Modeling of sgB[e] circumstellar disks

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The B[e] Phenomenon: Forty Years of Studies

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Main stellar types associated with outflowing disks

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

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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*)
  - sgB[e]: B supergiants with relative luminosity $\log(L_\star/L_\odot) \gtrsim 4.0$
  - HAeB[e] or pre-main sequence stars: very young stars - evidence of CM inflow rather than outflow
  - cPNB[e]: compact planetary nebula stars - low mass stars - evolving into planetary nebula (Ciatti+ *1974*)
  - SymB[e]: symbiotic stars - interacting binaries with a hot compact object and a cool giant - surrounded by a nebula
  - unclB[e]: unclassified stars - do not fit to any of the previous classes

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- Disk formation mechanisms still under debate - viscous disk $\times$ outlowing disk-forming wind? (Kraus+ *2007*, *2010*)

Basic hydrodynamics

Basic (magneto)hydrodynamics in conservative form:

- Continuity equation (mass conservation law)

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{V}) = 0$$

- Equation of motion (conservation of momentum, angular momentum)

$$\frac{\partial (\rho \vec{V})}{\partial t} + \vec{\nabla} \cdot (\rho \vec{V} \vec{V}) = -\vec{\nabla} p - \rho \vec{\nabla} \Phi + \frac{1}{\mu} (\vec{\nabla} \times \vec{B}) \times \vec{B} \quad (+\vec{f}_{visc} \, ...)$$

- Energy equation

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot (E \vec{V}) = -\vec{\nabla} \cdot (p \vec{V}) \, ... \, , \qquad E = \left(\rho \epsilon + \frac{\rho V^2}{2} + \frac{B^2}{2\mu} \right)$$

- Induction equation

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{V} \times \vec{B} \right)$$

- Equations of state

$$p = (\gamma - 1) \left(E - \frac{\rho V^2}{2} - \frac{B^2}{2\mu} \right), \quad p = \rho a^2$$

Determining equations of viscous disk structure

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

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

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

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

- Parameterization of temperature and viscosity:

$$T = T(R_{\text{eq}}) \left(\frac{R_{\text{eq}}}{R}\right)^p, \qquad \alpha = \alpha(R_{\text{eq}}) \left(\frac{R_{\text{eq}}}{R}\right)^n$$

- The full second order ϕ component of viscosity ($\partial/\partial\phi = 0$, $\partial/\partial z = 0$):

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

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 star,
M=14.5 $M_\odot$, R=5.8 $R_\odot$, $T_{\rm eff} = 30$ kK

Video otevřete kliknutím na následující odkaz:

Be_evolution.mp4

Right panel: disk of sgB[e] star,
M=40 $M_\odot$, R=75 $R_\odot$, $T_{\rm eff} = 20$ kK

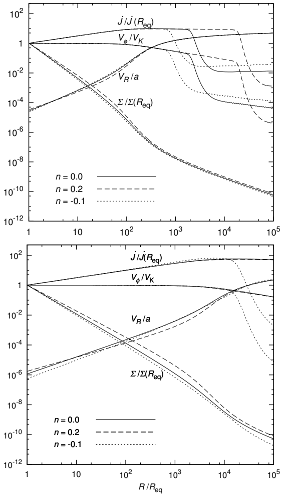
Video otevřete kliknutím na následující odkaz:

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 $t_{\rm visc} = \int_{R_{\rm eq}}^{R} V_\phi \, {\rm d}R/(\alpha a^2)$

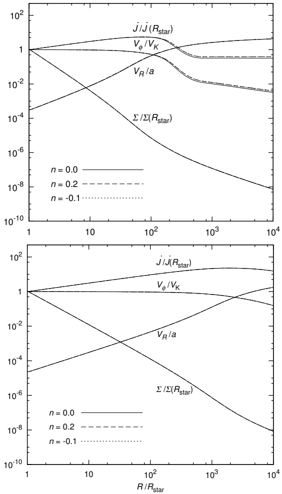
1-D hydrodynamic modeling of circumstellar viscous disks

B0 star



$T_{\rm eff} = 30\,{\rm kK}$
$\log g \approx 2.1$
$V_{\rm crit} \approx 560\,{\rm km/s}$

sgB[e] star

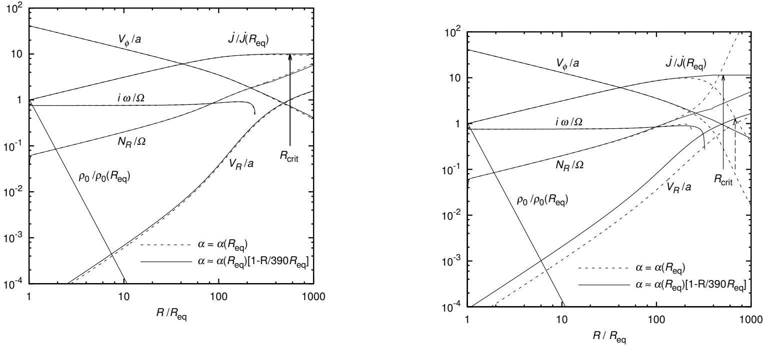


$T_{\rm eff} = 20\,{\rm kK}$
$\log g \approx 0.4$
$V_{\rm crit} \approx 250\,{\rm km/s}$

- Upper panels: $T = 0.6\,T_{\rm eff}$, lower panels: $T \sim 0.6\,T_{\rm eff}\,R^{-0.4}$
- $\alpha(R_\star) = 0.025$ (Penna+ *2012*), $\alpha \sim R^{-n}$
- Sonic point radius dependence on T profile, in sgB[e] disk significantly lower

1-D calculations of disk magnetorotational instability

- Powerful shearing instability (Balbus & Hawley *2003*) - main source of anomalous viscosity in Be star disks (cf. talk of J. Krtička)
- Is it true also in sgB[e] disks? (cf. Kraus+ *2007*)
- MS B3 star, $T_{\rm eff} = 20\,{\rm kK}$, $T = 0.6\,T_{\rm eff}$, $\alpha \approx 0.1\,(1 - R/390R_{\rm eq})$ (Krtička+ *2015*)

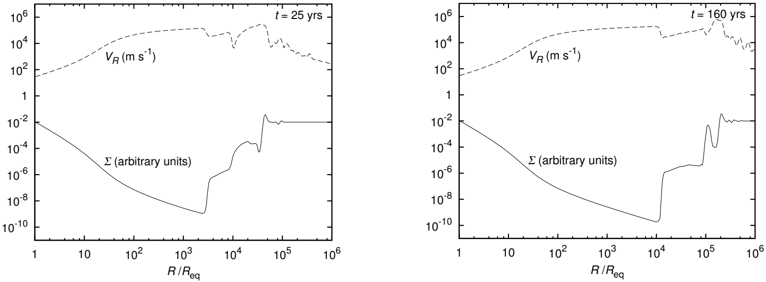


- Left panel: inner boundary viscosity $\alpha(R_{\rm eq}) = 0.025$, right panel: $\alpha(R_{\rm eq} = 0.1)$
- Magnetorotational instability calculated in the disk midplane ($N_z = 0$)
- In Keplerian region MRI frequency $\omega = 3/4\,i\Omega$
- The radius where MRI instability vanishes increases with decreasing viscosity

1-D hydrodynamic modeling of circumstellar viscous disks

- Models with very low constant initial density

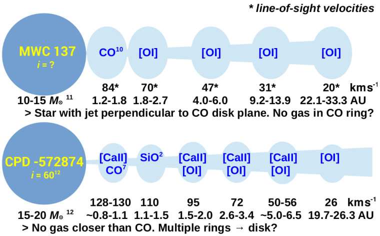
- B-type star, $T_{\text{eff}} = 25\,000$ K, $V_{\text{eq}} \approx 300\,\text{km s}^{-1}$
- Σ_{ini} is of a very low constant value throughout the entire isothermal disk with constant viscosity $\alpha = 0.025$
- Snapshots of evolved radial profiles of the disk Σ and V_R in two different times



- 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)



- Multiple rings are traced by emission of [OI], [CaII] and CO

1-D hydrodynamic modeling of circumstellar viscous disks

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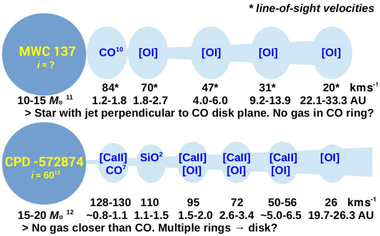
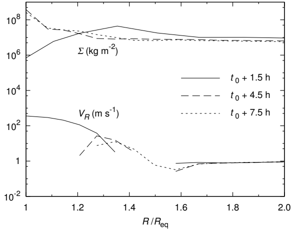


- Multiple rings are traced by emission of [OI], [CaII] and CO
- Models with subcritically rotating star
- Model with stellar radial pulsations: $V_\phi(R_{\rm eq})(t) = \dfrac{\sqrt{GM_\star R_{\rm eq}}}{R_{\rm eq} + (\delta R_{\rm eq})\sin\omega t}$



- ω corresponds to $P \geq 0.25$ d (6 hours) and $\delta R_{\rm eq} = 0.1 R_{\rm eq}$
- Pulsations in Σ and V_R up to 2-3 stellar radii, otherwise they rapidly decrease
- Three different times of Σ and V_R waves

1-D hydrodynamic modeling of circumstellar viscous disks

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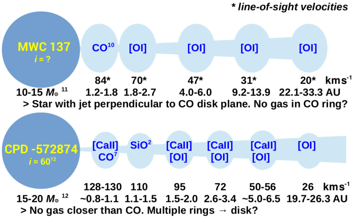


- Models with subcritically rotating star
- The model with sgB[e] star parameters: $V_\phi(R_\star) = 90\%$ of V_{crit}, $\alpha \geq 0.5$

Video otevřete kliknutím na následující odkaz:

subcritical.mp4

- The material may fall inwards and increase the angular momentum of the inner disk
- May these waves explain the rings?
- Probably not since no significant radial motion is detected (priv. comm. with G. Marvelias)
- Black line denotes the density in case of V_{crit}

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 ($z \ll R$):

$$\rho \approx \rho_0 \exp\left(-\frac{z^2}{2H^2}\right), \text{ where } \rho_0 \text{ is the disk midplane density}$$

- Vertical scale height: $H = aR/V_\phi, \quad \Sigma \approx \sqrt{2\pi}\rho_0 H.$
- Vertical thermal equilibrium:

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

- Including convection $\nabla_{\rm rad} > \nabla_{\rm ad}$ and satisfying the condition $F_z = 0$ at $z = 0$, we obtain the vertical temperature distribution (Lee+ *1991*)

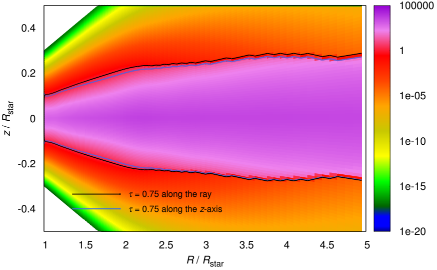
2-D hydrodynamic modeling

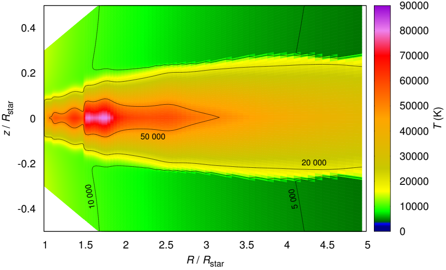
- Time-dependent 2-D calculations, $\dot{M}_{\rm disk} = 10^{-5}\,M_\odot\,{\rm yr}^{-1}$ (Kraus+ *2007*)

- 2-D calculation of disk temperature structure, vertical thermal and LTE radiative equilibrium, electron and Kramers opacity, stellar oblateness taken into account

- Optical depth in stellar direction $> 0.75 \rightarrow$ no penetration of irradiative flux

- left panel: profile of disk optical depth up to 5 stellar radii
- right panel: disk temperature profile up to the same distance

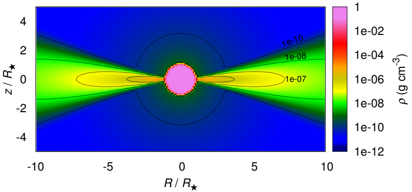




2-D hydrodynamic modeling

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

Conclusions

- The disk spreading velocity is in sgB[e] viscous disk model by order of magnitude lower than in classical Be disks.
- The disk base radial velocity is in the sgB[e] disk model significantly higher than in classical Be disks, the sonic point radius is significantly lower
- MRI is the main source of anomalous viscosity in Be disks. In sgB[e] disks this may be caused by other type of turbulence
- Disk or rings? Rings as a result of stellar pulsations or subcritical rotation with high α parameter? Or anything else?
- The substantial contribution of the viscous heating in the dense and optically thick inner disk region
- Significantly bipolar SN ejecta expansion due to the dense disk equatorial obstacle