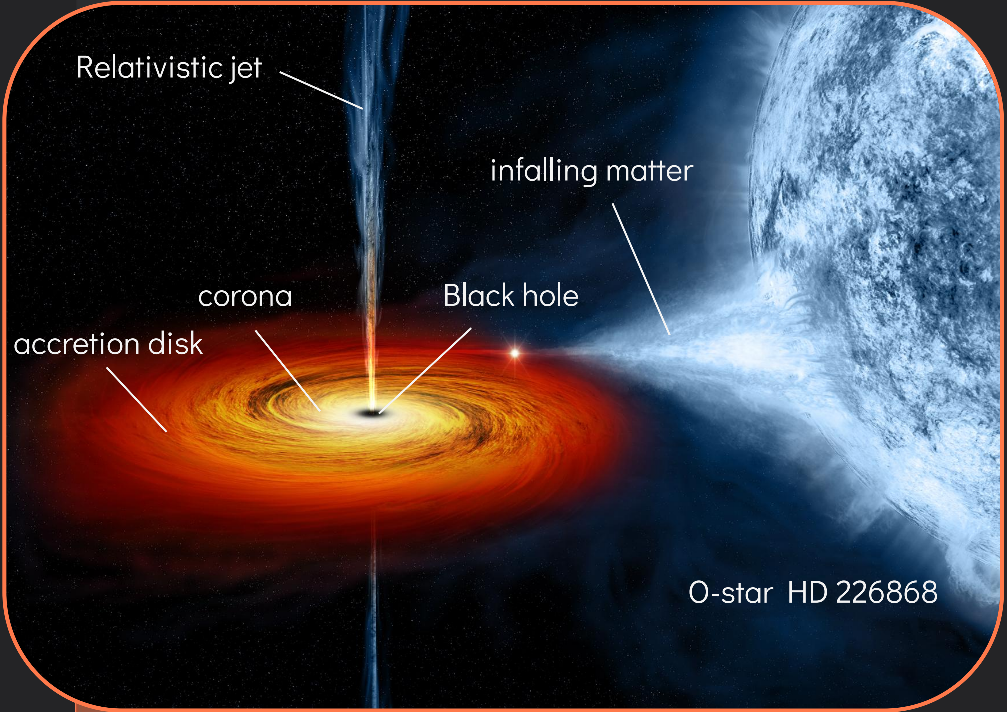
Star HDE 226868

- $M_S = 40.6 \pm 7.5\ M_\odot$
- $R_S = 22.3 \pm 1.8\ R_\odot$
- $T_{eff} = 31.1 \cdot 10^3 \pm 0.7$ K

Black hole

- $M_{BH} = 21.2 \pm 2.2\ M_\odot$
- $0.861 \leqslant a \leqslant 0.921$

H. Krawczynski et al. 2022
J. Čechura et al. 2015



Artist's impression of Cyg X-1:
Credit Chandra Observatory, NASA

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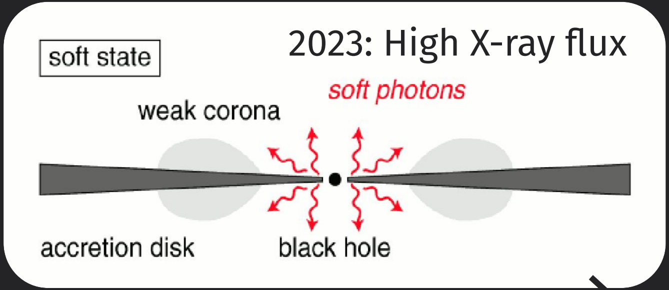
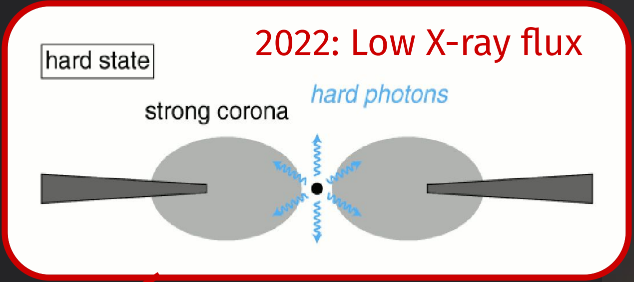
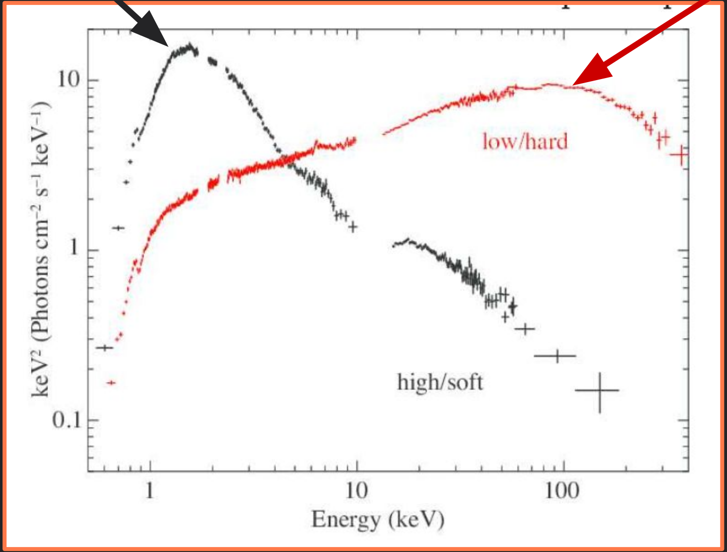
X-rays
Credit ESA/NASA

X-ray spectral states

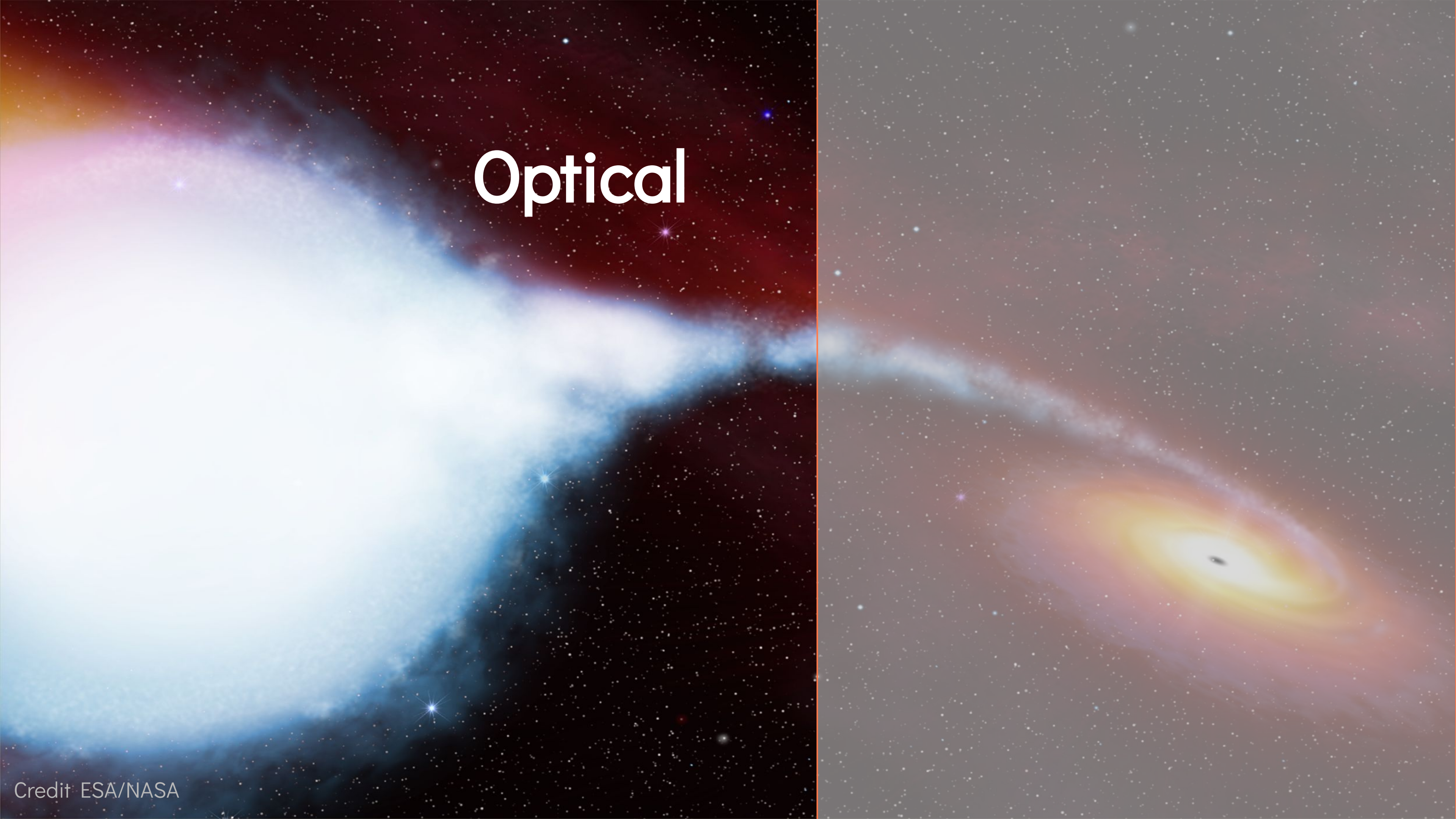


Meyer-Hofmeister et al. 2004





Yamada et al. 2013


Optical
Credit ESA/NASA

02

Observations

Observations

Credit: Zdeněk Bardon

1st run — March - July 2022

2nd run — March - July 2023
and 3 days in September 2023

67 spectra in total

Ondřejov, 2m Perek Telescope

Instrument	Total nb of spectra	Coverage	Order length	Resolution power in Hα region	Advantages
CCD700 (Single Order Spectrograph)	29	5100-8900Å 4000-5100Å	470Å 230Å	12000 24000	Wide range of wavelength
OES (Ondřejov Echelle Spectrograph)	38	3753-9195Å	70Å (in UV) 145Å (in IR)	40000	Resolution Spectral orders

La Palma, 1.2 m Mercator Telescope

Credit: Péter I. Pápics

1st run	October 2011
2nd run	October 2012
3rd run	August 2014
4th run	May - September 2019
5th run	July - September 2020

58 spectra in total

Instrument	Coverage	Resolution power in Hα region	Advantages
HERMES Echelle Spectrograph	3770-9000Å	85000	High resolution spectra

1 spectrum on the 28th of July 2023

Instrument	Coverage	Resolution power in Hα region	Advantages
FIES Echelle Spectrograph	3770-8300Å	67000	Radial velocity

Credit: Peter Laursen

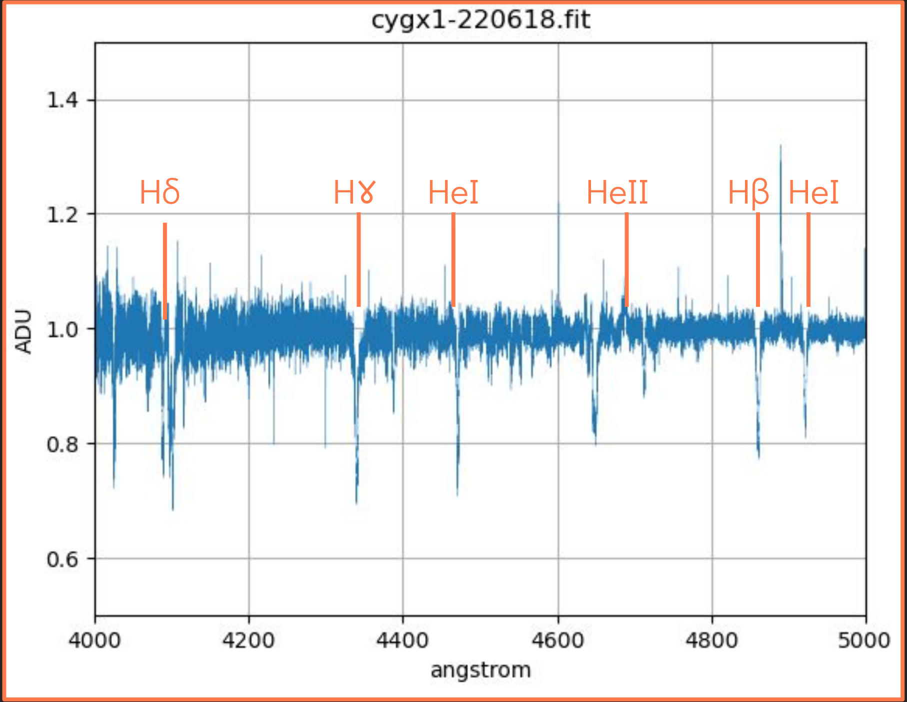
La Palma, 2.56 m Nordic Optical Telescope (NOT)

Spectra

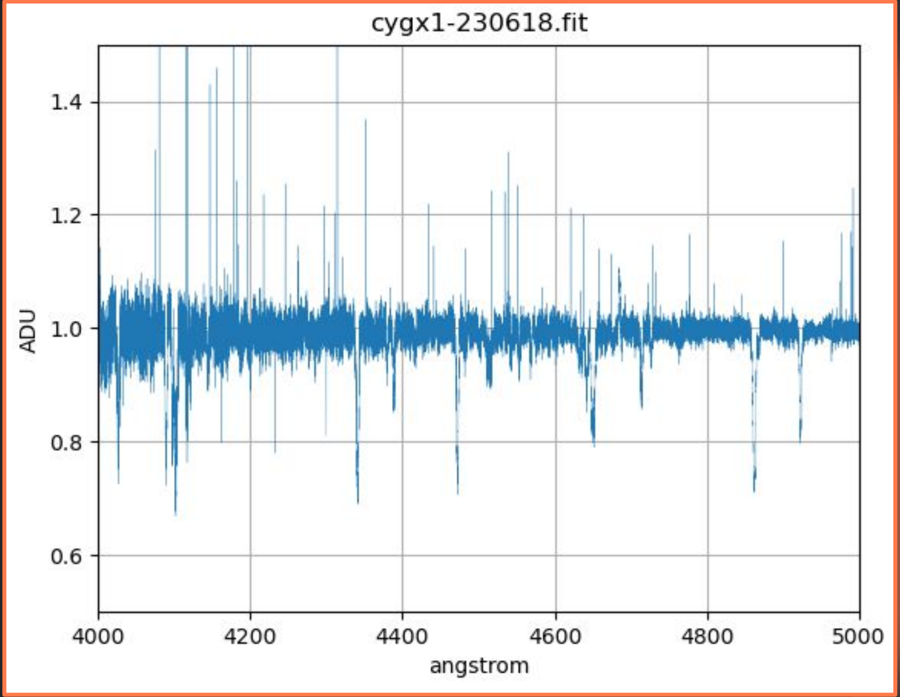
λ= 5000 - 6000 Å

Ondřejov Observatory
OES Spectrograph

June 2022



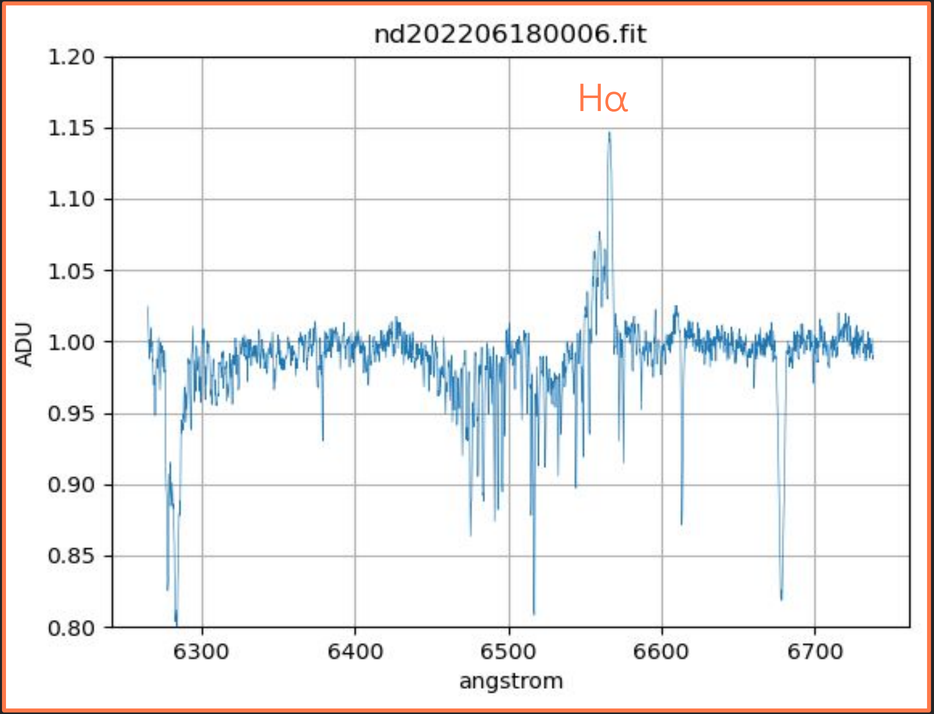
June 2023



λ= 6264 - 6737 Å

Ondřejov Observatory
CCD700 Spectrograph

June 2022



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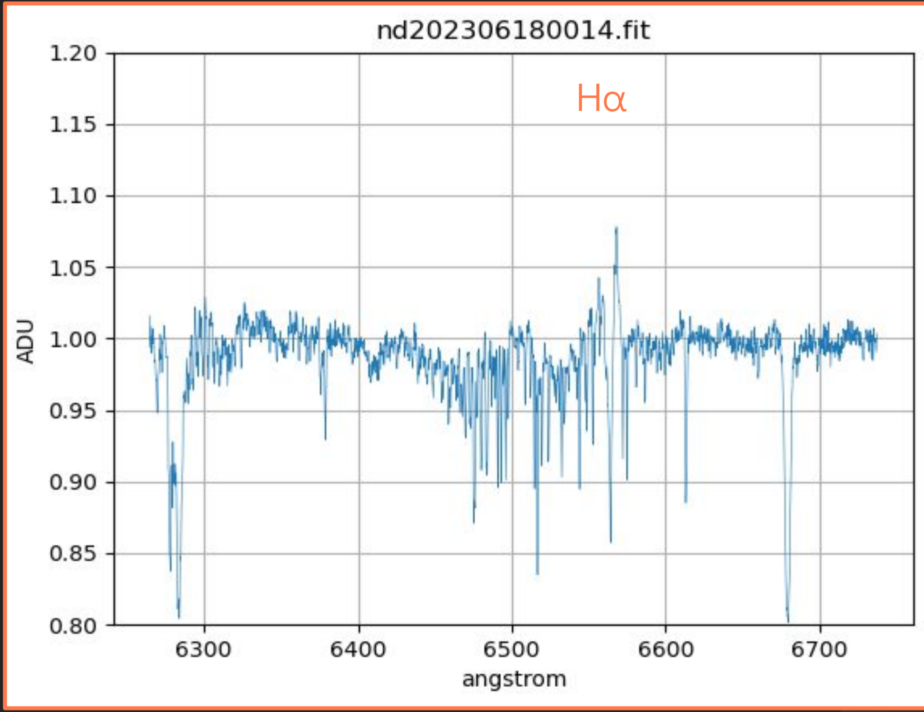
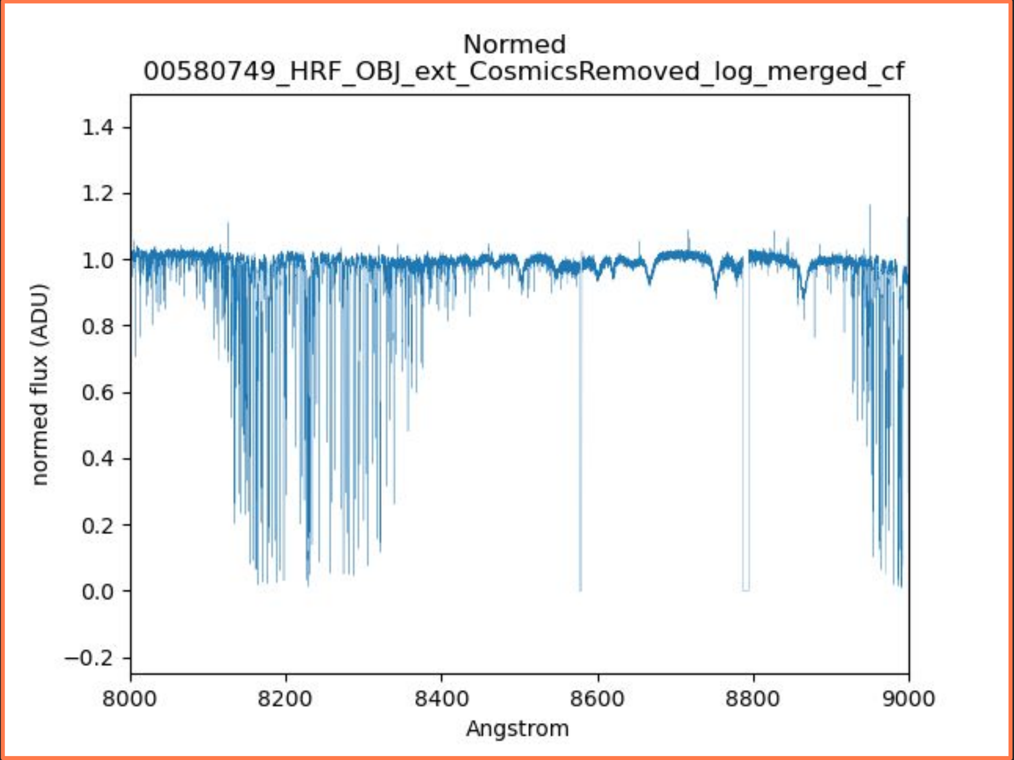


La Palma Observatory

λ= 8000 - 9000 Å



Other lines detected:

- Copper: CuII λ8511
- Radon: RnII λ8600
- Nitrogen: NI λ8686
- Neon: NeI λ8780

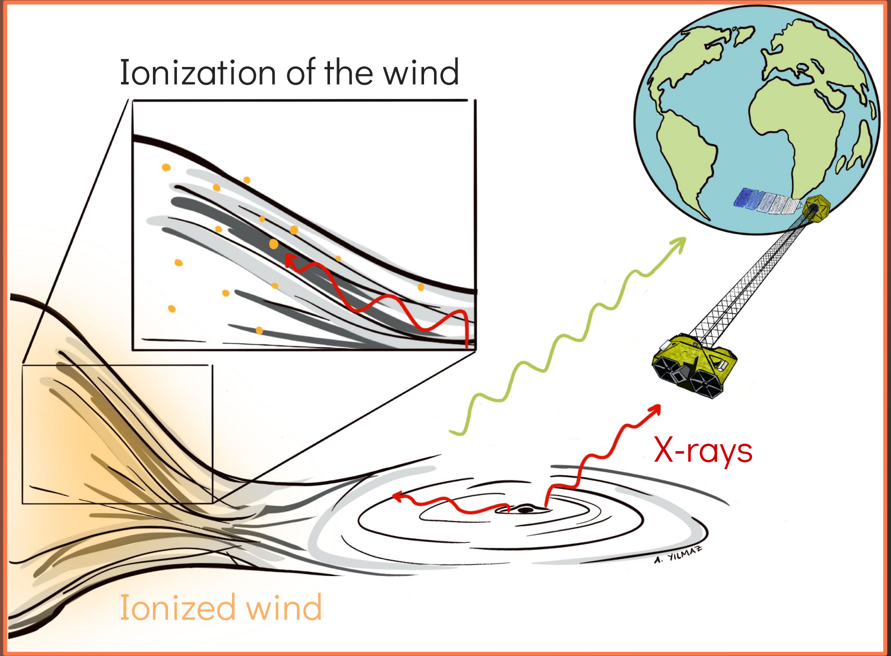
etc.....

03

Method

Method of disentangling

- Developed by Petr Hadrava in 2004



Credit: Anastasiya Yilmaz

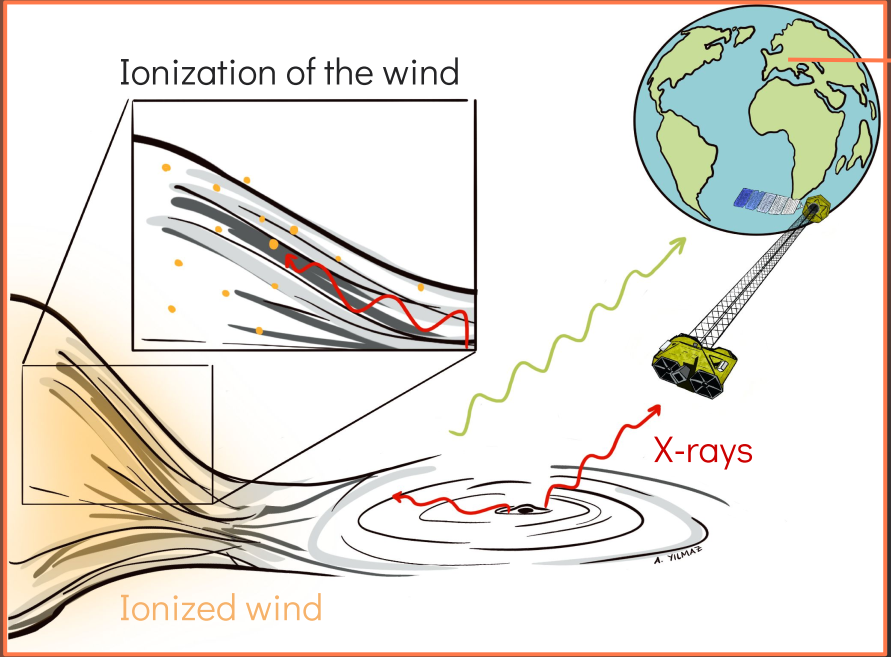
What does it do?

- Combine multiple Doppler shifted spectra
- Isolate spectral lines
- Calculate the orbital parameters

How does it do it?

- Switch on/off the component spectrum
- Choose the orbit
- Fourier Transform of the spectra

Method of disentangling



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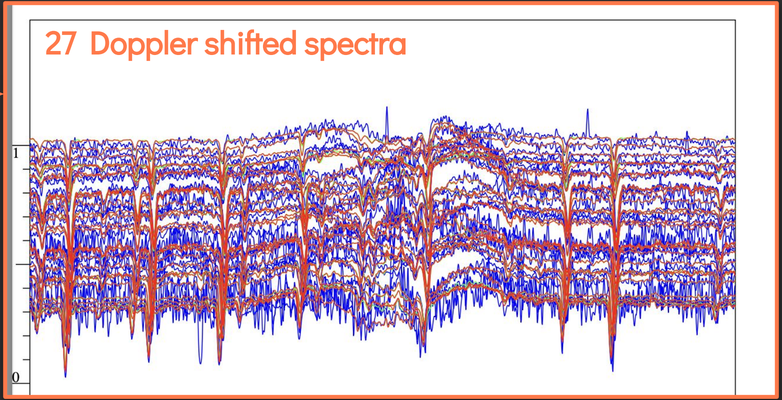

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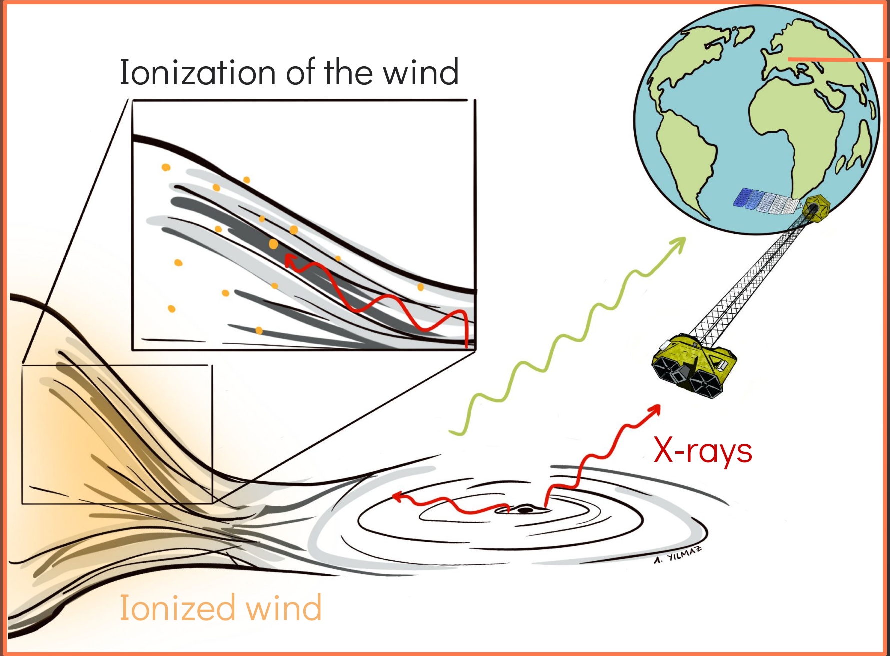

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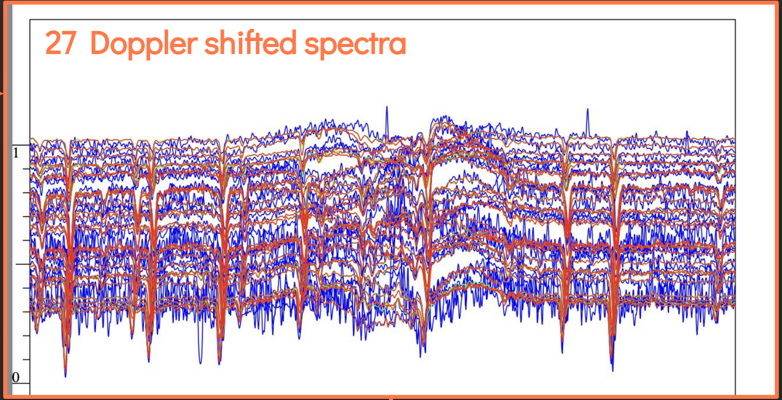

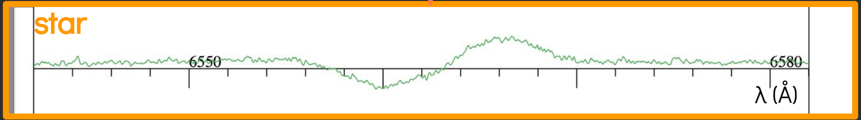

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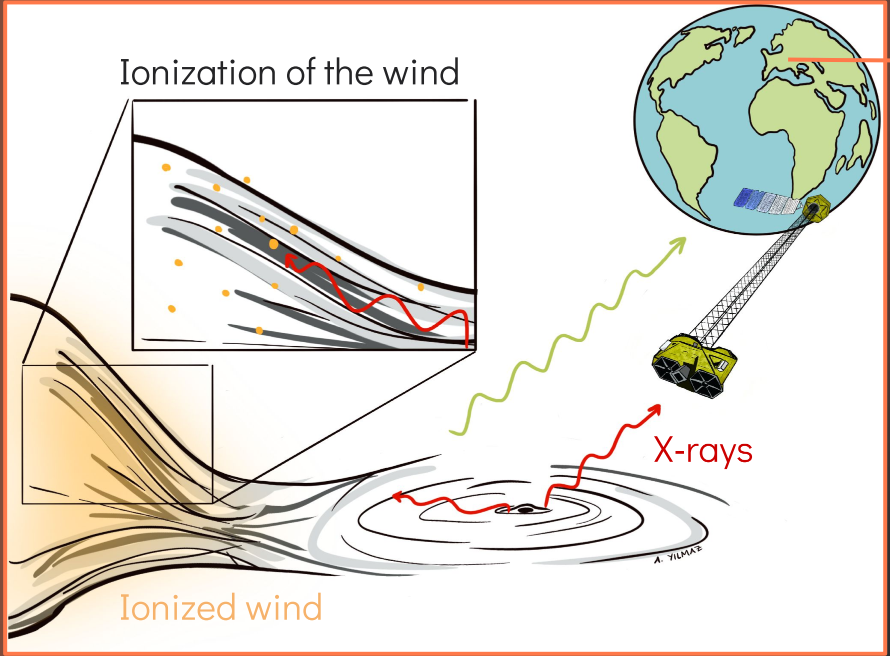

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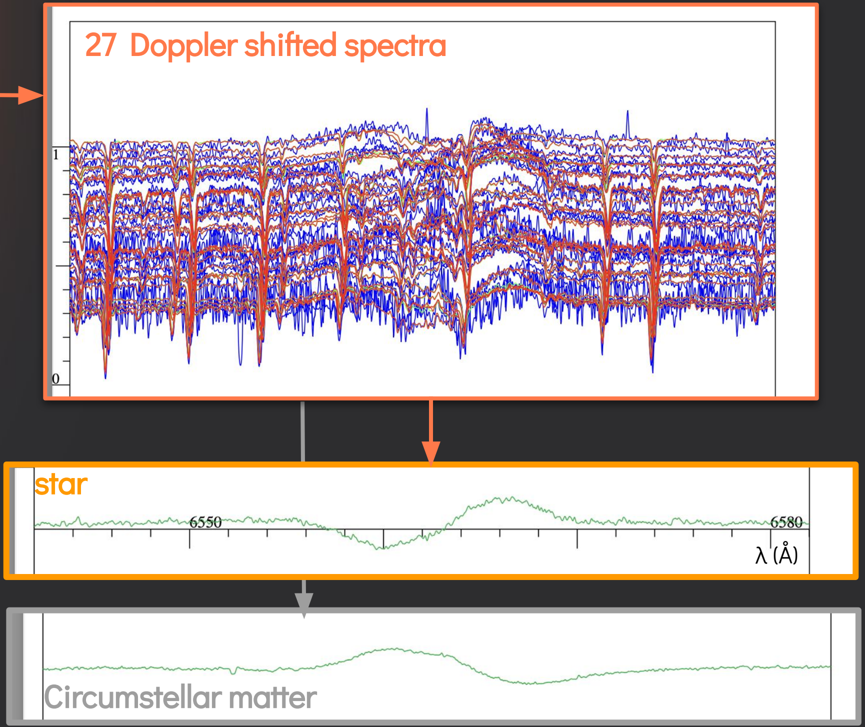
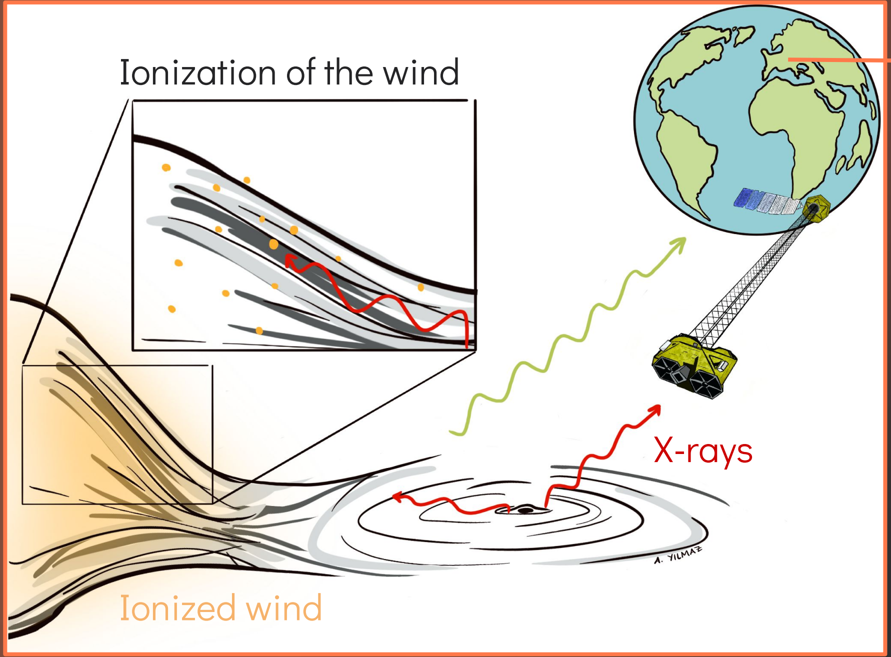


Method of disentangling



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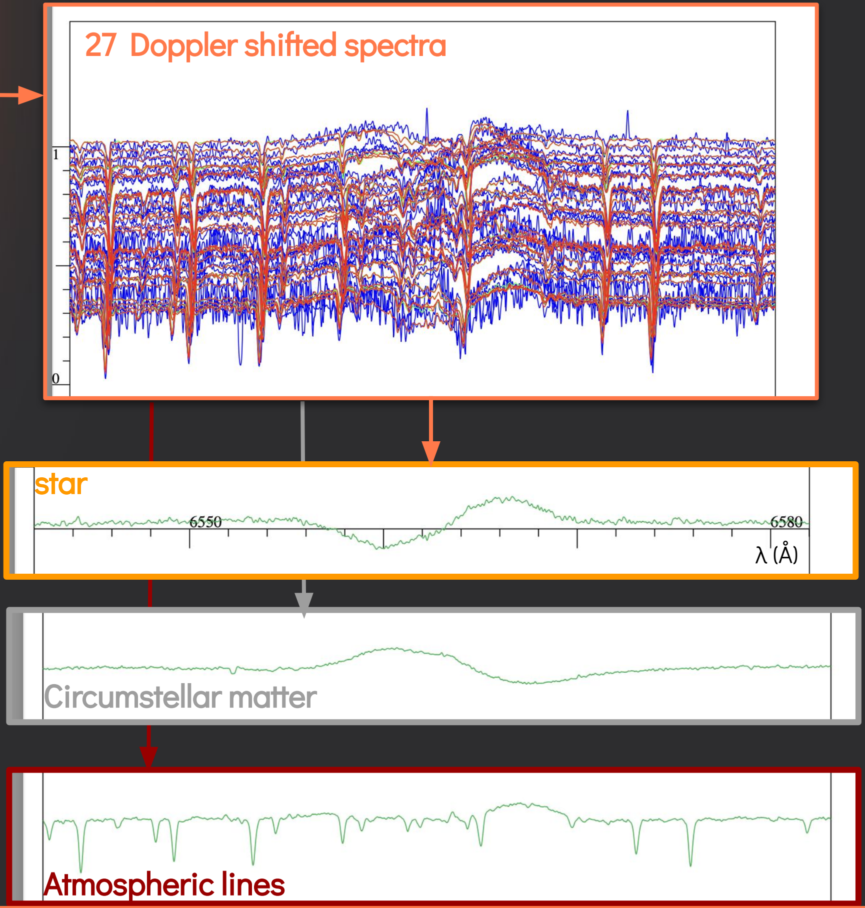
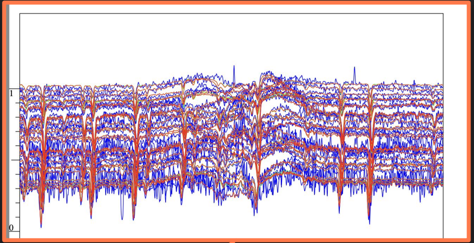
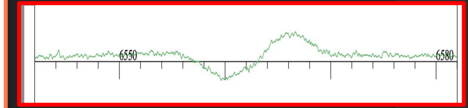


Hypothesis and parameters

- Non relativistic regime vj (t) << c
- We have more than 2 spectra at different phases
- Intrinsic observed spectrum Ij (x) constant in time, only variable in Doppler shift





$$I(x,t;p) = \sum_{j=1}^{n} I_j(x) * s_j(t)\delta(x - v_j(t;p))$$

Fourier Transform

$$\tilde{I}(y,t;p) = \sum_{j=1}^{n} \tilde{I}_j(y)\,\tilde{\Delta}_j(y,t,p)$$

Parameters

- I (x,t:p) : composite spectrum of whole stellar system
- x = c lnλ : logarithmic wavelength
- p : orbital parameters
- vj : instantaneous radial velocity
- sj : strength factor
- Δ : broadening function

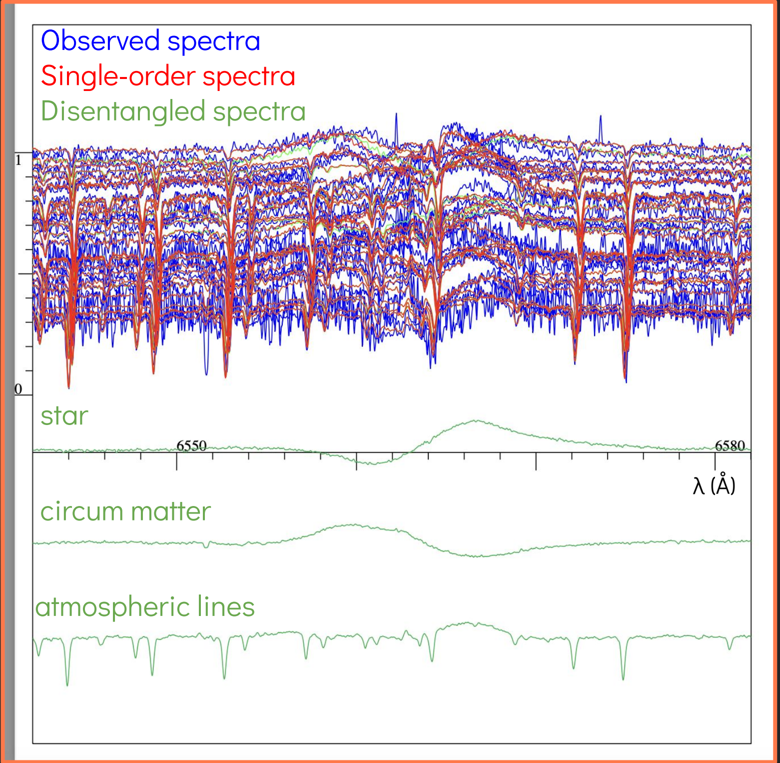
04

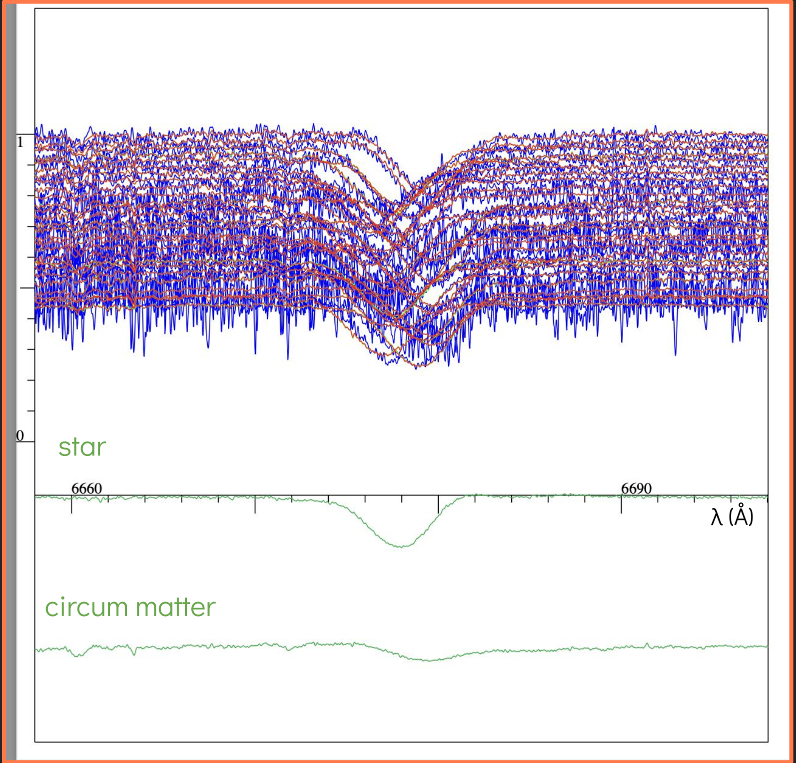
Results

Hα λ6562

Disentangled spectra

HeI λ6678





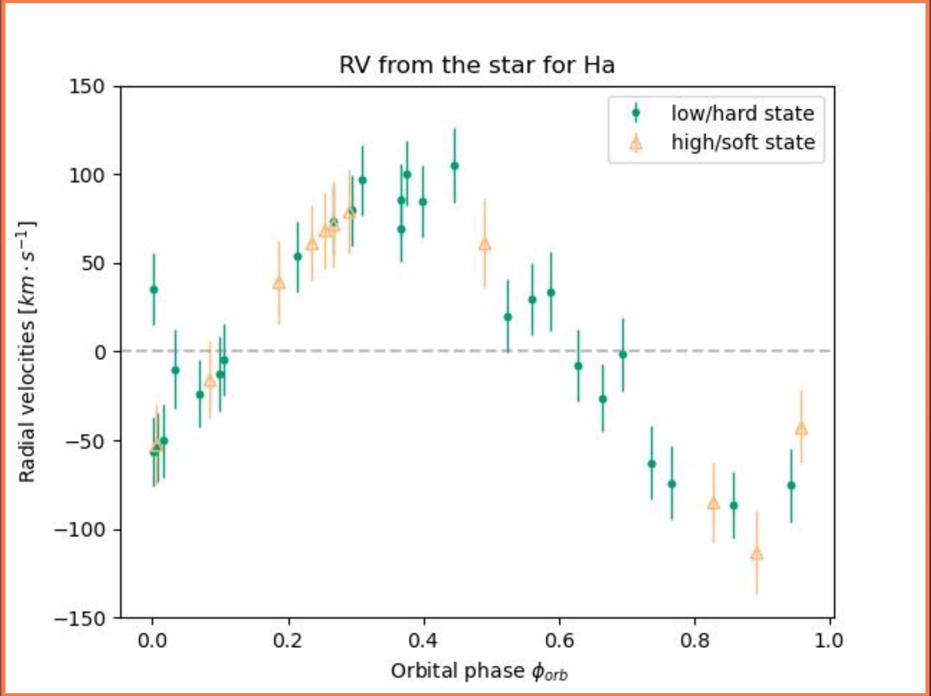
- P-Cygni profile: blue-shifted absorption and red-shifted emission

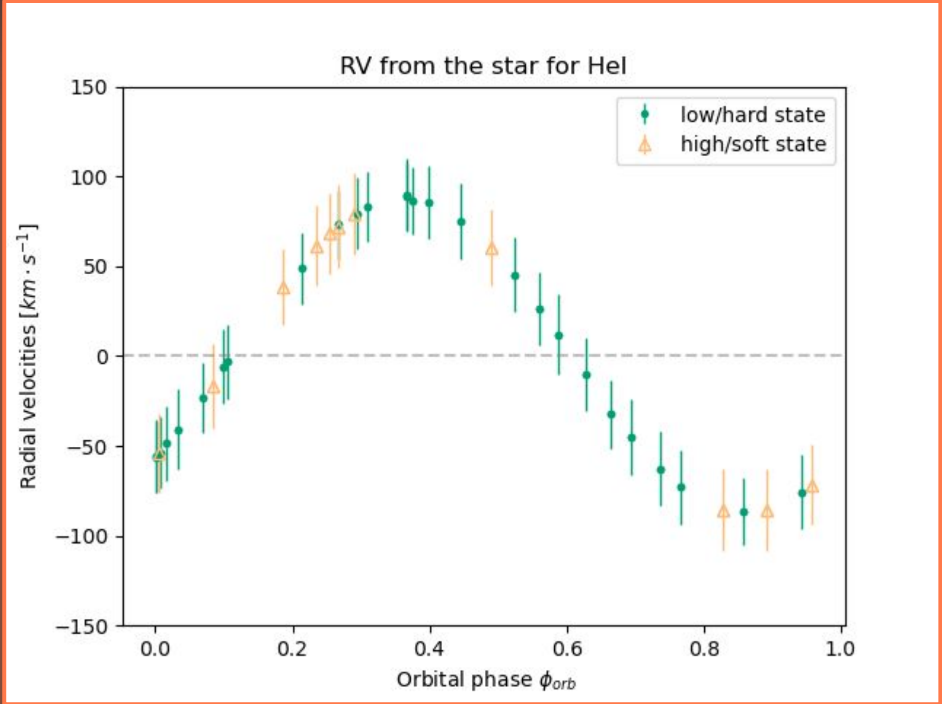
- Blue-shifted absorption without emission
- No circumstellar matter for HeI

Hα λ6562

Radial velocity curves

HeI λ6678



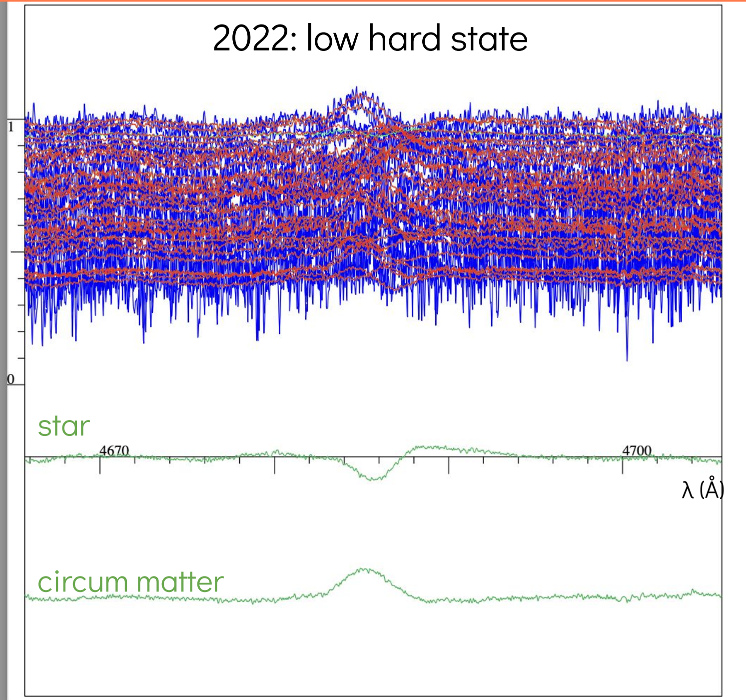


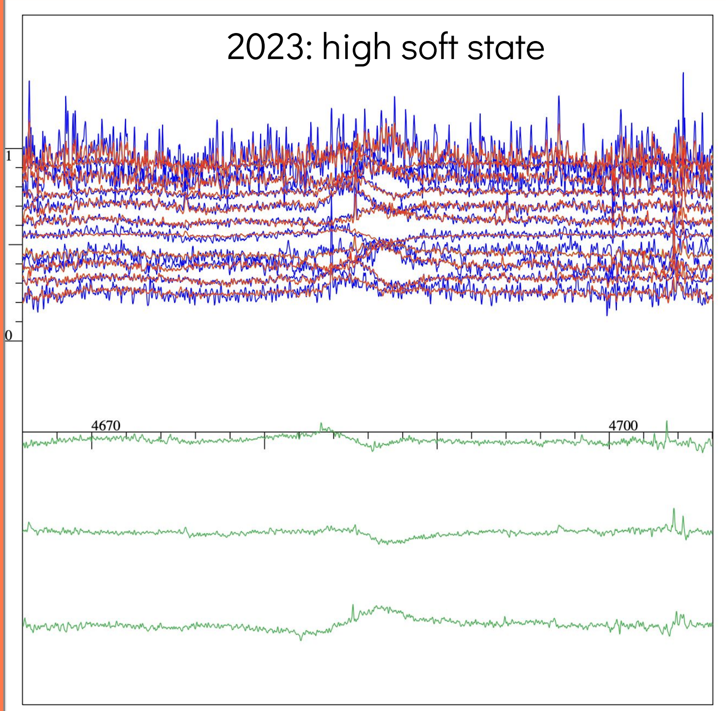
- Vr > 0 → star moves away from us
- Vr < 0 → star moves toward us

- Same intrinsic orbital modulation
- Higher Vr variability for Hα than for HeI

Example of fully ionized Helium

HeII λ4686





- P-cygni profile for the star component
- Red-shifted emission, not only absorption → HeII in denser equatorial part of the star
- Emission feature in the circumstellar matter

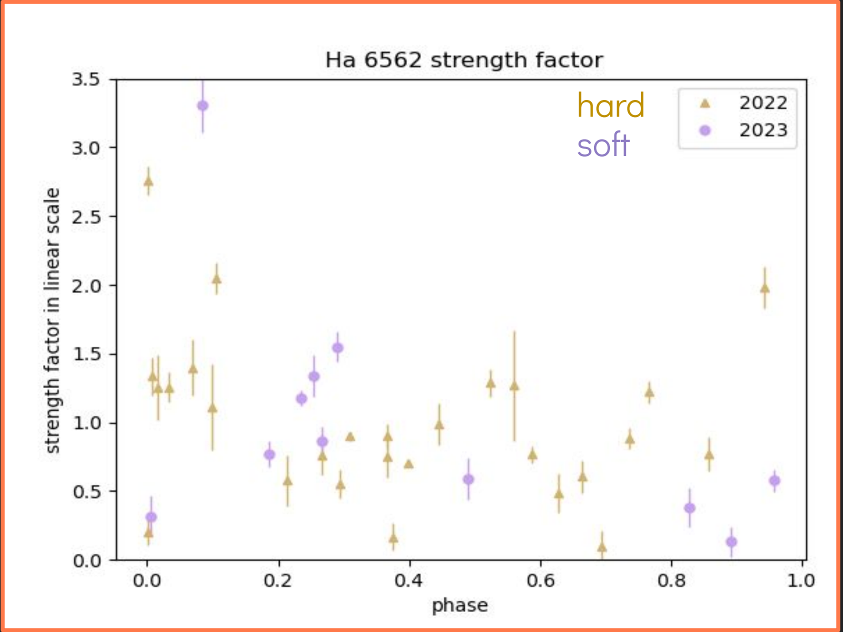
Disentangled values of the orbital parameters

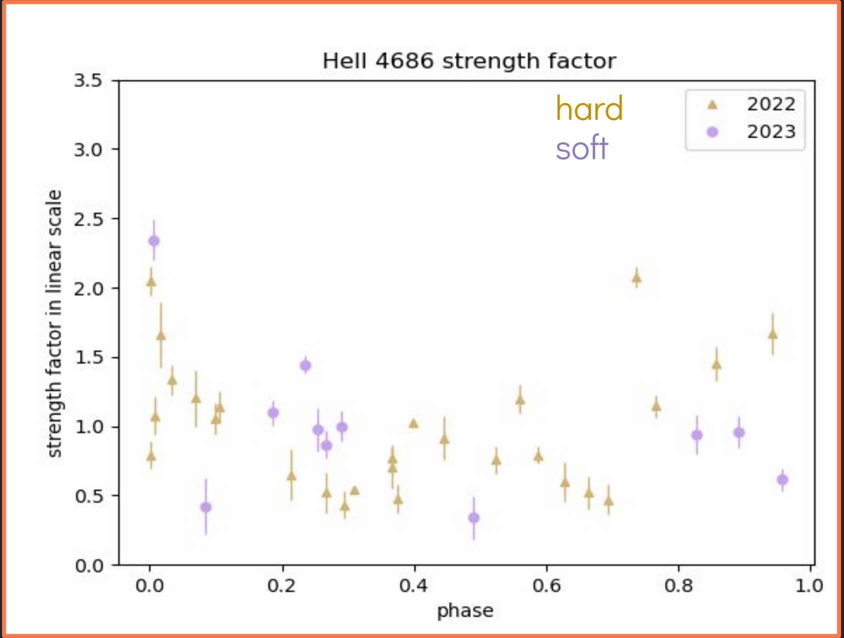
Period	2022: low hard state			2023: high soft state		
Lines (Ångstrom)	Hα λ6562	HeI λ6678	HeII λ4686	Hα λ6562	HeI λ6678	HeII λ4686
Periastron epoch (MJD)	52872.82	52872.93	52872.94	52871.12	52872.94	52872.92
K1 (km/s)	95.78 ± 0.02	88.07 ± 0.01	87.51 ± 0.03	96.24 ± 0.04	82.30 ± 0.08	82.60± 0.02

- Similar periastron epoch
- Larger discrepancy for semi-amplitude

$$K1 = \frac{v_{r,max} - v_{r,min}}{2}$$: semi-amplitude of the radial velocity

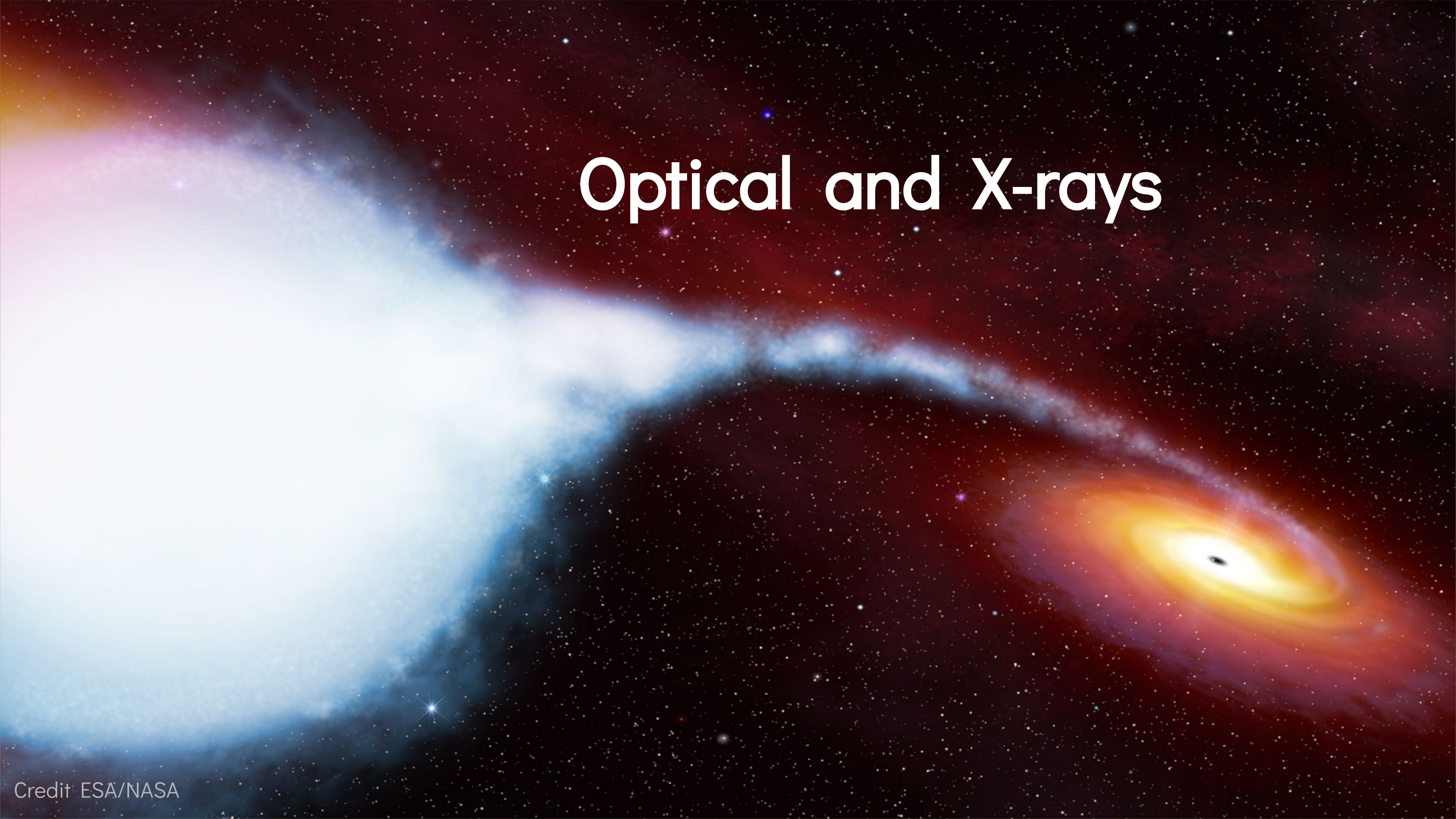
Strength factors with respect to phase





- Maxima at ϕ = 0 → inferior conjunction of the star
- Minima at ϕ = 0.5 → superior conjunction of the star
- s-factor in average lower during soft state

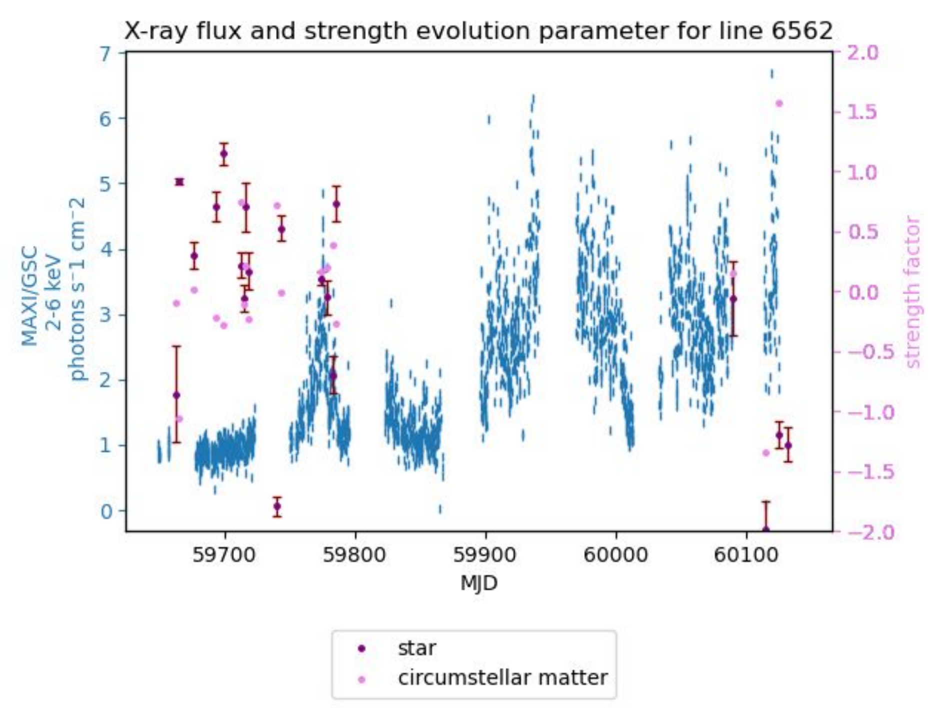
Optical and X-rays



Credit ESA/NASA

X-ray and optical anticorrelation

Hα λ6562



- When X-ray flux increases:
  → accretion rate increases
  → wind more photoionized
  → wind density decreases
  → size of ionized region increases
  → Hα emission decreases

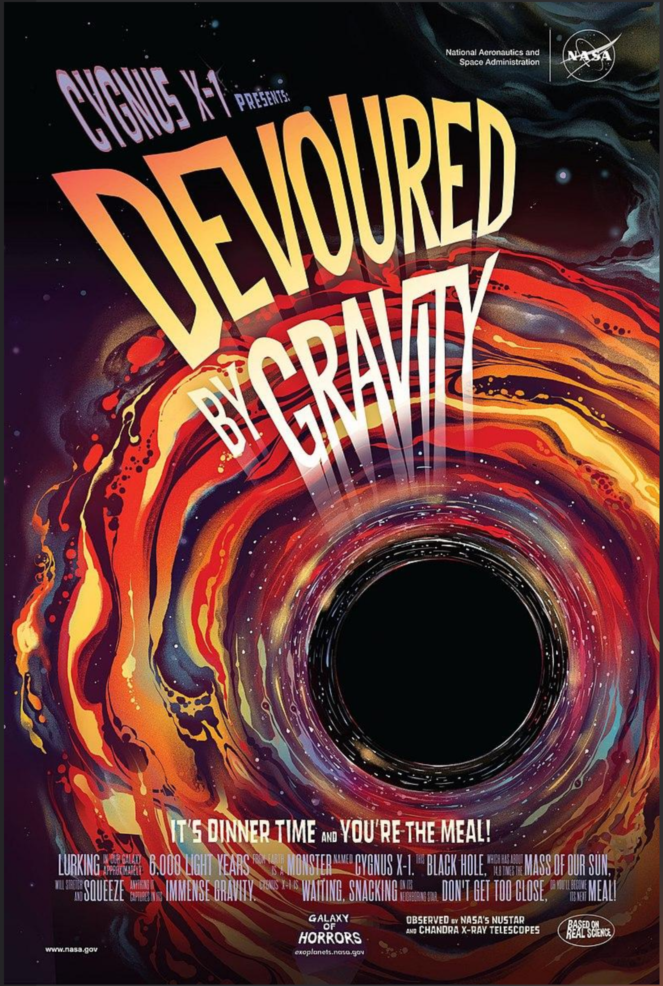
⇨ When X-ray flux increases, Hα emission decreases

⇨ X-ray change of states influences the wind outflow

05

Conclusions

- Strong variability of the lines shows presence of variable circumstellar matter in the system
- Ionised Helium emission detected in the circumstellar matter
- Line emission strongly dependent on the wind density and the X-ray photoionization
- X-ray flux anticorrelated to Hα emission
- Stellar wind strength impact the accretion rate in the disk

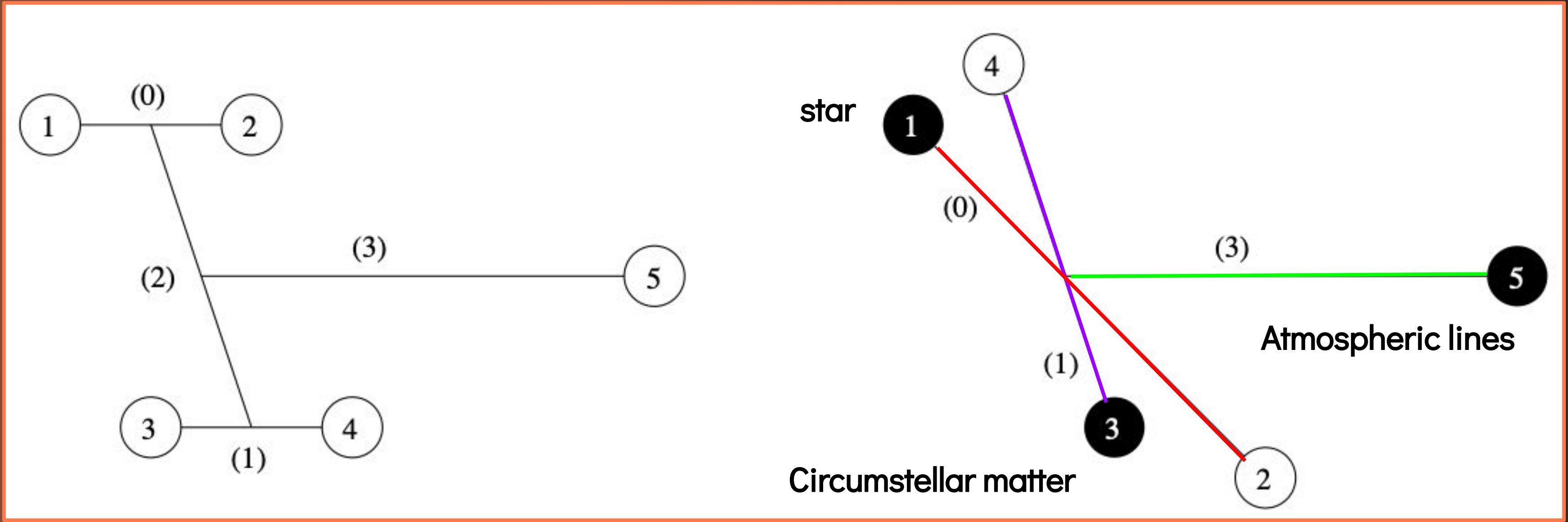


Thank you for your attention

Credit: NASA's "Galaxy of Horrors" poster for Cygnus X-1

Appendix

Method of disentangling



Petr Hadrava 2004

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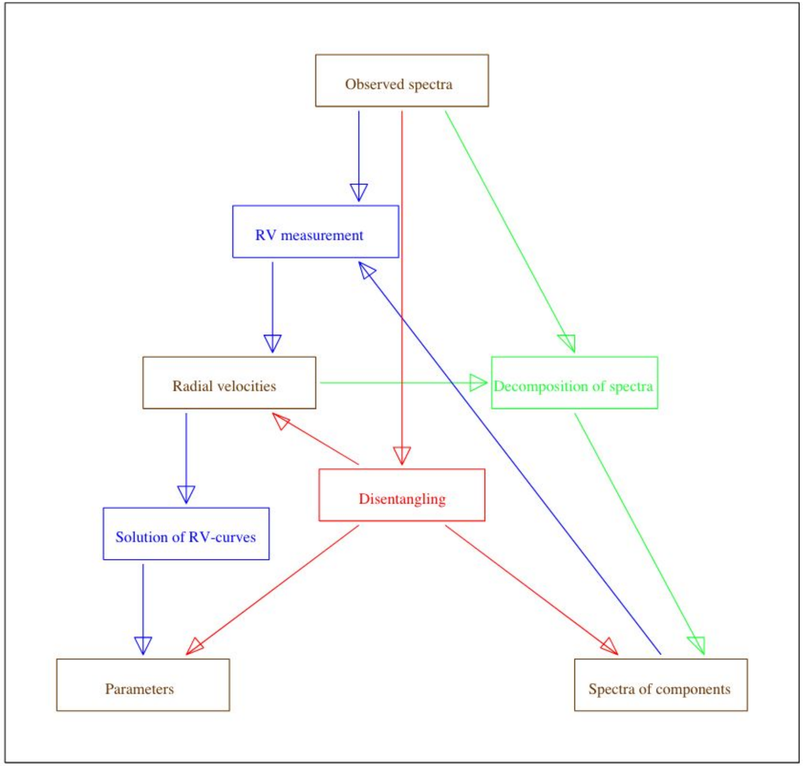


Figure 1: A scheme of disentangling method compared with the classical processing of spectra of binary stars: orbital parameters are determined from the observed spectra with an intermediate step of radial-velocity measurement (blue), spectra of components may be separated using known radial velocities (green), while in disentangling all unknown quantities are determined together as the best fit of the observations

Table A.1: Numbering of orbital elements

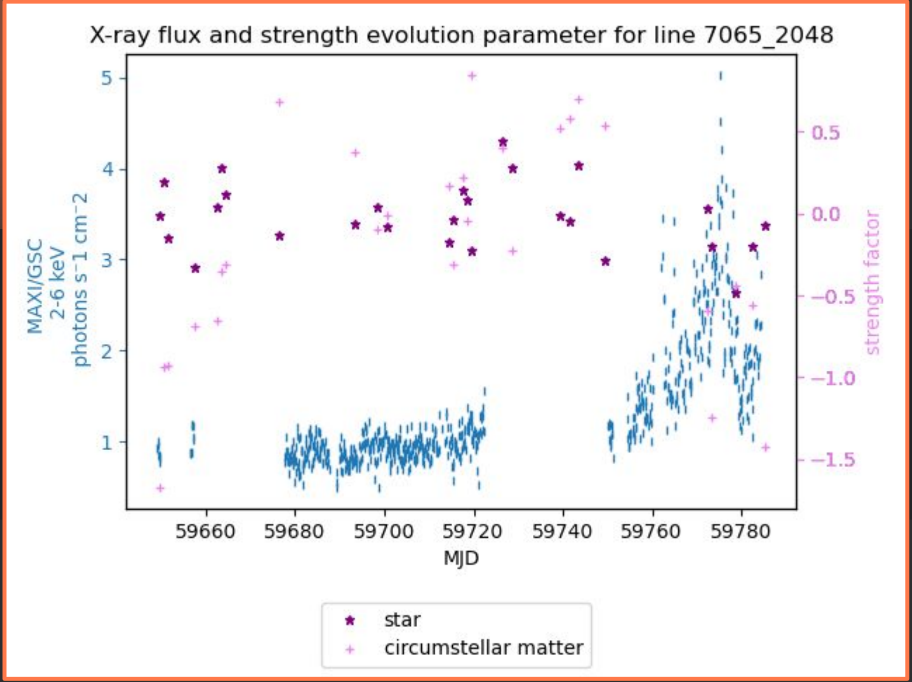
i	orbital element	
1	P	period [in days]
2	t_0	time of periastron passage [in days]
3	e	eccentricity
4	ω	periastron longitude [in degrees]
5	K	semiamplitude of radial velocity of the component with the lower index [in km/s]
6	q	the mass ratio of the component with the higher to that with the lower index
7	$\dot{\omega}$	the rate of periastron advance [in degrees/day]
8	$\dot{P}$	the time derivative of the period
9	$\dot{e}$	the time derivative of the eccentricity [in day^{-1}]
10	$\dot{K}$	the time derivative of K-velocity [in km/s/day]
11	$\dot{q}$	the time derivative of mass ratio [in day^{-1}]

Petr Hadrava 2004

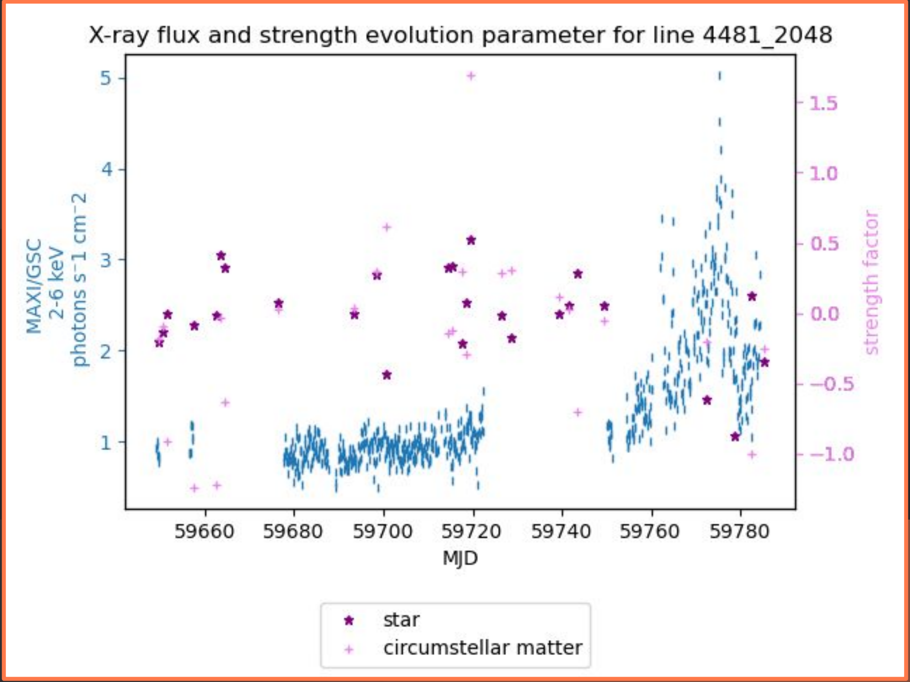
$$I_{tell}(x,t) = (\mathrm{e}^{-\tau(x,t)} - 1)I_0(x,t) \simeq -\tau(x,t)I_0(x,t)$$

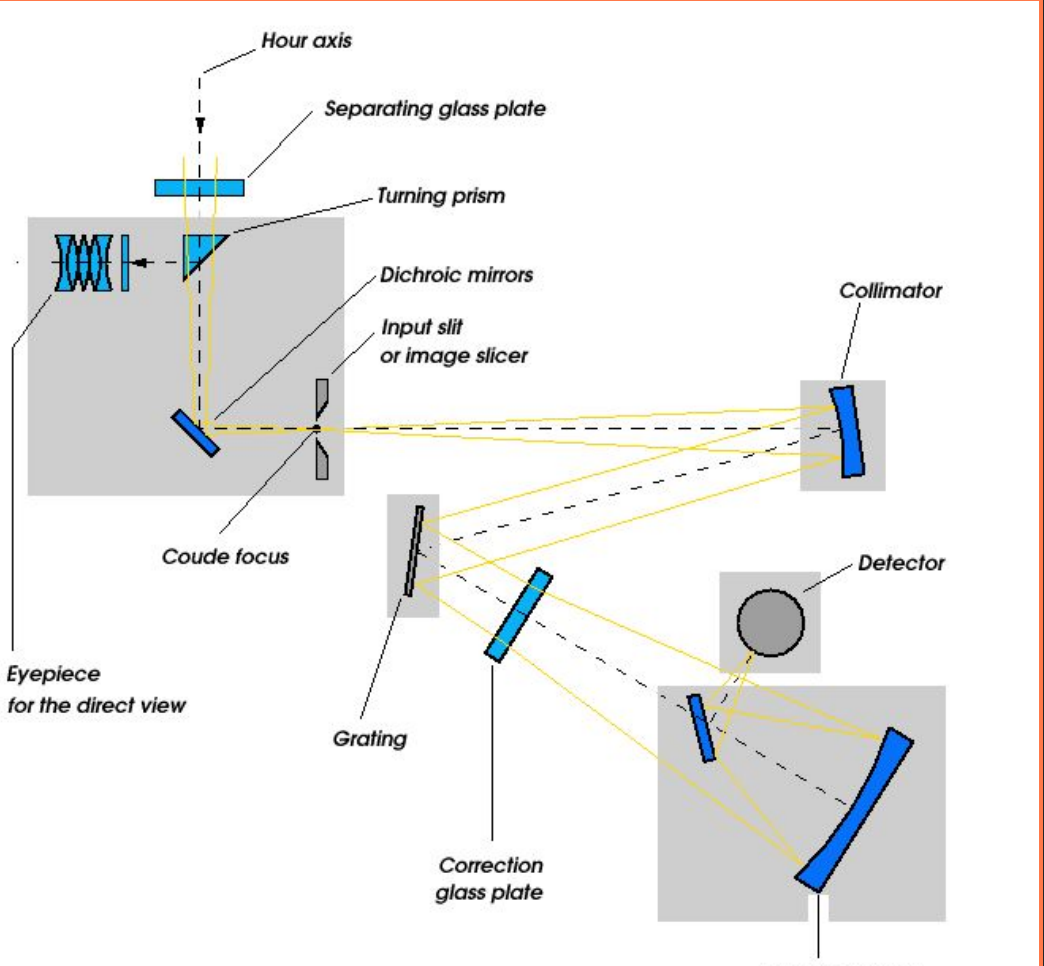
In high Fourier modes

HeI7065=7065.2



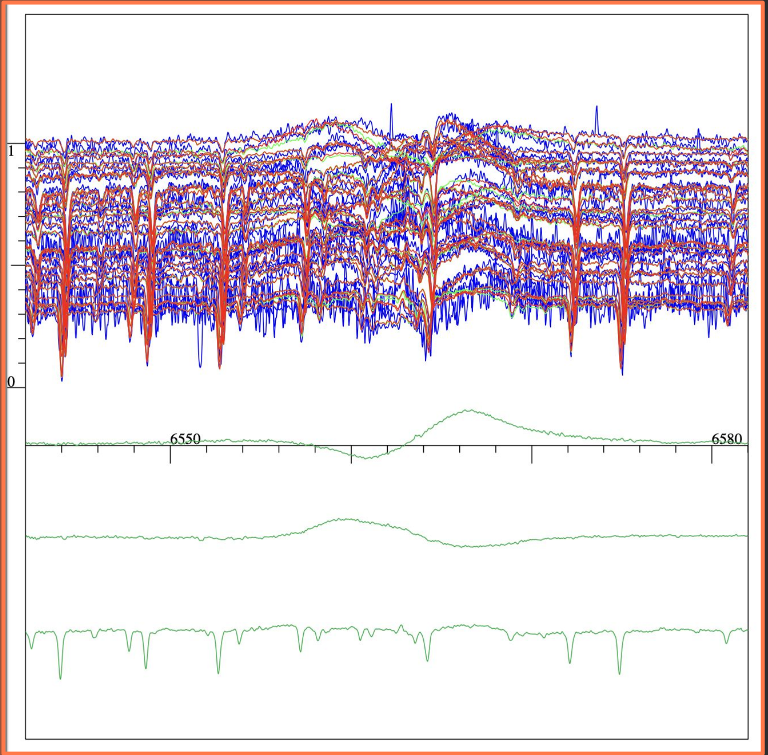
MgII4481=4481.3

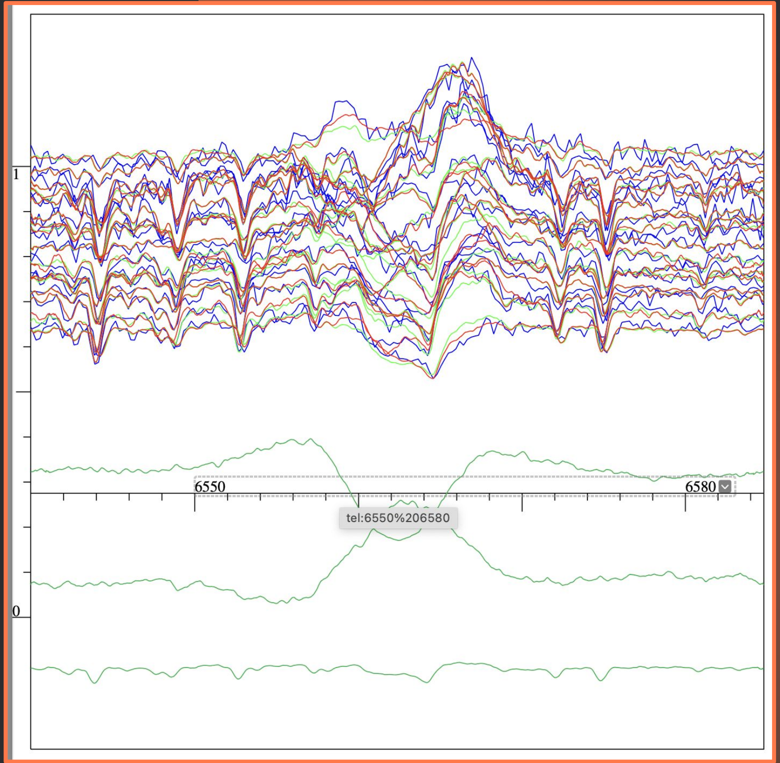




D700 Spectrograph

Hα=6562.8518





OES Spectrograph

CCD700 Spectrograph