

Radiative Transfer in Axial Symmetry

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picture: <http://chandra.harvard.edu/photo>

Outline

Description of the method

Method applicability

- limb darkening

- stellar rotation

- stellar wind

- discs

description of the method

method preview

- axial symmetry
- LTE, NLTE
- hydrogen
- parallel version (in final test phase)
- input – $n_e(r, \theta)$, $T(r, \theta)$, $v(r, \theta)$
 $\chi(r, \theta)$, $S(r, \theta)$
- output – line profile, intensity map
- Korčáková & Kubát, 2005, A&A 440, 715

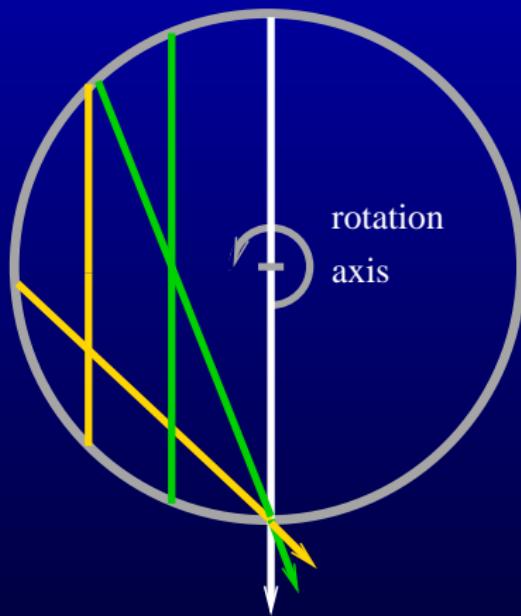
basic idea

- solution of the radiative transfer equation in separate planes
- polar coordinates in every plane
- combination of the short and long characteristic methods
- velocity field – Lorentz invariance of RTE

longitudinal planes

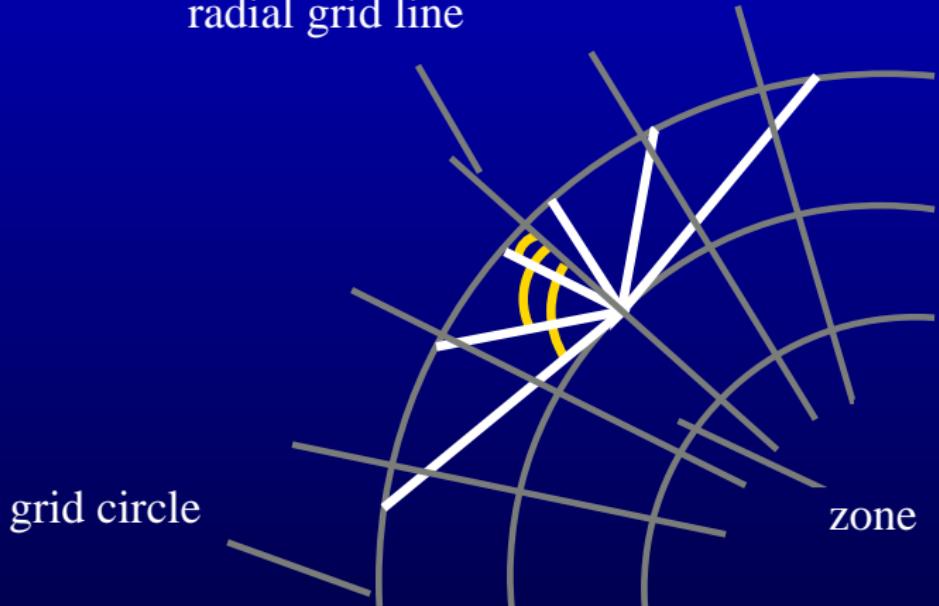


whole radiation field



upper boundary condition

radial grid line



grid circle

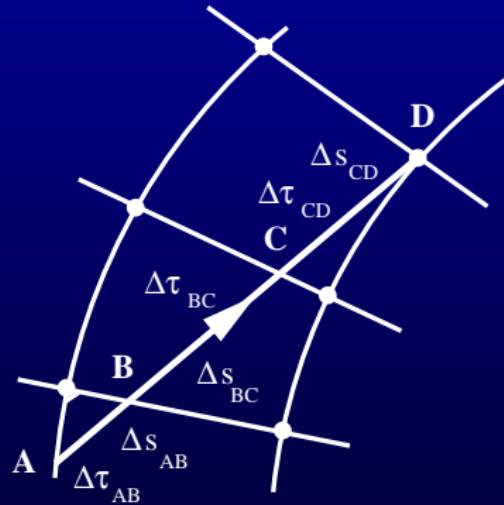
zone

integration

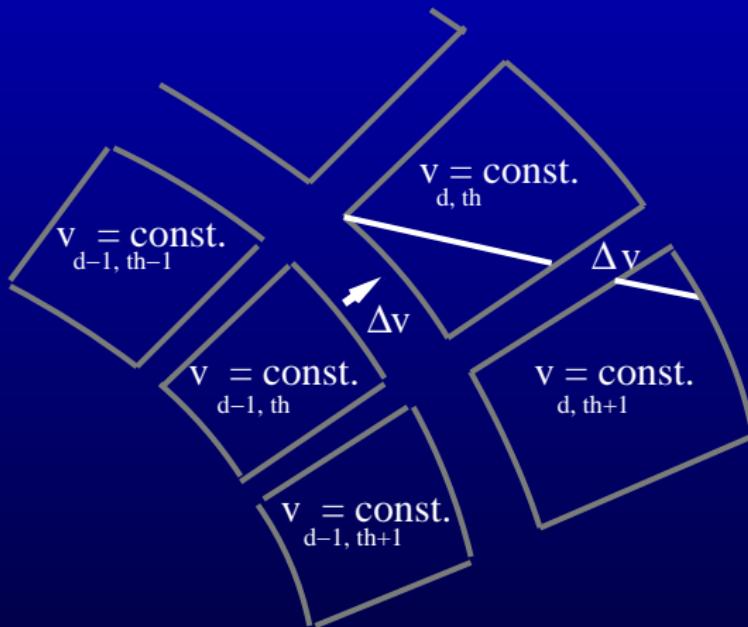
$$I_{(B)} = I_{(A)} e^{-\Delta\tau_{(AB)}} + \int_0^{\Delta\tau_{(AB)}} S(t) e^{[-(\Delta\tau_{(AB)} - t)]} dt$$

$S(t)$:

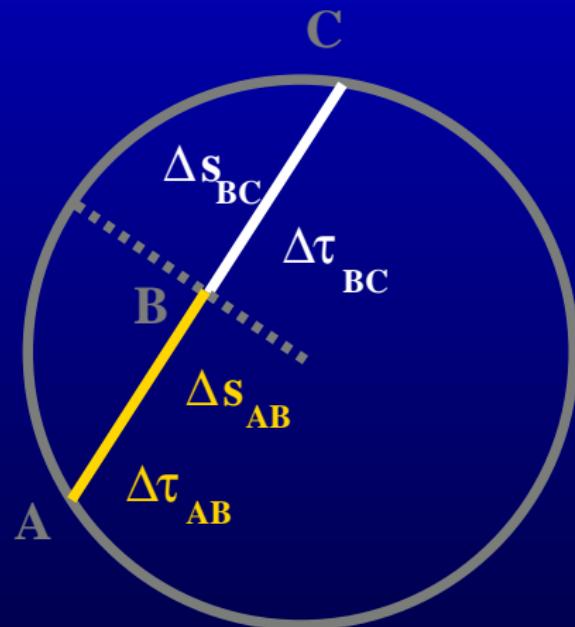
- bound-bound
- bound-free
- free-free
- Thomson scattering



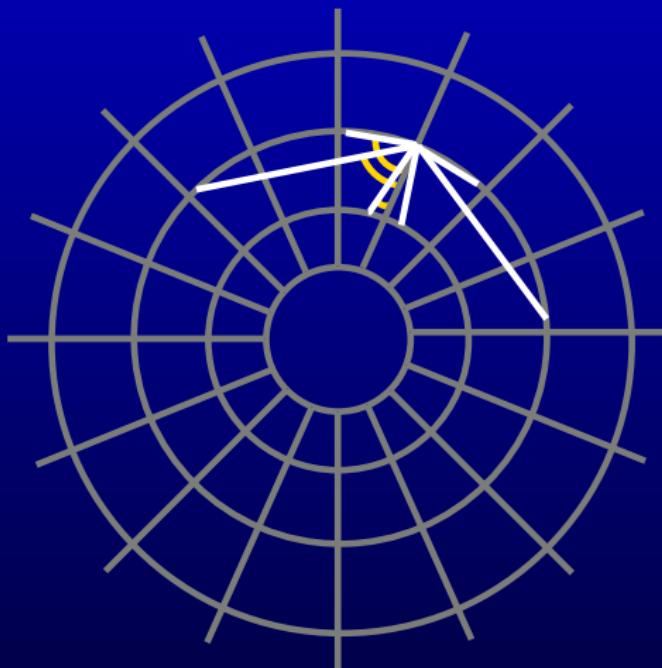
velocity field



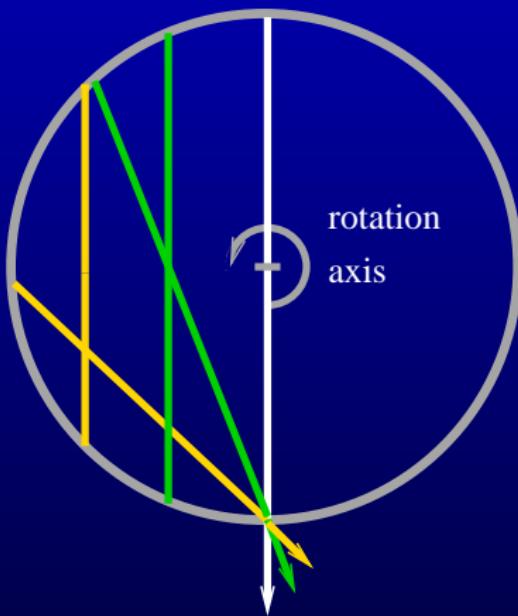
solution in the central region



lower boundary condition

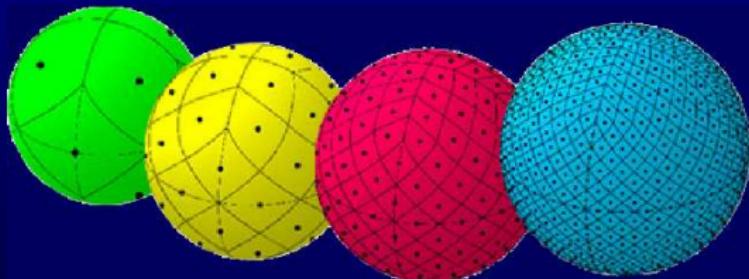


mean intensity



- the grid is defined by global properties
- advantage – better description in outer regions, where the radiation field is strongly anisotropic

- disadvantage – not possible to use an area method
- HEALPix (Hierarchical Equal Area isoLatitude Pixelization)
Gorski, Hivon, Banday, Wandelt, Hansen, Reinecke, Bartelmann, 2005, ApJ 622, 759
<http://healpix.jpl.nasa.gov/>



parallelization

- MPI
- memory \times computational time \times communication
- formal solution of the radiative transfer equation is splitted into the nodes by lines
- solution of the NLTE rate equations is distributed to the nodes by frequencies at the given point
- in final test phase

advantages

- a better description of the global character of the radiation field than by the short characteristic method
- not so time consuming as the long characteristic method
- arbitrary velocity field

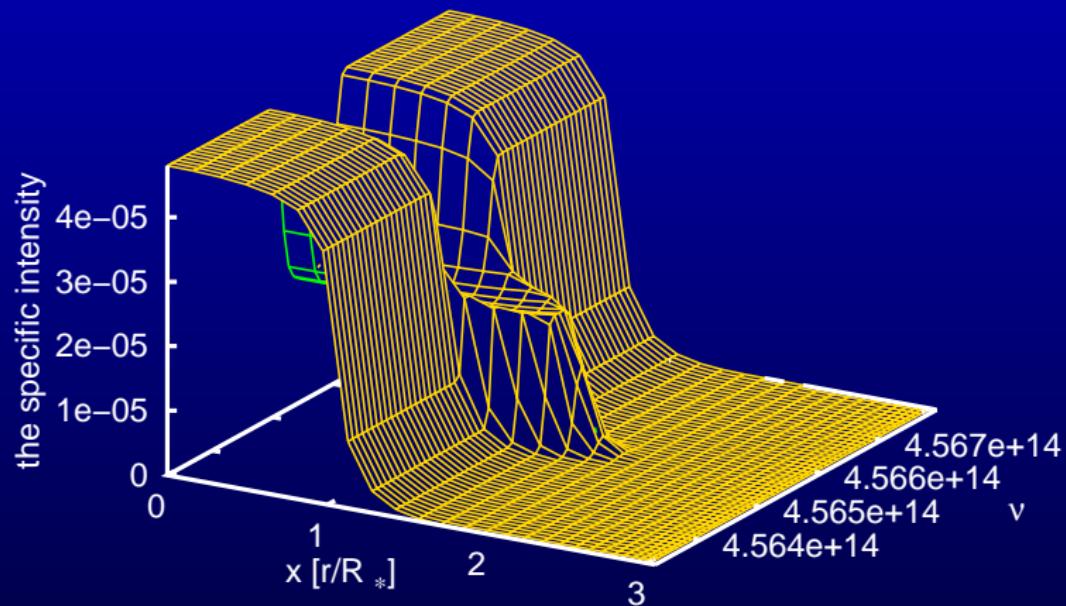
disadvantages

- high velocity gradients \Rightarrow a finer grid
- computing time $\sim f^2$ (f – number of frequency points)

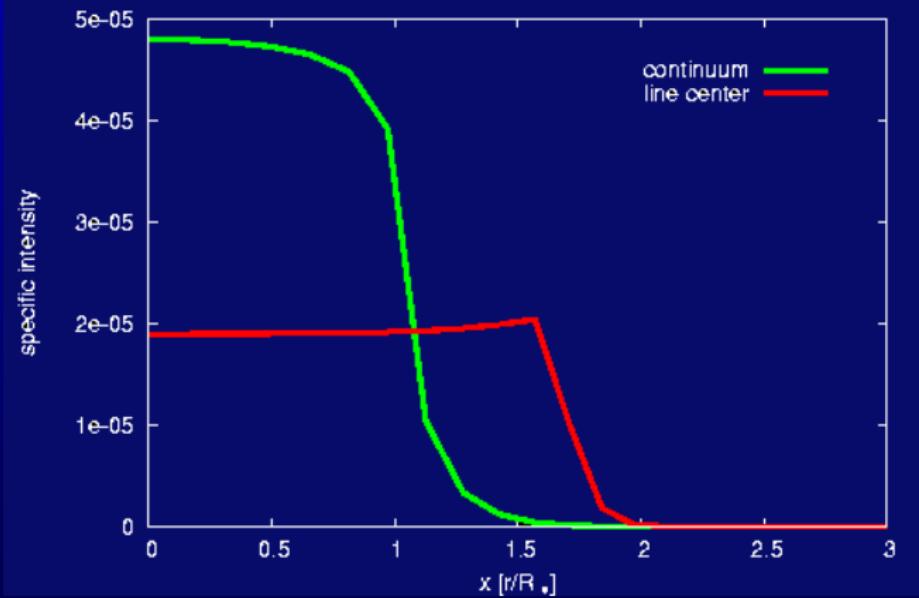
method applicability

- limb darkening
- stellar rotation
 - gravity darkening, differential rotation
- stellar wind
 - optically thin + optically thick regions
 - polar + equatorial regions
 - Be, B[e] stars, ...
- discs
 - cataclysmic variables, protostellar discs
- central object + surrounding medium
 - protoplanetary nebulae

limb darkening



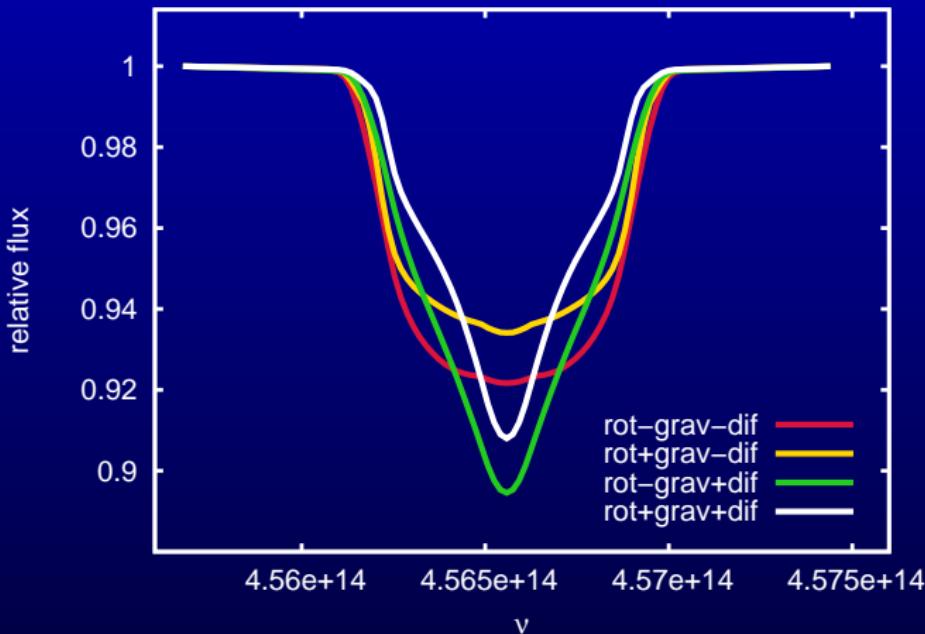
limb darkening



stellar rotation

- rapidly rotating stars
- gravity darkening
- differential rotation

extended rapidly rotating atmosphere

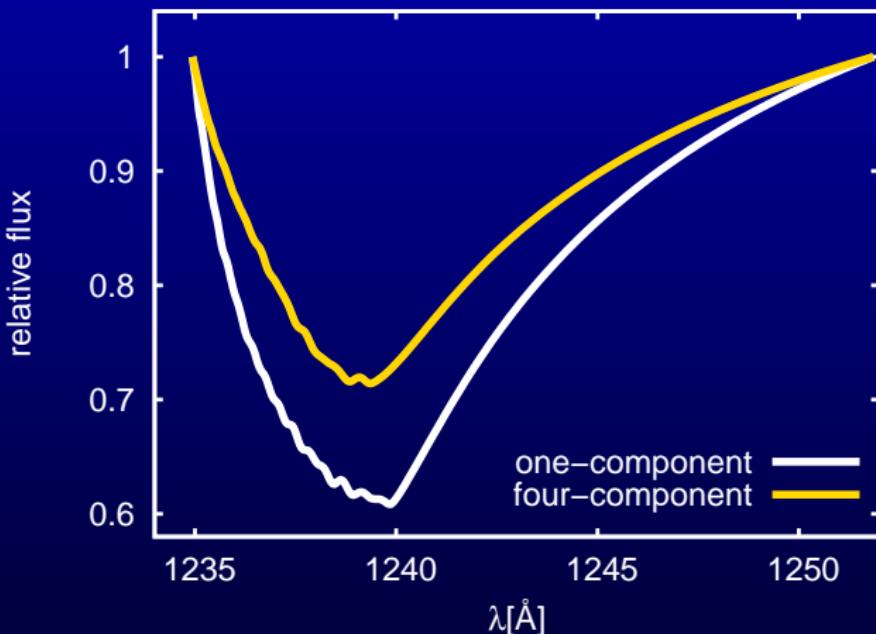


stellar wind

- optically thick atmospheric regions + optically thin wind
- polar + equatorial region
- static layers + fast outer region
- stellar wind + rotation
- Be, B[e] stars

– N V line 1242 Å

Krtička, Korčáková, Kubát, 2008, ASPC 388, 191



discs

- protostellar discs
- cataclysmic variables =
central white dwarf + transition region
+ disc + hot corona
 - disc – optically thick or thin
 - impossible to include a hot spot



technique

- structure, χ and S from AcDc code
Nagel et al., 2004, A&A, 428, 109
 - disc = set of concentric rings
 - consistent solution of:
 - radiative transfer equation
 - hydrostatic equation
 - energy balance equation
 - rate equation
 - equation of charge and particle conservation
- 2D grid
- interpolation of S and χ to the new grid
Steffen, 1990, A&A, 239, 443
- Kepler rotation law
- radiative transfer using the 2.5D code

choice of the systems

- the quiescent phase – optically thinner \Rightarrow effects connected with the velocity field better visible
- SS Cyg
 - H α
 - H γ
- an AM CVn system
 - HeI 4923 Å

SS Cyg

- an intermediate polar

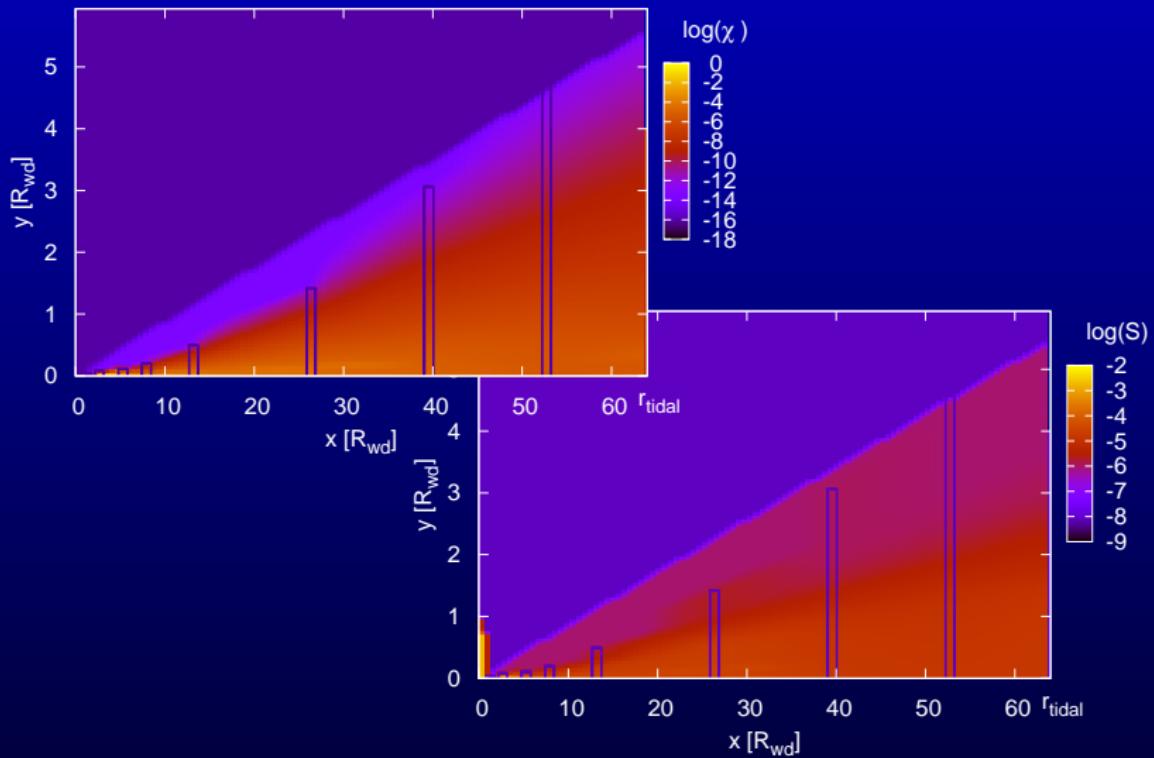
M_{wd}^*	$(0.81 \pm 0.19)M_\odot$
$q^* = M_K/M_{wd}$	0.683 ± 0.012
a^*	$(1.36 \pm 0.11) \times 10^{11}\text{cm}$
R_{wd}^{**}	$0.011 R_\odot$
P^*	0.27512973 days
i^*	$45^\circ - 56^\circ$

* Bitner et al., 2007, ApJ, 662, 564

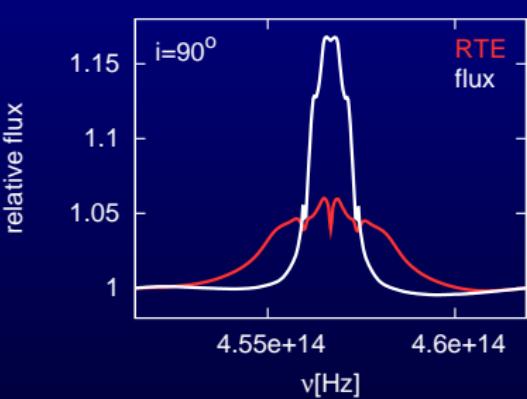
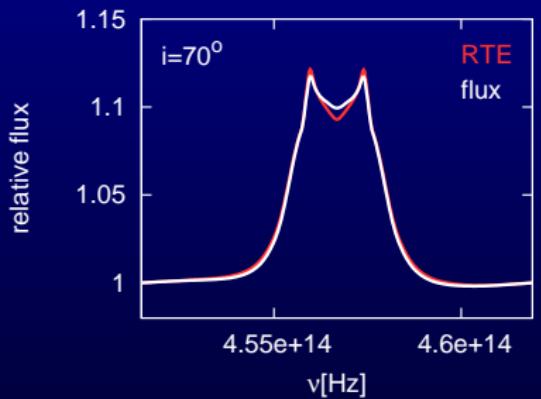
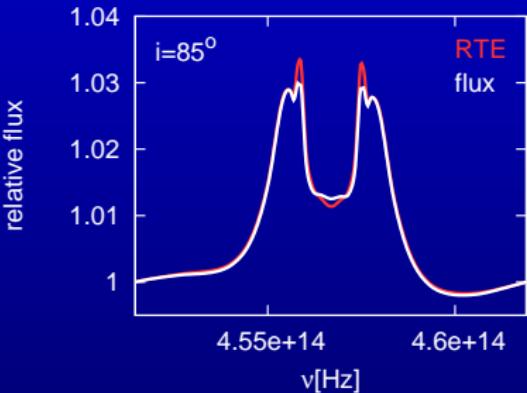
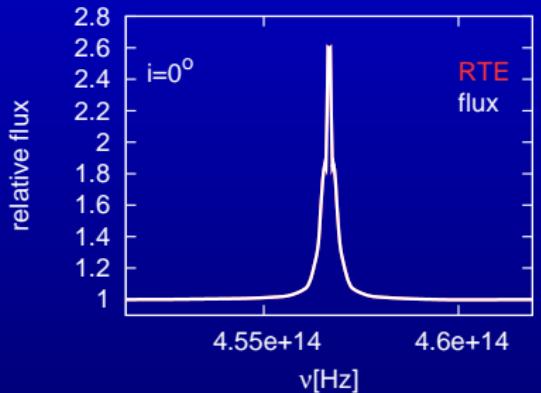
** Wood, 1995, LNP, 443, 41

- model – H + He – 8 rings;
 $\dot{M} \in <1 \times 10^{-11}, 1 \times 10^{-9}> M_\odot\text{yr}^{-1}$

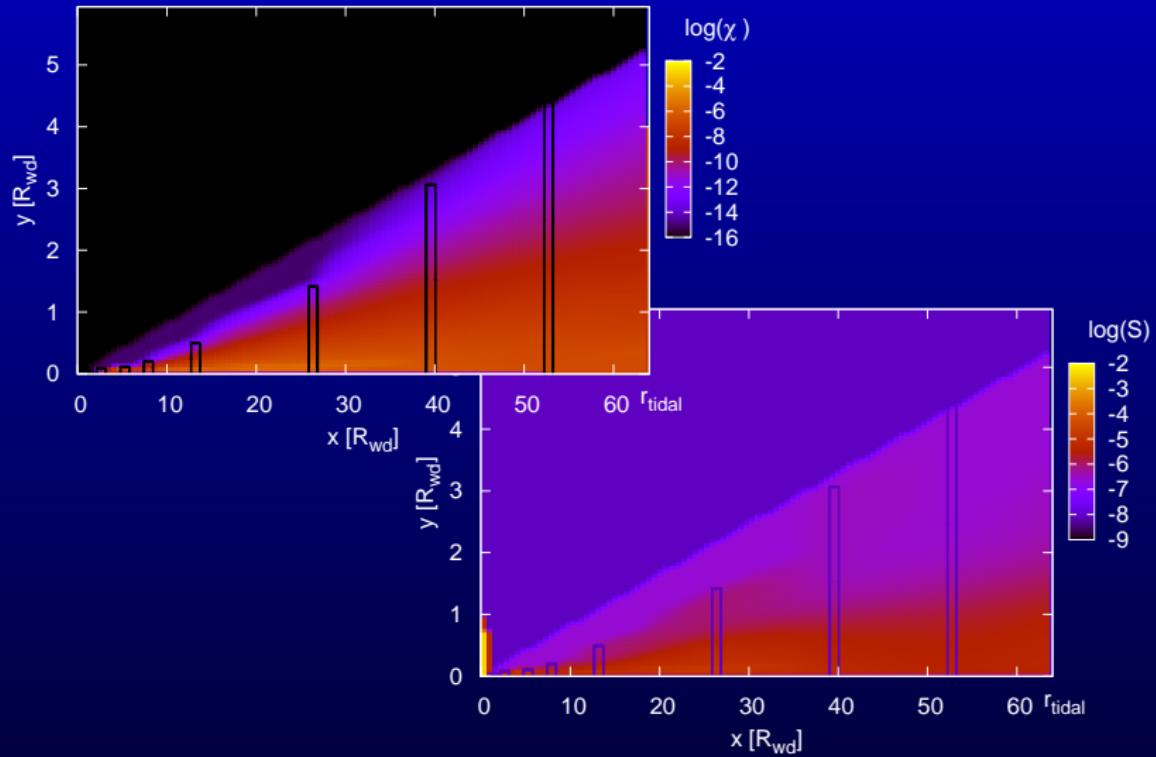
SS Cyg – quiescent phase – H α



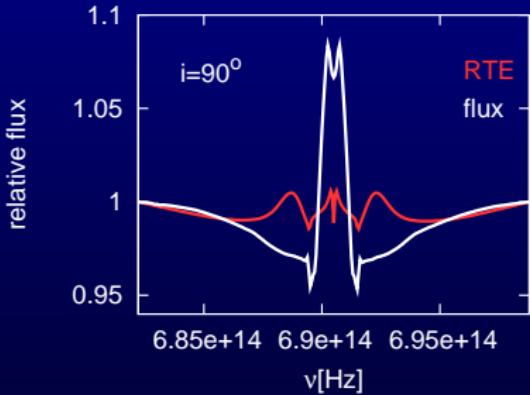
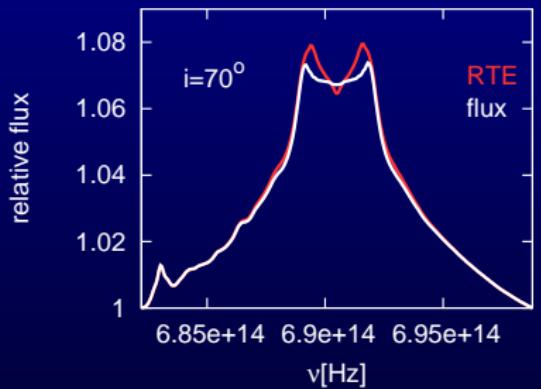
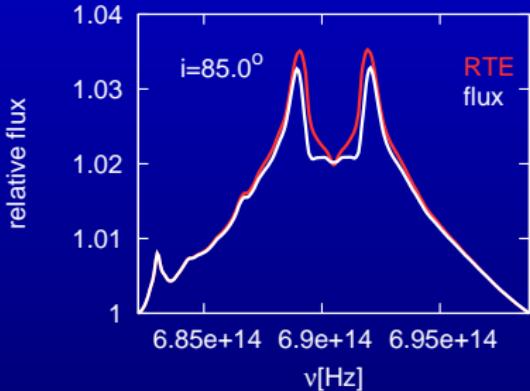
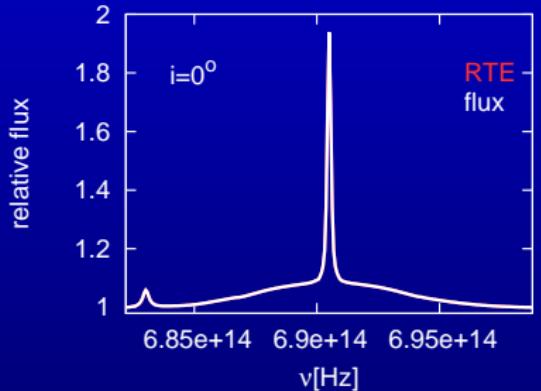
SS Cyg – quiescent phase – H α



SS Cyg – quiescent phase – H γ



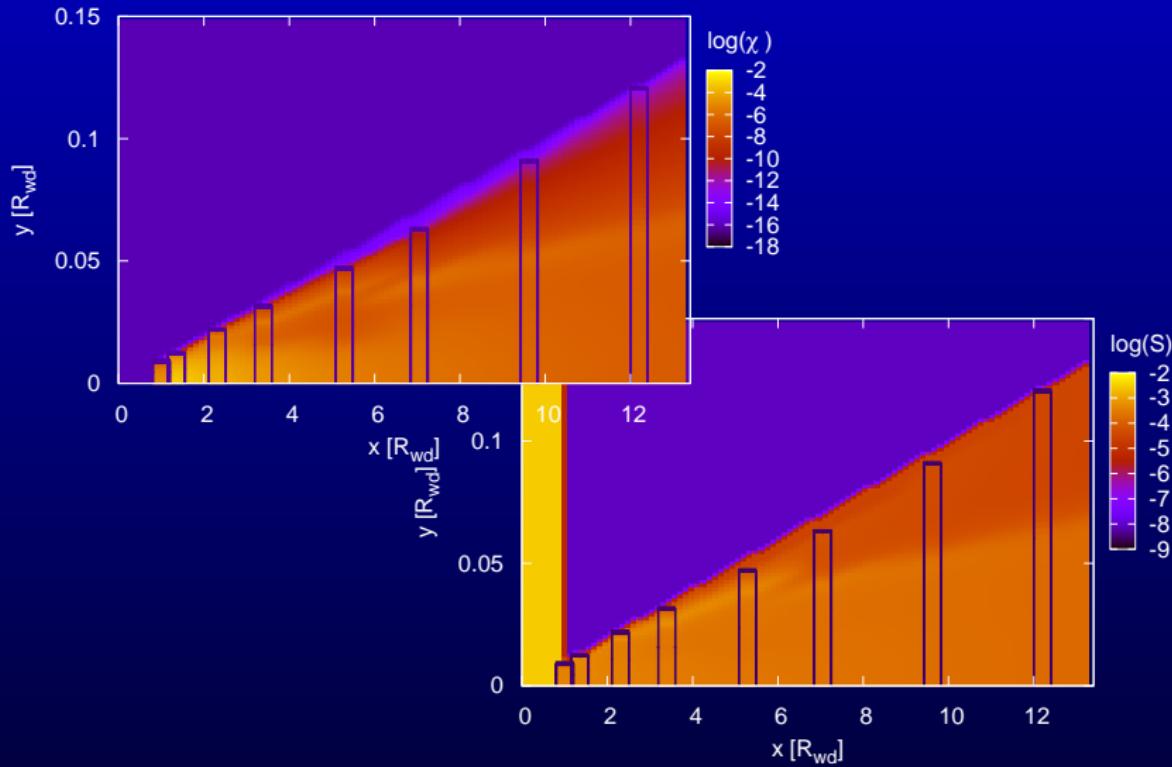
SS Cyg – quiescent phase – H γ



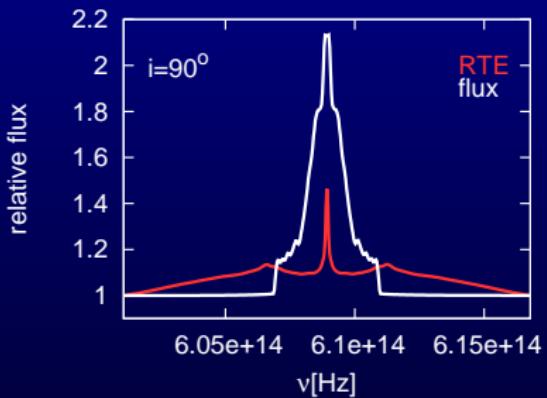
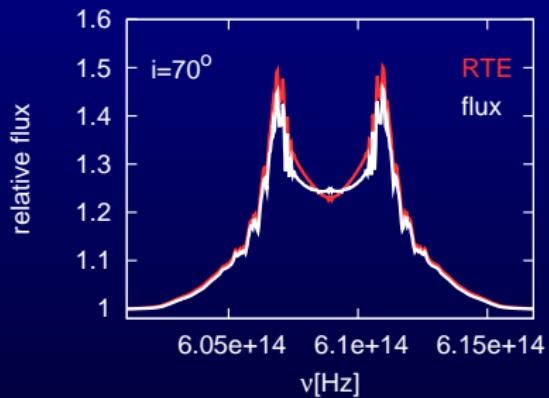
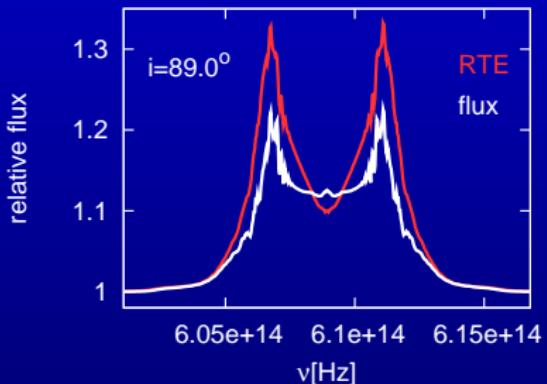
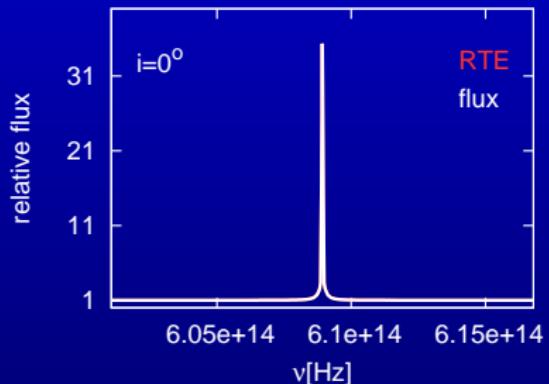
an AM CVn star

- $P_{\text{orb}} < 1 \text{ hour} \implies$ compact donors
- nature
 - white dwarf (neutron star) + white dwarf
 - white dwarf (neutron star) + helium core burning star
 - white dwarf (neutron star) + main-sequence star
- model (GP Com)
 - quiescence phase
 - 9 rings
 - $\dot{M} \sim 10^{-11} M_{\odot} \text{yr}^{-1}$
 - Hel 4923Å

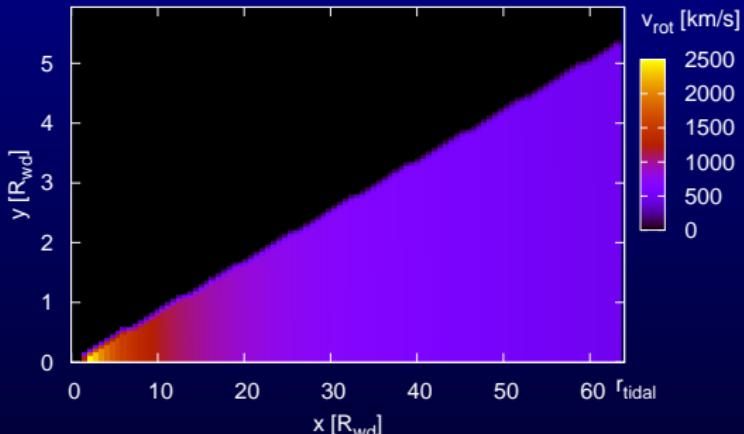
An AM CVn star – HeI 4923Å



an AM CVn star – HeI 4923Å



- face-on view
 - rotation velocity field has a negligible influence
 - static disc approximation for the radiative transfer is valid with high accuracy
- edge-on view
 - important difference



Where it can play the role?

- edge-on view – opening angle $\sim 10^\circ$
 - not so small probability
 - self-shielding disc (e.g. V348 Pup)
 - occulting systems – some UX UMa or SW Ser systems
 - low luminosity
 - dust is not important in most CVs (in contrast to polars)
- extended area
 - wind
 - important corona – polars, intermediate polars

conclusion

- axial symmetry + wind + rotation \implies
 - rapidly rotating stars
 - extended stellar atmospheres
 - stellar winds
 - discs