Modeling of hydrodynamic behavior of Be and Be/X-ray binaries' disks

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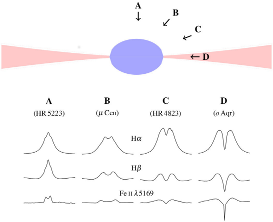
Contents

Be phenomenon

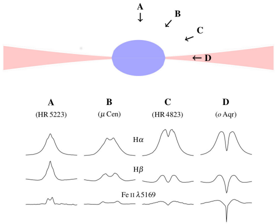
- *Be star* is "a non-sg B-type star with Balmer spectral lines in emission"



- *Fastest rotators* among all (nondegenerate) types of stars on average $\rightarrow$ dense equatorial (near) Keplerian outflowing disks (e.g., Rivinius+ 2013a)

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 - cf. talk of D. Baade)
- We calculate *self-consistent time-dependent* models of disk density-temperature structure using own 2D codes (Kurfürst & Krtička *accepted*, Kurfürst+ *submitted*)
- We investigate the influence of a compact (NS) companion within the models

Basic hydrodynamics

Basic hydrodynamics in axisymmetric $(\partial/\partial\phi = 0)$ case:

- *Continuity equation* (mass conservation law)

$$\frac{\partial \rho}{\partial t} + \frac{1}{R}\frac{\partial}{\partial R}\left(R\rho V_R\right) = 0$$

- The corresponding *radial momentum conservation equation* is

$$\frac{\partial V_R}{\partial t} + V_R\frac{\partial V_R}{\partial R} = \frac{V_\phi^2}{R} - \frac{1}{\rho}\frac{\partial\left(a^2\rho\right)}{\partial R} - \frac{GM_\star R}{\left(R^2+z^2\right)^{3/2}}$$

- The explicit 2D form of the *conservation equation of the angular momentum*

$$\frac{\partial}{\partial t}\left(R\rho V_\phi\right) + \frac{1}{R}\frac{\partial}{\partial R}\left(R^2\rho V_R V_\phi\right) = R\,\sigma_{R\phi},$$

  where $\sigma_{R\phi}$ is the viscous torque (including second-order shear viscosity)

- *Equation of state* (disk temperature primarily maintained by external source of energy - central star)

$$p = \rho a^2$$

Basic hydrodynamics

Determining equations of viscous disk structure

- Integrated disk column (surface) density $\Sigma = \int\limits_{-\infty}^{\infty} \rho \, \mathrm{d}z$
- Shear viscous stress

$$\sigma_{R\phi} \approx \eta \frac{dV_\phi}{dR} \approx \nu \Sigma \frac{dV_\phi}{dR} \approx \alpha a \lambda \Sigma \frac{dV_\phi}{dR}, \qquad \eta = f \rho \lambda V_{\mathrm{turb}}$$

- Kinematic viscosity ν, viscosity parameter α (Shakura & Sunyaev 1972)

$$\nu = \eta / \rho \sim \lambda V_{\mathrm{turb}} \approx \alpha a \lambda, \qquad \alpha = V_{\mathrm{turb}} / a$$

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- Parameterization of viscosity (parameterization of temperature only in ICs):

$$\alpha = \alpha_0 \left(\frac{R_{\mathrm{eq}}}{R}\right)^n, \alpha_0 \text{ is disk base viscosity} \quad \rightarrow$$

  we calculate also models with decreasing (non-constant) α (Kurfürst+ 2014)
- The full second order ϕ component of viscosity ($\partial/\partial\phi = 0$, $\partial/\partial z = 0$):

$$\sigma_{R\phi} = -\frac{1}{R^2} \frac{\partial}{\partial R} \left(\alpha a^2 R^3 \rho \frac{\partial \ln V_\phi}{\partial R} - \alpha a^2 R^2 \rho \right)$$

2-D hydrodynamic modeling

Time-dependent 2-D calculations

- Calculation of vertical hydrodynamic and thermal structure of the disk
- Vertical *hydrostatic equilibrium* in the thin disk ($z \ll R$):

$$\rho \approx \rho_{\rm eq} \exp\left(-\frac{z^2}{2H^2}\right), \text{ where } \rho_{\rm eq} \text{ is the disk midplane density}$$

- Vertical *scale height*: $H = aR/V_\phi, \quad \Sigma \approx \sqrt{2\pi}\rho_{\rm eq} H.$
- Vertical *thermal* and *radiative* equilibrium in regions with $\tau > 0.75$:

$$\frac{dT}{dz} = \nabla \frac{T}{p}\frac{dp}{dz}, \quad \nabla = d\ln T/d\ln p, \quad \nabla_{\rm rad} = \frac{3\kappa p}{16\sigma T^4}\frac{F_z}{g_z}$$

- Satisfying the condition $F_z = 0$ at $z = 0$, we obtain the vertical temperature distribution in the optically thick regions (Lee+ 1991)

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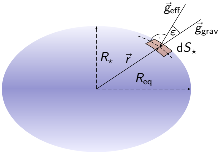
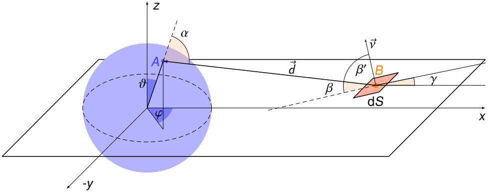
- Satisfying the condition $F_z = 0$ at $z = 0$, we obtain the vertical temperature distribution in the optically thick regions (Lee+ 1991)
- In *optically thin domain* with $\tau < 0.75$ we employ LTE and *radiative* (gray) *equilibrium* of the gas with the impinging external stellar irradiative flux
- Included *radiative cooling* in domains with $T \geq 15\,000\,\mathrm{K}$ (Rosner+ 1978, Carlsson & Leenaarts 2012)

$$Q_T = -\frac{\mathrm{d}F_{\rm cool}}{\mathrm{d}z} = -n_{\rm e} n_{\rm H} P(T), \quad P(T) \text{ is tabulated (radiative losses).}$$

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:

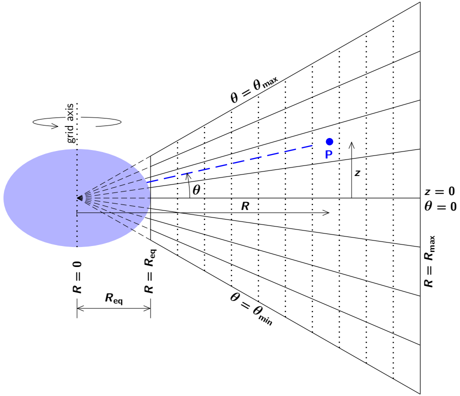
$$F_\star(\Omega, \vartheta) = \int_0^{2\pi} d\varphi \int_0^1 I(\mu)\,\mu\,d\mu = \pi\, I(1)\left(1 - \frac{u}{3}\right), \quad \text{where} \quad \mu = \cos\alpha$$

- 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

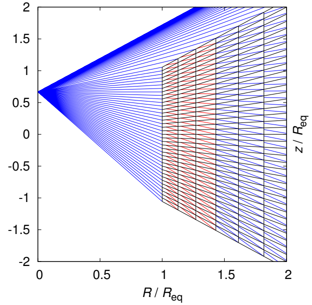
(Kurfürst & Krtička *accepted*, Kurfürst+ *submitted*)



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)

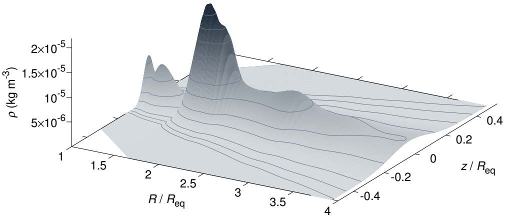
To open the video - click on the following link:

disk2Ddensity.mp4

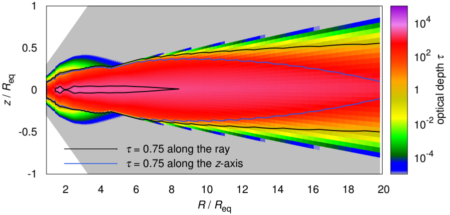
2-D hydrodynamic modeling of circumstellar viscous disks

- 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) $\approx 2 \times 10^4\, R_\mathrm{eq}$:

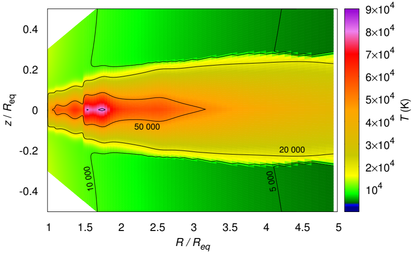


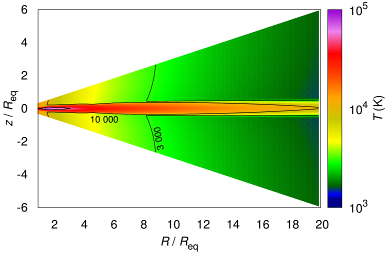
- The profile of the optical depth in the same disk (up to 20 R_eq):



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.

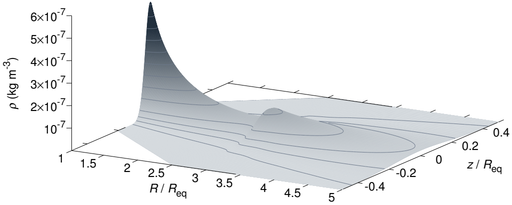
- *Right panel*: The same, up to 20 stellar equatorial radii.

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

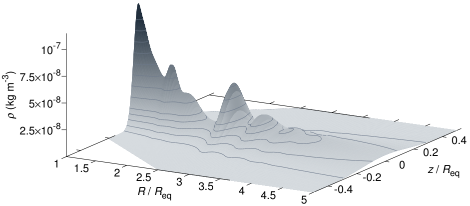
2-D hydrodynamic modeling of circumstellar viscous disks

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

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

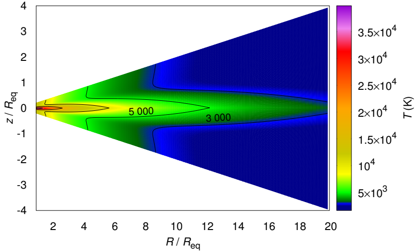


- Inner disk density: $\dot{M} = 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$, $\alpha = \alpha_0 = 1.0$, periodic density waves if $\alpha_0 \gtrsim 0.5$:

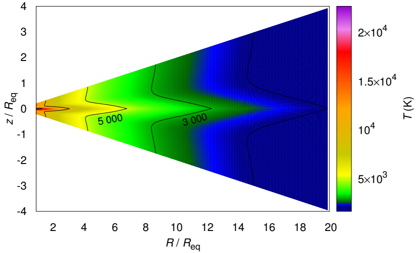


2-D hydrodynamic modeling of circumstellar viscous disks

- 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

$$r_{\mathrm{acc}} = \frac{2GM_X}{V_{\mathrm{rel}}^2},$$

  where M_X is the mass of NS.
- BHL approximation may be however an excessive simplification, e.g., in case of very small disk scale-height H (Okazaki & Negueruela 2001)

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  where M_X is the mass of NS.
- BHL approximation may be however an excessive simplification, e.g., in case of very small disk scale-height H (Okazaki & Negueruela 2001)
- Two extreme cases for aligned disk-NS systems:
  - Corotating NS: $V_{\mathrm{rel}} = V_R$
  - Disk truncated far from NS: $V_{\mathrm{rel}} = V_R^2 + V_\phi^2$
- In systems with low eccentricity we expect the disk truncation at 3 : 1 resonance radius (Okazaki & Negueruela 2001) $\rightarrow R_1/R_3 \approx 0.48$
- If $r_{\mathrm{acc}} > H$, NS accretes all the disk material $\rightarrow$ X-ray luminosity:

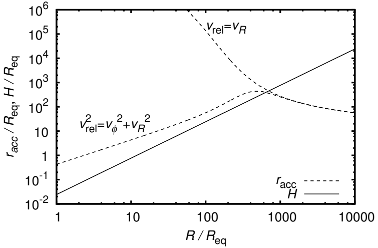
$$L_X = \frac{GM_X\dot{M}}{R_X},$$

  where $\dot{M}$ is the accretion rate and R_X is the NS radius.

Disks of Be/X-ray binaries

(Krtička+ 2015)

- Comparison of $r_{\rm acc}$ and disk scale-height H:



- Sample of Be/X-ray binaries ($r_{\rm acc} > H$, $\dot{M} \sim 10^{-13} - 10^{-9}\ M_\odot\ {\rm yr}^{-1}$) :

Parameters of selected Be/X-ray binaries:

Binary	Sp. Type	$T_{\rm eff}$ [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 and X-ray heating of the ambient disk gas (the same in following models)

- Hypothetical corotating BeXRB, $T_0 \approx 32\,000\,\mathrm{K}$, $L_X \approx 5 \cdot 10^{35}\,\mathrm{erg\,s^{-1}}$, $\dot{M} = 10^{-10}\,M_\odot/\mathrm{yr}$, $D \approx 390\,R_\odot \approx 45\,R_{\mathrm{eq}}$, $r_{\mathrm{acc}}/H \propto 10^4$, complete time of displayed simulation: 1.17 yr

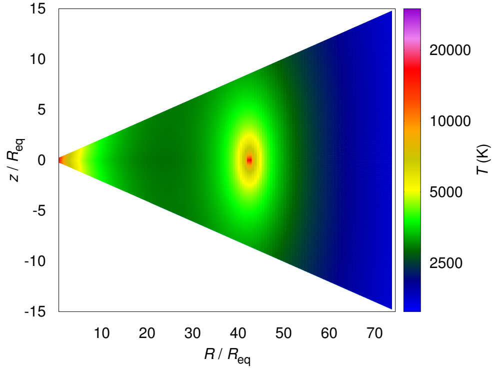
To open the video - click on the following link:

lower_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
- Hypothetical corotating BeXRB, $T_0 \approx 15\,000\,\mathrm{K}$, $L_X \approx 5 \cdot 10^{35}\,\mathrm{erg\,s^{-1}}$, $T_X \geq 26\,000\,\mathrm{K}$, $\dot{M} = 10^{-10}\,M_\odot/\mathrm{yr}$, $D \approx 390\,R_\odot \approx 45\,R_{\mathrm{eq}}$, $r_{\mathrm{acc}}/H \propto 10^4$



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

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

- 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

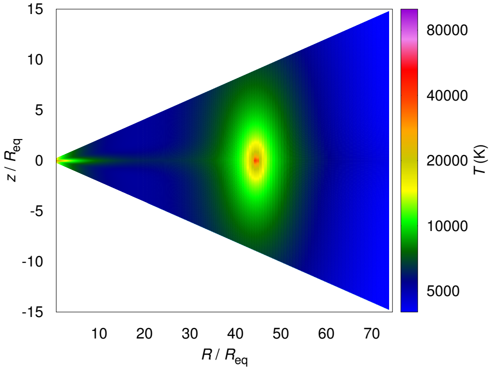
To open the video - click on the following link:

higher_density.mp4

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

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

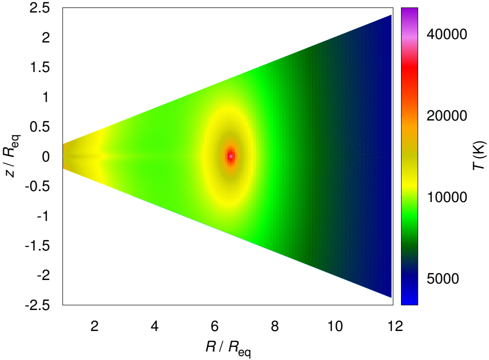
- GRO J1008-57 - type, B0eV, $T_0 \approx 32\,000\,\mathrm{K}$, $L_X \approx 3 \cdot 10^{37}\,\mathrm{erg\,s^{-1}}$, $T_X \geq 51\,000\,\mathrm{K}$, $\dot{M} = 2.85 \cdot 10^{-9}\,M_\odot/\mathrm{yr}$, $D \approx 390\,R_\odot \approx 45\,R_{\mathrm{eq}}$, $r_{\mathrm{acc}}/H \propto 10^4$



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

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

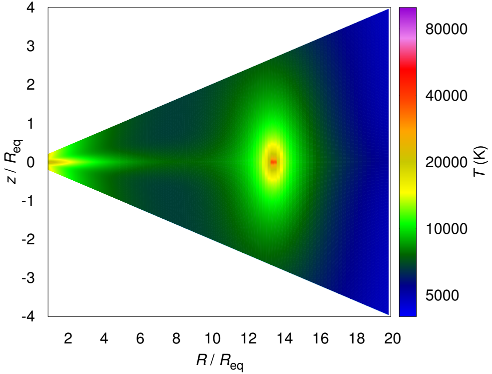
- V615Cas - type, B0Ve, $T_0 \approx 16\,200\,\mathrm{K}$, $L_X \approx 5 \cdot 10^{35}\,\mathrm{erg\,s^{-1}}$, $T_X \geq 40\,000\,\mathrm{K}$, $\dot{M} = 5 \cdot 10^{-11}\,M_\odot/\mathrm{yr}$, $D \approx 43\,R_\odot \approx 6.6\,R_{\mathrm{eq}}$, $r_{\mathrm{acc}}/H \propto 10^5$



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

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

- 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

Conclusions

- The higher values of the α viscosity parameter and/or high mass loss rates lead to unstable disk behavior, producing waves or bumps in the inner disk region
- The viscous-heated disk midplane strips disappear for $\dot{M} < 10^{-10}\, M_{\odot}\, \mathrm{yr}^{-1}$.
- The inner disk structure is not affected by presence of NS binary
- The disk density truncation in the NS direction begins approximately at $3:1$ resonance radius (cf. Okazaki & Negueruela 2001)
- The disk is truncated relatively near the central star (inside sonic point radius), in case of a critically rotating star $\dot{M}$ should increase.
- Future calculations $\rightarrow$ models with eccentric and inclined (non-aligned) orbits of NS, models where $r_{\mathrm{acc}} < H$.