Research of hot stars at Masaryk university

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45 YEARS OF HVAR OBSERVATORY AND 20 YEARS OF ACT:
THE ROLE OF 1-M CLASS TELESCOPES NOW AND IN THE FUTURE

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Contents

Hot stars with winds or outflowing disks

O-type stars - extremely luminous objects with strong clumped isotropic winds (Krtička+ 2000 - 2017)

Be phenomenon - "a non-sg B-type star with Balmer spectral lines in emission" (cf. Krtička+ 2011, Kurfürst+ 2014)

B[e] phenomenon:

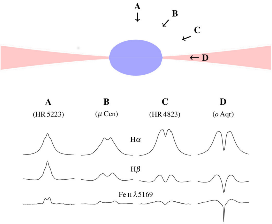
- B-type stars with forbidden optical emission lines (Conti 1976)
- Different populations with different mechanisms responsible for feeding CE with gas (Lamers+ 1998, Miroshnichenko 2007)
  - we investigate: sgB[e] - B supergiants with relative luminosity $\log(L_\star/L_\odot) \gtrsim 4.0$ (cf. Kurfürst+ 2017)
  - Disk formation mechanisms still under debate - viscous disk $\times$ outlowing disk-forming wind? (Kraus+ 2007, 2010)

PopIII stars - first stars in universe (Marigo+ 2001)

LBV stars - aspherically expanding nebulae that can be bipolar, elliptical or irregular (e.g., η Car - Smith & Townsend 2007)

Be phenomenon

- *Be star* is "a non-sg B-type star with Balmer spectral lines in emission"



- *Fastest rotators* among all (nondegenerate) types of stars on average → dense equatorial (near) Keplerian outflowing disks (e.g., Rivinius+ 2013a)
- *Viscosity* plays a key role in the outward transport of mass and angular momentum (Lee+ 1991, Okazaki 2001)
- *Exact mechanism of disk creation* still uncertain (probably non-radial pulsations)
- We calculate *self-consistent time-dependent* models of disk density-temperature structure using own 2D codes (Kurfürst & Krtička *accepted*, Kurfürst+ *submitted*)

1-D hydrodynamic modeling of circumstellar viscous disks

- Time-dependent 1-D hydrodynamic calculations using own MHD code (Kurfürst, Feldmeier & Krtička 2014)
- In the models we recognize the wave that converges the initial state to the final stationary state

Left panel: disk of classical Be (B0-type) star (Harmanec 1988), M=14.5 $M_{\odot}$, R=5.8 $R_{\odot}$, $T_{\rm eff}$ = 30 kK

To open the video - click on the following link:

Be_evolution.mp4

Right panel: disk of popIII star (Marigo+ 2001), M=50 $M_{\odot}$, R=30 $R_{\odot}$, $T_{\rm eff}$ = 30 kK

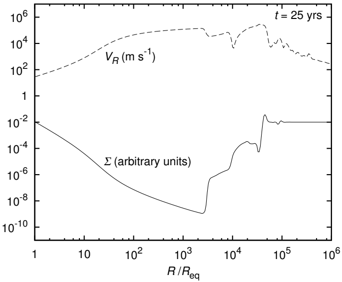
To open the video - click on the following link:

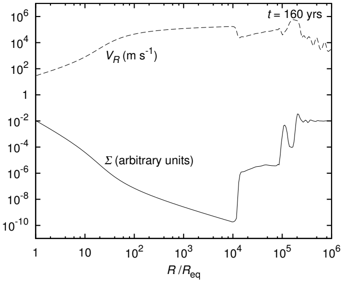
B[e]_evolution.mp4

- In supersonic region - a shock wave with propagation speed $D = a\sqrt{\Sigma_1/\Sigma_0}$
- The shock propagation time $t_{\rm dyn} \approx R/D = 0.3R/a$ - the disk evolution time
- Corresponding disk viscous time $t_{\rm visc} = \int_{R_{\rm eq}}^{R} V_{\phi}\,{\rm d}R/(\alpha a^2)$

1-D hydrodynamic modeling of circumstellar viscous disks

- Models with very low constant initial density
- B-type star, $T_{\text{eff}} = 25\,000$ K, $V_{\text{eq}} \approx 300\,\text{km s}^{-1}$
- Σ_{ini} is of a very low constant value throughout the entire isothermal disk with constant viscosity $\alpha = 0.025$
- Snapshots of evolved radial profiles of the disk Σ and V_R in two different times

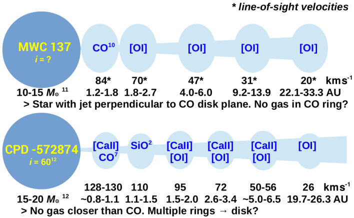




- Rarefaction wave propagates radially with time (cf. Kurfürst+ 2014)
- The gas is moved to the edge of the unperturbed ISM
- Density bumps at the edge of ISM - bow shocks ?

1-D hydrodynamic modeling of circumstellar viscous disks

- B[e] CE - disks or rings? (courtesy from G. Maravelias)



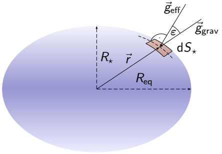
- Models with subcritically rotating star
- The model with sgB[e] star parameters: $V_\phi(R_\star) = 90\%$ of V_{crit}, $\alpha \geq 0.5$

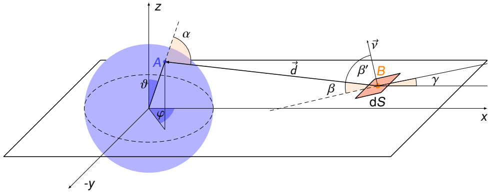
To open the video - click on the following link:

subcritical.mp4

- The material may fall inwards and increase the angular momentum of the inner disk
- May these waves explain the rings?
- Black line denotes the density in case of V_{crit}

2-D hydrodynamic modeling of circumstellar viscous disks - assumptions and tools





- *Left panel*: Rotationally oblate star (Roche model) - von Zeipel theorem:

$$\vec{F}_\star(\Omega,\vartheta) = -\frac{L_\star}{4\pi G M_\star\left(1-\dfrac{\Omega^2}{2\pi G\langle\rho\rangle}\right)}\vec{g}_{\rm eff}(\Omega,\vartheta),$$

- *Right panel*: Scheme of the geometry of the disk irradiation by a central star
- Radiative flux from one half of the stellar surface:

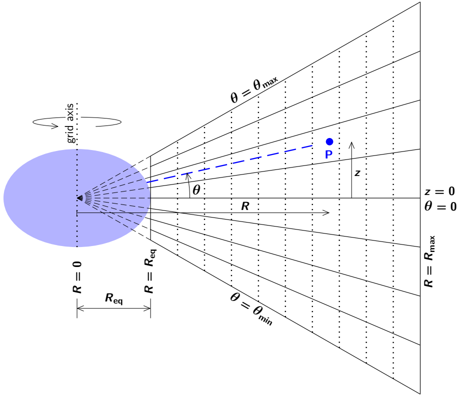
$$F_\star(\Omega,\vartheta) = \int_0^{2\pi} d\varphi \int_0^1 I(\mu)\,\mu\,d\mu = \pi\, I(1)\left(1-\frac{u}{3}\right), \quad \text{where} \quad \mu = \cos\alpha$$

- Irradiative flux that impinges each point B in the disk (cf. Smak 1989):

$$\mathcal{F}_{\rm irr} = \frac{1}{\pi}\iint_{\vartheta,\varphi} F_\star(\Omega,\vartheta)\,dS_\star\,\frac{[1-u(1-\mu)]\ \mu\sin\beta}{(1-u/3)\ d^2},$$

2-D hydrodynamic modeling of circumstellar viscous disks - assumptions and tools - grid in non-orthogonal "flaring" coordinates

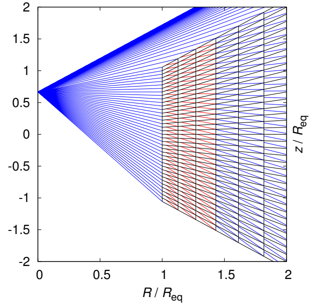
(Kurfürst & Krtička *accepted*, Kurfürst+ *submitted*)



Transformation equations from the flaring into Cartesian coordinates:

$$x = R\cos\phi,\ y = R\sin\phi,\ z = R\tan\theta.$$

Optical depth we calculate using short characteristics method:



We use two types of own HD codes:

- operator-split (ZEUS-like) finite volume for 2D smooth hydrodynamic calculations
- unsplit (ATHENA-like) finite volume algorithm based on the Roe's method

2-D hydrodynamic modeling of circumstellar viscous disks

- Self-consistent time-dependent 2-D calculations

- 2-D calculation of disk density structure up to 100 stellar radii
- conical computational grid (R - z plane)
- vertical hydrostatic equilibrium
- propagation of the disk density transforming wave (Kurfürst+ 2014)

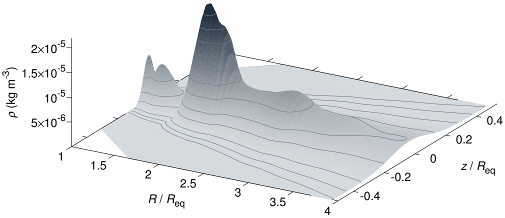
To open the video - click on the following link:

disk2Ddensity.mp4

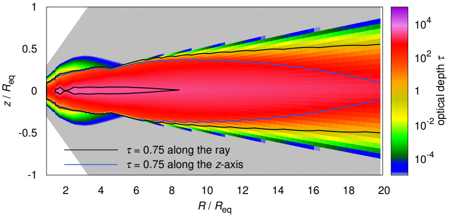
2-D hydrodynamic modeling of circumstellar viscous disks

- Self-consistent time-dependent 2-D calculations of inner dense disk structure (Kurfürst & Krtička *accepted*, Kurfürst+ *submitted*)

- Inner disk density: $\dot{M} = 10^{-6}\, M_{\odot}\,\mathrm{yr}^{-1}$, $\alpha = \alpha_0 = 0.1$, R_{s} (sonic point radius) $\approx 2 \times 10^4\, R_{\mathrm{eq}}$:

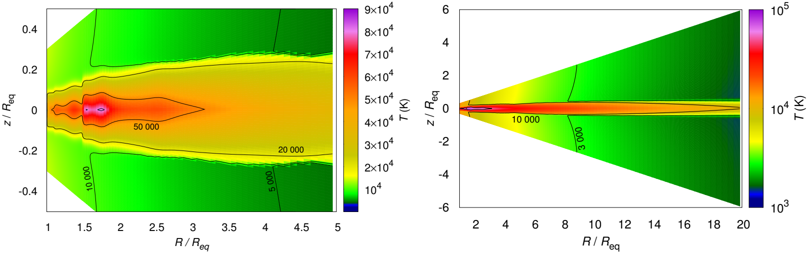


- The profile of the optical depth in the same disk (up to 20 R_{eq}):



2-D hydrodynamic modeling of circumstellar viscous disks

- Self-consistent time-dependent 2-D calculations of inner dense disk structure



- *Left panel*: Temperature distribution in the dense inner disk, $\dot{M} = 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$, $\alpha = \alpha_0 = 0.1$. The region of increased temperature near disk midplane is generated by viscosity.

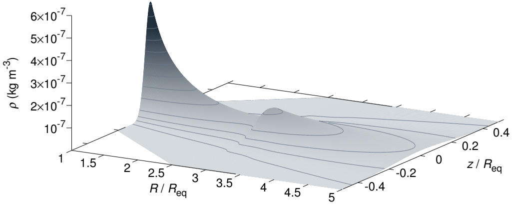
- *Right panel*: The same, up to 20 stellar equatorial radii.

- The maximum temperature in the disk core, $T_{\max} \approx 80\,000\,\mathrm{K}$.

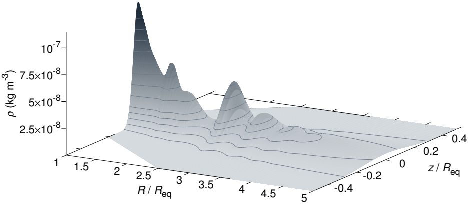
2-D hydrodynamic modeling of circumstellar viscous disks

- Self-consistent time-dependent 2-D calculations of inner dense disk structure

- Inner disk density: $\dot{M} = 10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$, $\alpha = \alpha_0 = 0.1$, $R_\mathrm{s} \approx 2.5 \times 10^4\, R_\mathrm{eq}$:

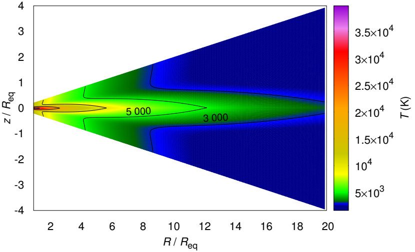


- Inner disk density: $\dot{M} = 10^{-8}\, M_\odot\, \mathrm{yr}^{-1}$, $\alpha = \alpha_0 = 1.0$, periodic density waves (viscous instability) if $\alpha_0 \gtrsim 0.5$:

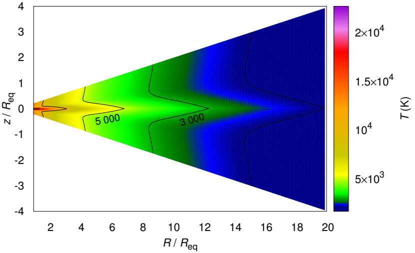


2-D hydrodynamic modeling of circumstellar viscous disks

- Self-consistent time-dependent 2-D calculations of inner dense disk structure
- T profile in the dense inner disk, $\dot{M} = 10^{-8}\, M_{\odot}\, \mathrm{yr}^{-1}$, $\alpha = \alpha_0 = 0.1$:



- T profile in the dense inner disk, $\dot{M} = 10^{-9}\, M_{\odot}\, \mathrm{yr}^{-1}$, $\alpha = \alpha_0 = 0.1$:



Disks of Be/X-ray binaries

(Krtička+ 2015)

- X-ray emission in the Be/X-ray binaries comes from accretion onto NS (Reig 2011)
- Binary separation D - constraint on the outer disk radius
- Bondi-Hoyle-Littleton (BHL) approximation - NS accretes from radius

$$r_{\mathrm{acc}} = \frac{2GM_X}{V_{\mathrm{rel}}^2}, \quad \text{if } r_{\mathrm{acc}} > H \quad \rightarrow \quad L_X = \frac{GM_X\dot{M}}{R_X}.$$

  where M_X is the mass of NS, H is vertical disk scale-height $\dot{M}$ is the accretion rate and R_X is the NS radius.

- In systems with low eccentricity we expect the disk truncation at $3:1$ resonance radius (Okazaki & Negueruela 2001) $\rightarrow R_1/R_3 \approx 0.48$

Parameters of selected Be/X-ray binaries:

Binary	Sp. Type	T_{eff} [kK]	R [$R_\odot$]	D [$R_\odot$]	L_X [erg s^{-1}]
V831 Cas	B1V	24	4.5	480	2×10^{35}
IGR J16393-4643	BV	24	4.5	18.8	4×10^{35}
V615 Cas	B0Ve	26	4.9	43	5×10^{35}
HD 259440	B0Vpe	30	5.8	510	1.2×10^{33}
HD 215770	O9.7IIIe	28	12.8	260	6.5×10^{36}
CPD-632495	B2Ve	34	7.0	177	3.5×10^{34}
GRO J1008-57	B0eV	30	5.8	390	3×10^{37}

2D time-dependent models of Be/X-ray binaries' disks

- We include NS gravity (generating tidal effects) and X-ray heating of the ambient disk gas (the same in following models)
- GRO J1008-57 - type, B0eV, $T_0 \approx 32\,000\,\mathrm{K}$, $L_X \approx 3 \cdot 10^{37}\,\mathrm{erg\,s^{-1}}$, $\dot{M} = 2.85 \cdot 10^{-9}\,M_\odot/\mathrm{yr}$, $D \approx 390\,R_\odot \approx 45\,R_{\mathrm{eq}}$, $r_{\mathrm{acc}}/H \propto 10^4$, complete time of displayed simulation: 0.72 yr

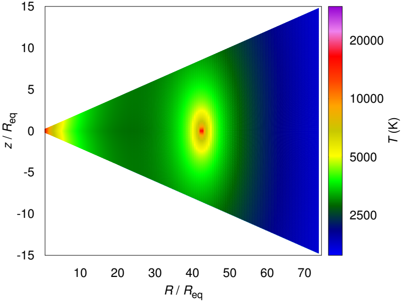
To open the video - click on the following link:

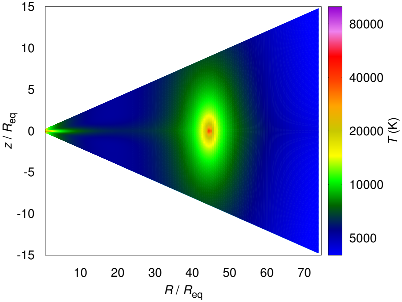
higher_density.mp4

- Density profile in radial - vertical plane in the direction of NS

2D time-dependent models of Be/X-ray binaries' disks

- We include NS gravity and X-ray heating of the ambient disk gas (the same in following models), T_X is the maximum disk gas temperature in proximity of NS
- *Left panel*: hypothetical corotating BeXRB, $T_0 \approx 15\,000\,\mathrm{K}$, $L_X \approx 5 \cdot 10^{35}\,\mathrm{erg\,s^{-1}}$, $T_X \geq 26\,000\,\mathrm{K}$, $\dot{M} = 10^{-10}\,M_\odot/\mathrm{yr}$, $D \approx 390\,R_\odot \approx 45\,R_{\mathrm{eq}}$, $r_{\mathrm{acc}}/H \propto 10^4$
- *Right panel*: GRO J1008-57 - type, B0eV, $T_0 \approx 32\,000\,\mathrm{K}$, $L_X \approx 3 \cdot 10^{37}\,\mathrm{erg\,s^{-1}}$, $T_X \geq 51\,000\,\mathrm{K}$, $\dot{M} = 2.85 \cdot 10^{-9}\,M_\odot/\mathrm{yr}$, $D \approx 390\,R_\odot \approx 45\,R_{\mathrm{eq}}$, $r_{\mathrm{acc}}/H \propto 10^4$

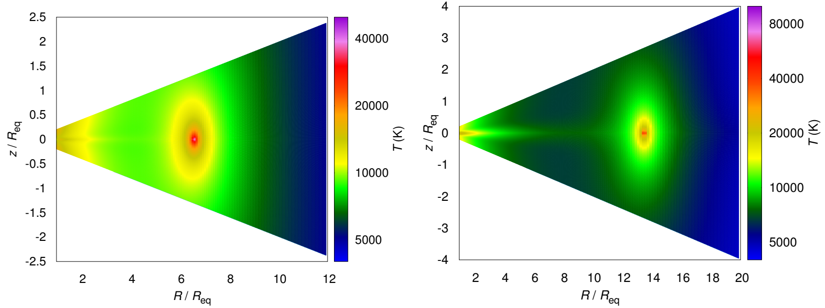




- Temperature profile in radial - vertical plane in the direction of NS

2D time-dependent models of Be/X-ray binaries' disks

- *Left panel*: V615Cas - type, B0Ve, $T_0 \approx 16\,200\,\mathrm{K}$, $L_X \approx 5 \cdot 10^{35}\,\mathrm{erg\,s^{-1}}$, $T_X \geq 40\,000\,\mathrm{K}$, $\dot{M} = 5 \cdot 10^{-11}\,M_\odot/\mathrm{yr}$, $D \approx 43\,R_\odot \approx 6.6\,R_\mathrm{eq}$, $r_\mathrm{acc}/H \propto 10^5$
- *Right panel*: HD215770 - type, O9.7IIIe, $T_0 \approx 22\,500\,\mathrm{K}$, $L_X \approx 6.5 \cdot 10^{36}\,\mathrm{erg\,s^{-1}}$, $T_X \geq 60\,000\,\mathrm{K}$, $\dot{M} = 6 \cdot 10^{-10}\,M_\odot/\mathrm{yr}$, $D \approx 260\,R_\odot \approx 13.5\,R_\mathrm{eq}$, $r_\mathrm{acc}/H \propto 10^4$



- Temperature profile in radial - vertical plane in the direction of NS

Chemically peculiar (CP) stars

Main characteristics of CP stars:

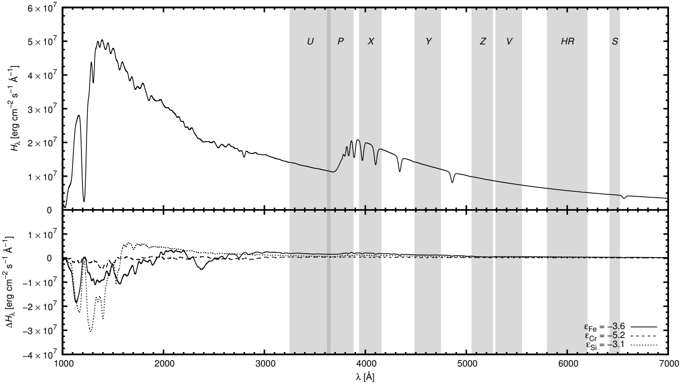
- early-type stars with unusual features in their spectra caused by abnormal abundance of heavier elements in their surface layers
- radiative diffusion, magnetic field, slow rotation
- inhomogeneous horizontal distribution of chemical elements
- line blanketing, backwarming, spectral energy redistribution (Molnar 1973)
- rotation of the star - observed variability
- line profile variations

Example star - φ Dra: (Prvák+ 2015)

Basic parameters of the star φ Dra:

spectral type	A0
type of peculiarity	α^2 CVn
effective temperature T_{eff}	12 500 K
surface gravity log g	4.0
inclination i	60°
rotational velocity projection $v_{\text{rot}} \sin i$	95 km s^{-1}

φ Dra: SED

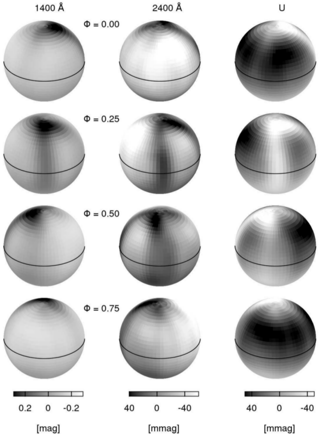


Upper plot: Emergent flux from a reference model atmosphere (code TLUSTY) with roughly solar composition.

Lower plot: Emergent flux from the model atmospheres with increased abundance of silicon and iron, respectively, minus the flux from the reference model (Prvák+ 2015)

φ Dra: emergent intensity from the surface of φ Dra

(Prvák+ 2015)

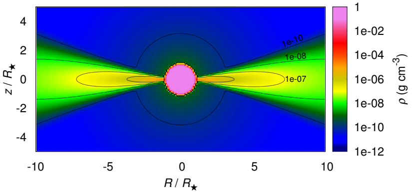


- 1400 Å, 2500 Å, U-band of the ten-colour system at various rotational phases.
- intensities: $-2.5 \log(I/I_0)$, where $\langle \log I_0 \rangle = 0$.
- Si and Fe abundant regions appear as dark spots
- abundance maps adopted from Kuschnig (1998a)

2-D hydrodynamic modeling

- Time-dependent 2-D calculation of adiabatic interaction between SN ejecta and circumstellar disk, $\dot{M}_{\mathrm{disk}} = 10^{-5}\, M_{\odot}\, \mathrm{yr}^{-1}$ (Kraus+ *2007*)

- SN progenitor: sgB[e] star, M=40 $M_{\odot}$, R=75 $R_{\odot}$, time of simulation: 50 hrs



initial density profile

Video otevřete kliknutím na následující odkaz:

SN_CSM_interaction_density.mp4

Video otevřete kliknutím na následující odkaz:

SN_CSM_interaction_velocity.mp4

Video otevřete kliknutím na následující odkaz:

SN_CSM_interaction_temperature.mp4

Future work

- All the models contribute to better understandig of evolution of hot stars connected with their mass loss rate
- 2-D MHD modeling of disk and stellar magnetic fields, using own 2D MHD code
- To finish, precise and test the full LTE radiative code (currently in progress)
- LTE and NLTE modeling of stellar and disk thermal and density structure, using the currently developed Monte Carlo radiative code (Fišák+ 2015)
- Modeling of disk and stellar spectra, comparison with observations
- ... 3D modeling