Modern view of the nearest vicinity of UXORs based on modeling their emission spectra

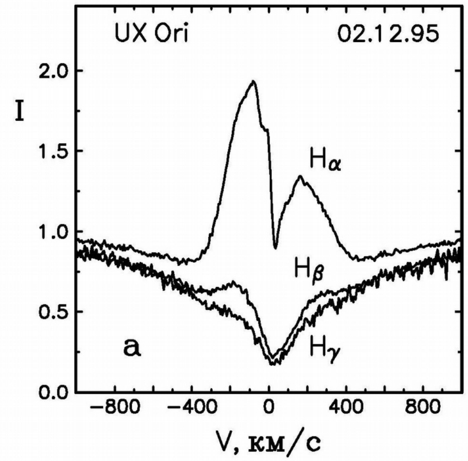
L.V. Tambovtseva and V.P. Grinin

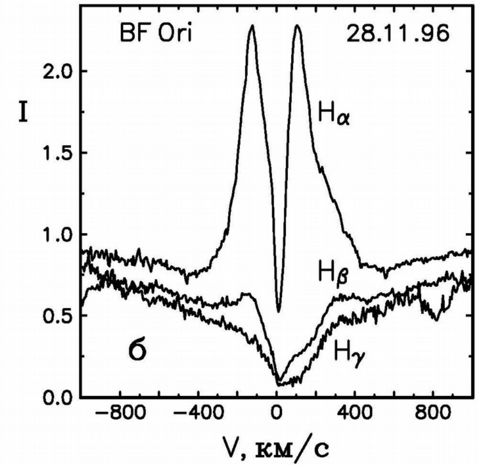
Pulkovo Astronomical observatory, Saint-Petersburg, RUSSIA

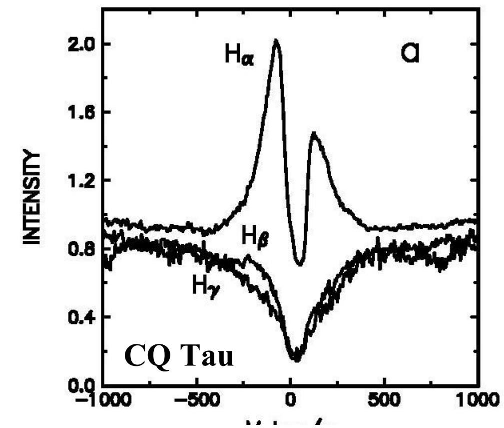
- Specific features of modeling emission spectra in UXORs
- Additional reasons for the line profiles variability in comparison to other Herbig stars
- Modeling the hydrogen emission spectra
- The Br γ problem. Spectroscopic and interferometric Br γ modeling in VV Ser
- Conclusion

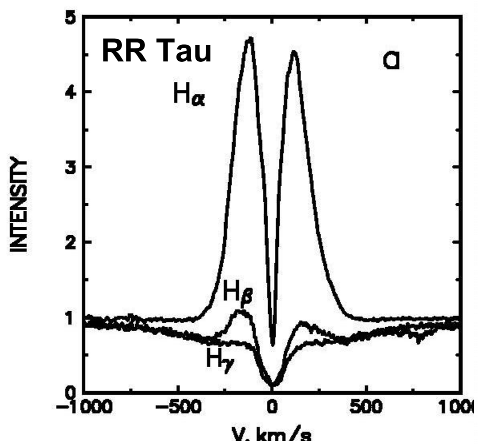
lvtamb@mail.ru

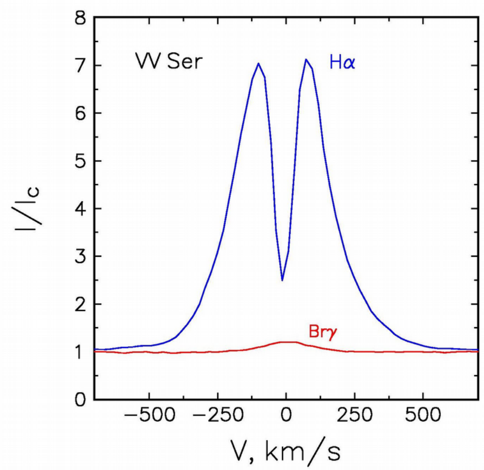
Grinin et al. 2001
(all spectra of UXORs;
different elements)











VV Ser:
Hα (mean) Mendigutia + (2011)
Brγ Garcia Lopez + (2016)

Table 3. New values of the stellar parameters.

Name	$T_{\rm eff}$ (K)	log g	$V_{\rm H}$ (km s^{-1})	$v \sin i$ (km s^{-1})
UX Ori	9500	4.0	+18	140
CQ Tau	7000	3.5	+20	90
BF Ori	8750	4.0	+18	40
RR Tau	9750	3.5	+11	140
WW Vul	8500	3.5	−12	150

Mora + (2001)

215

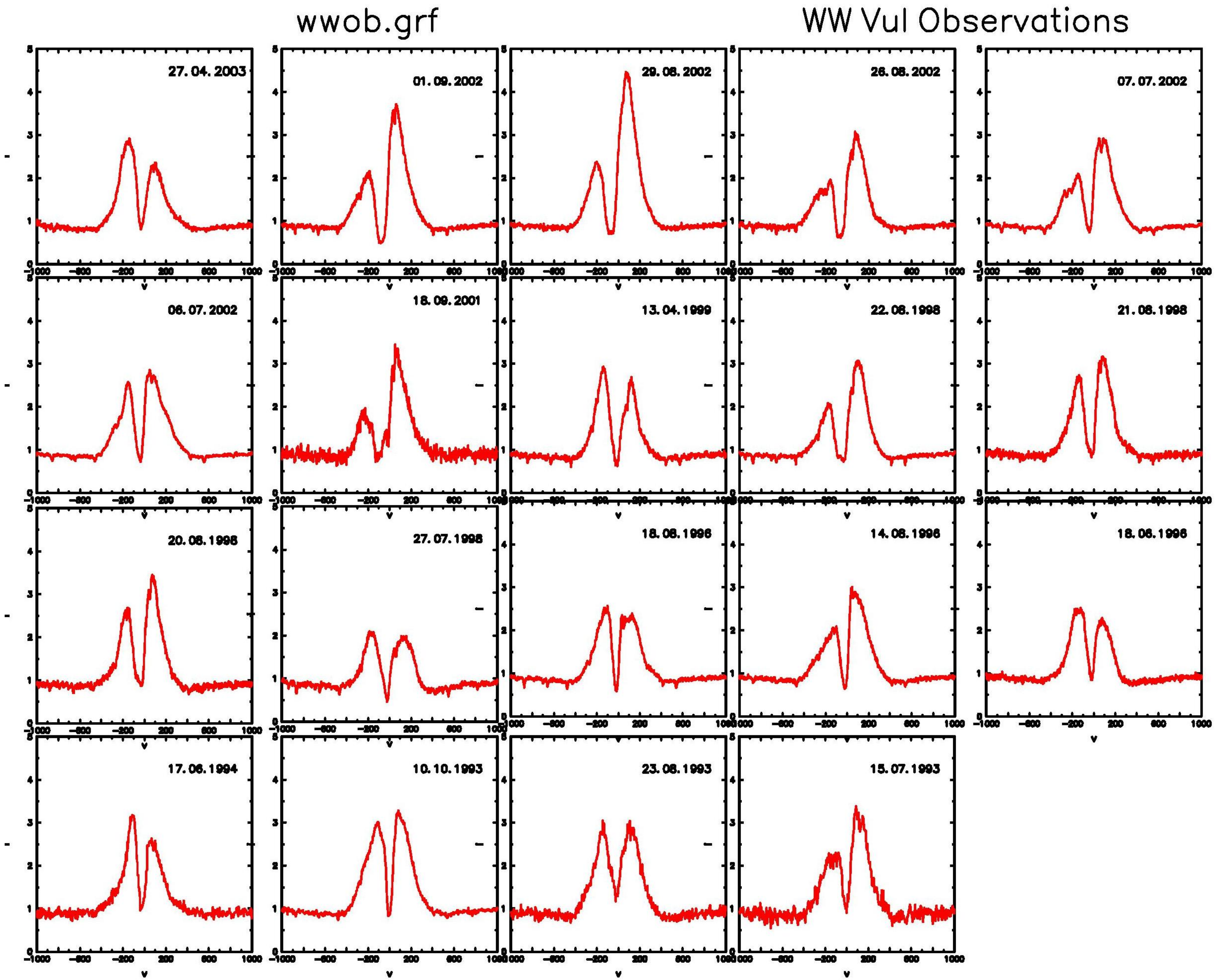
37

210

compactness of MA:

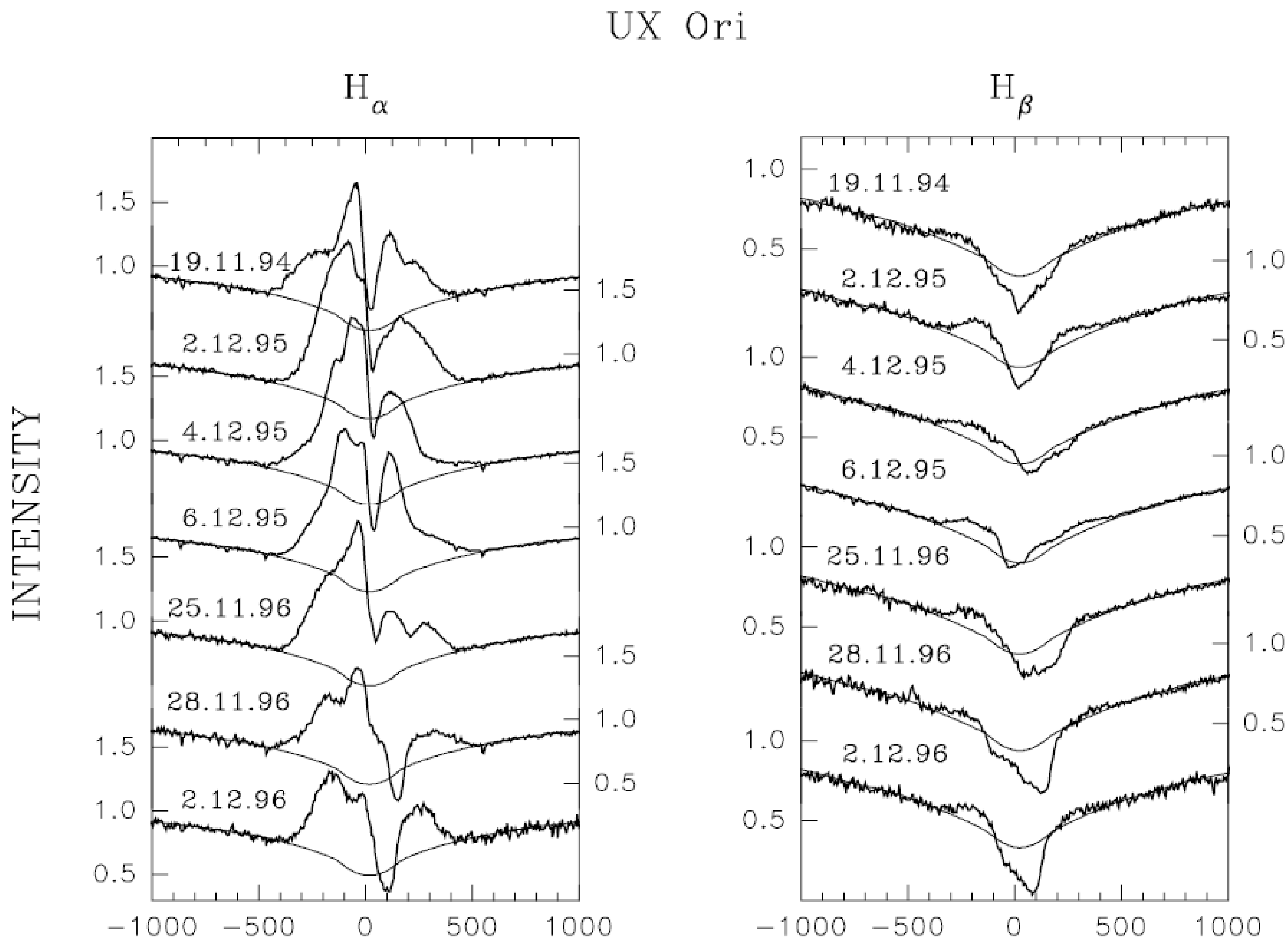
Grinin & Tambovtseva 2011
Garcia Lopez + 2015, 2016
Caratti o Garatti + 2015

Cauley & Johns-Krull (2014)
(He I 10830)



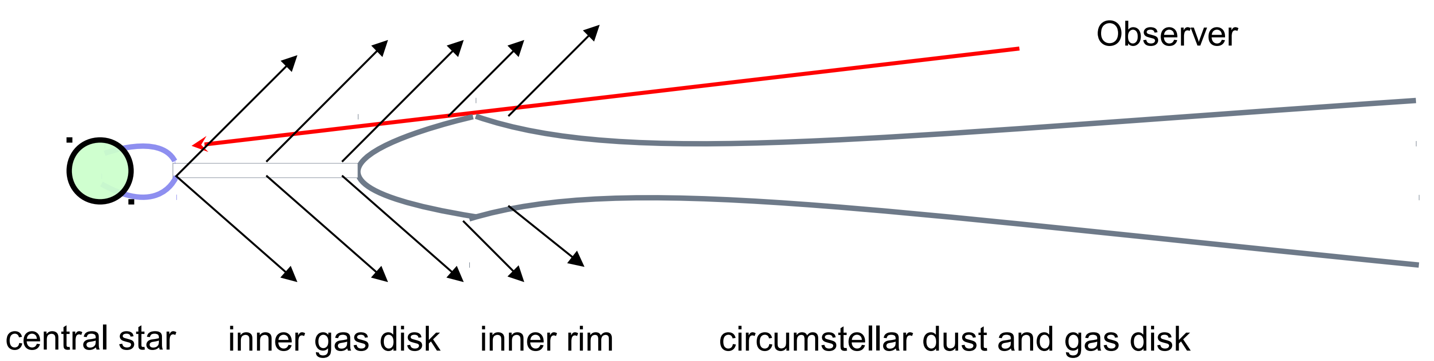
wwob.grf
WW Vul Observations
27.04.2003
01.09.2002
29.08.2002
26.08.2002
07.07.2002
06.07.2002
18.09.2001
13.04.1999
22.08.1998
21.08.1998
20.08.1998
27.07.1998
18.08.1996
14.08.1996
18.06.1996
17.06.1994
10.10.1993
23.08.1993
15.07.1993

V. P. Grinin et al.: UXORs-spectra (2001)

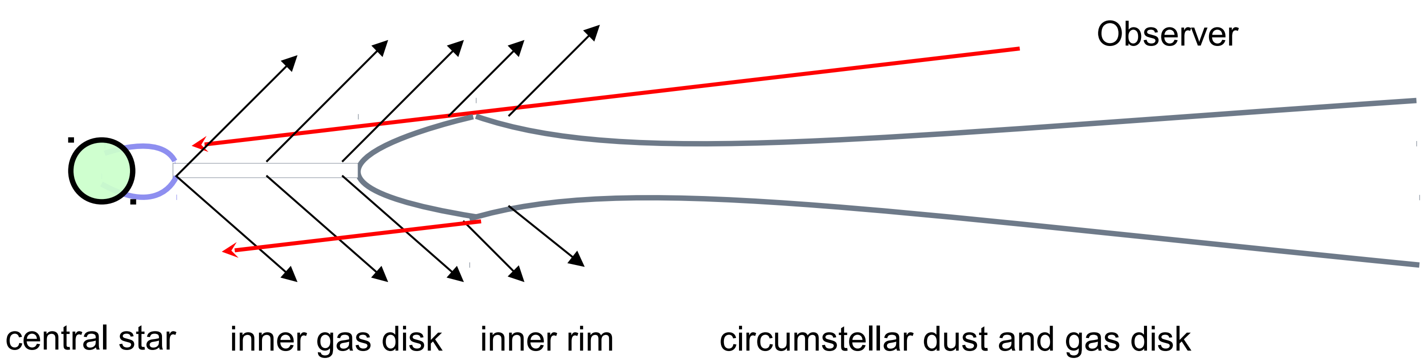


Natta et al. 2000 (accretion events in UX Ori in details)

UX Ori type stars (UXORs)



UX Ori type stars (UXORs)



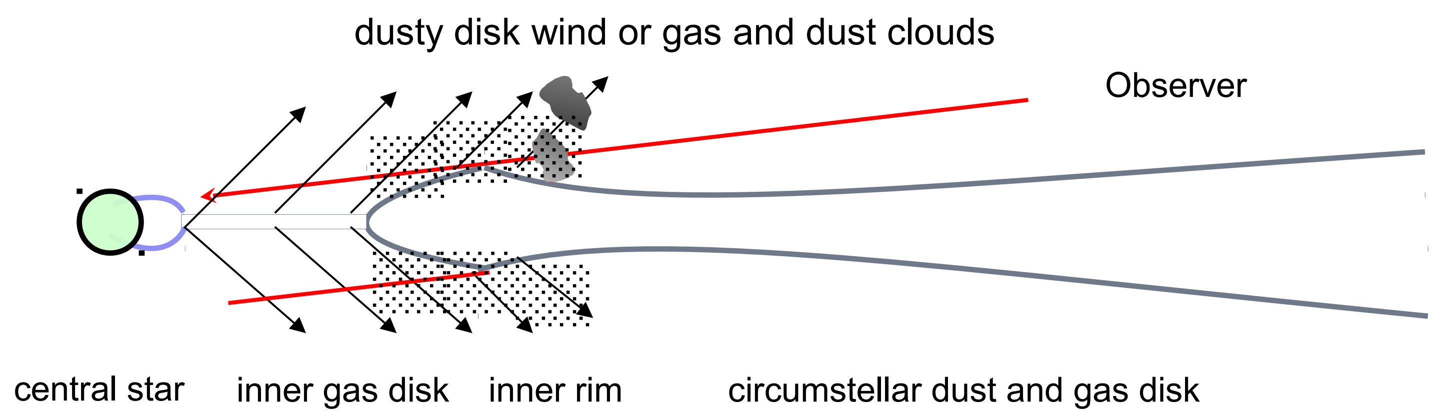
Obscuration of the

- densest,
- rapidly rotating,
- low radial velocity disk wind regions;

2. Asymmetry of the line profiles;

3. Strong emission lines variability.

4. Noticeable contribution of the light scattered by dust to the line radiation



1. Obscuration of the
   - densest,
   - rapidly rotating,
   - low radial velocity disk wind regions;

2. Asymmetry of the line profiles;

3. Strong emission lines variability.

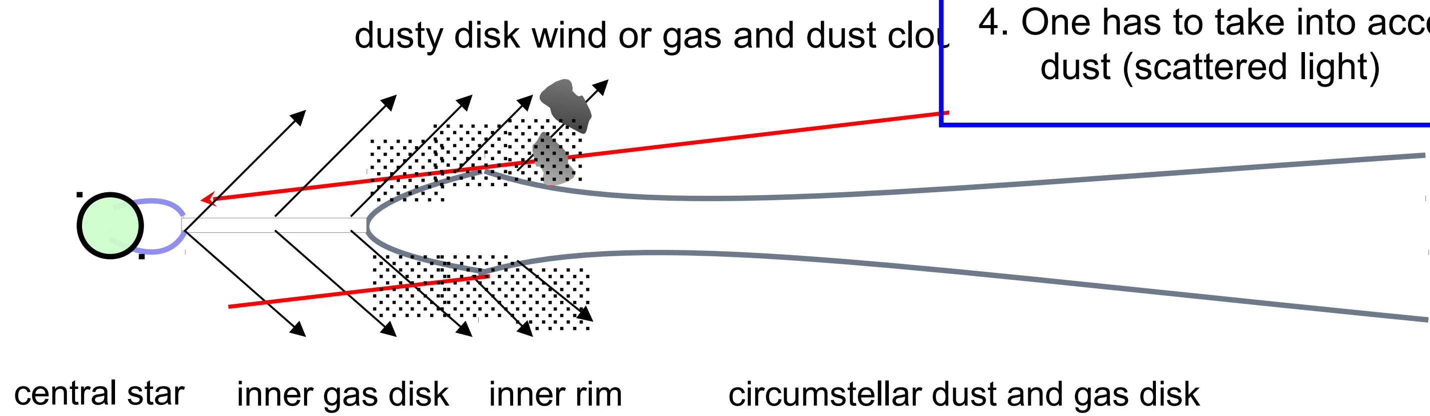
4. Noticeable contribution of the light scattered by dust to the line radiation

1. These stars need a photometric monitoring (an informational source for cyclic activity, revealing protoplanets, emission lines modeling, etc.

2. Spectra modeling can give reliable information about a usual state of the star if it will be observed at the normal (bright) state (out of eclipse).

3. When modeling the line profile with strong accretion features, one can distinguish between the event: obscuration by the gas and dust cloud or a fall of the large portion of the matter onto the star.

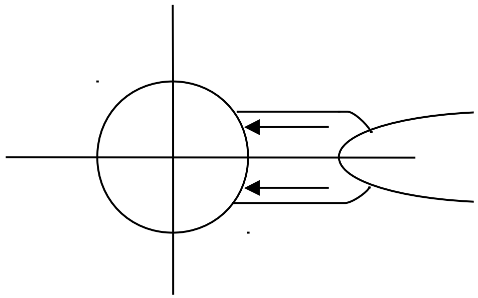
4. One has to take into account a presence of the dust (scattered light)



Previous modeling:

	Stars	Emitting regions
Tambovtseva et al. 1999, 2001	UX Ori, RR Tau, CQ Tau, WW Vul, BF Ori	flat-like magnetosphere
2008, 2019	+ VV Ser	+ classical magnetosphere + mcf – disk wind + polar wind + scattered light
Muzerolle et al. 2004	UX Ori (Vrot=70km/s)	classical magnetosphere
Mendigutia et al. 2011	BF Ori (Vrot=40 km/s)	classical magnetosphere

Flat-like magnetosphere
rotating gas, free-fall motion (HAEBEs)



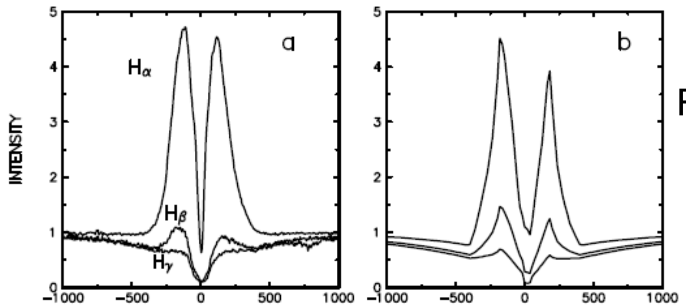
$$v(r)\frac{dv}{dr} = -\frac{GM}{r^2} + \frac{u^2(r)}{r}$$

$$\dot{M} = 2\pi r h v \rho(\mathrm{r})\mathrm{v}(\mathrm{r})$$

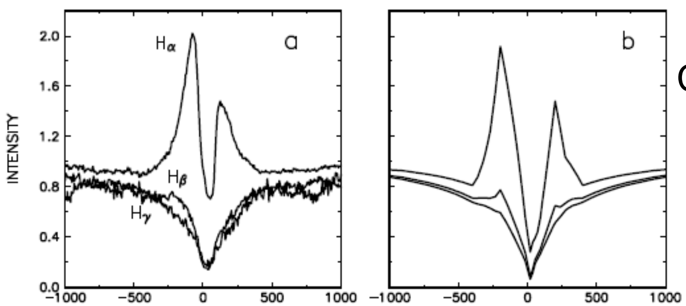
$$T(r) = T_0 (r/R_{¿})^{-\alpha}$$

α : 1/2 ÷ 1/3

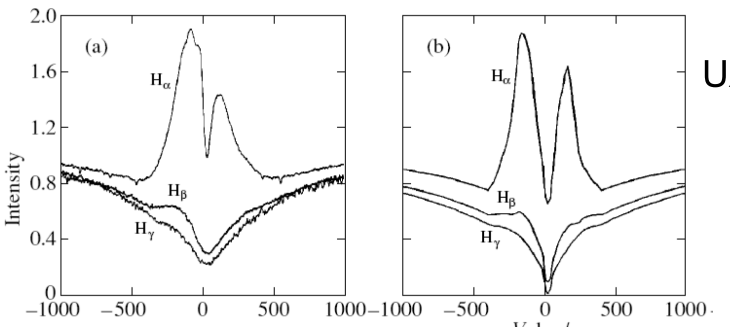
UXORs



RR Tau

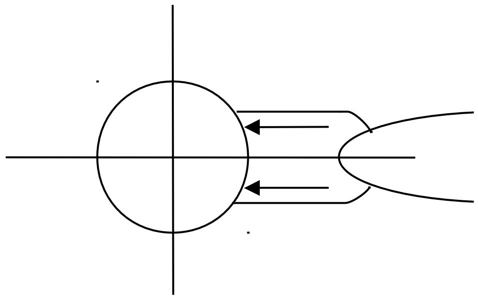


CQ Tau



UX Ori

Disk accretion + gaseous disk



UXORs

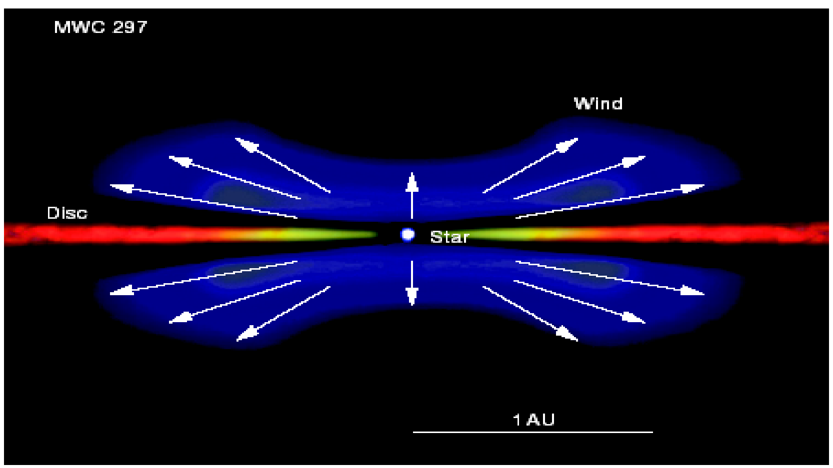
Flat-like magnetosphere
rotating gas, free-fall motion (HAEBEs)

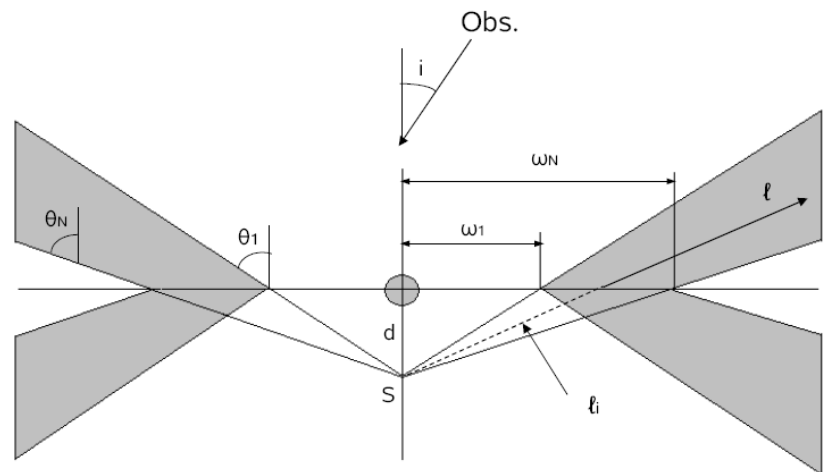
$$v(r)\frac{dv}{dr}=-\frac{GM}{r^2}+\frac{u^2(r)}{r}$$

$$\dot{M}=2\pi rhv\rho(\mathrm{r})\mathrm{v}(\mathrm{r})$$

$$T(r)=T_0(r/R_{¿})^{-\alpha}$$

α : 1/2 ÷ 1/3





$$\frac{\dot{M}_w}{\dot{M}_{acc}}=0.1$$

Blandford & Payne 1982, Pudritz & Norman 1986,
Königl & Pudritz 2000, Ferreira 2007, 2013

Intensity of the radiation:

$$J_{ik} = (1- < \beta_{ik} >) S_{ik} + J^{\star}_{ik} W \beta^{\star}_{ik}$$

Source function:

$$S(r) = \frac{2hv^3}{c^2} \left(\frac{n_k(r)}{n_i(r)} \frac{g_i}{g_k} - 1 \right)^{-1}$$

Mean escape probability of the quantum in the line *ik* from the given point of the medium:

$$< \beta_{ik}(l,\theta) > = \int \beta_{ik}(r,l,\mathsf{s}) \frac{d\Omega}{4\pi} ,$$

$$\beta_{ik}(l,\theta,\mathsf{s}) = \frac{1 - e^{-\tau_{ik}}}{\tau_{ik}}$$

The integral is taken over all solid angles Ω (ℓ,θ)

The effective optical depth of the emitting region at the point with co-ordinates (ℓ,θ):

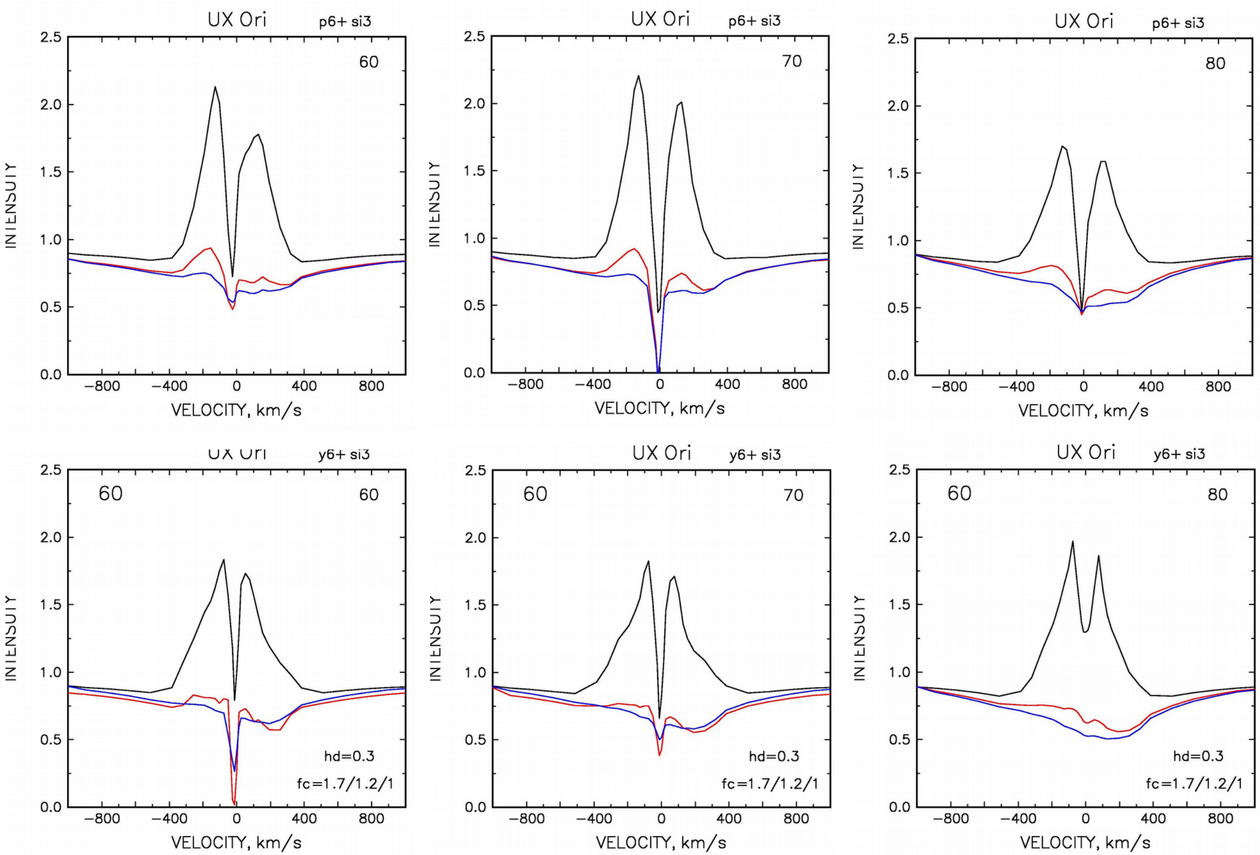
$$\tau_{ik}(l,\theta,\mathsf{s}) = \kappa_{ik}(l,\theta)\, v_t\, |dv_{\mathsf{s}}/ds|^{-1}$$

SEI = Sobolev + Exact Integration

$$I_w(\nu) = \int_A I_w(\nu,x,y)\,dx\,dy$$

$$I_w(\nu,x,y) = \int_{z_{min}}^{z_{max}} S(\mathbf{r}) \phi(\nu - \nu_0 \frac{\mathsf{v}_z(\mathbf{r})}{c})\, e^{-\tau(\nu,\mathbf{r})} \kappa(\mathbf{r}) dz$$

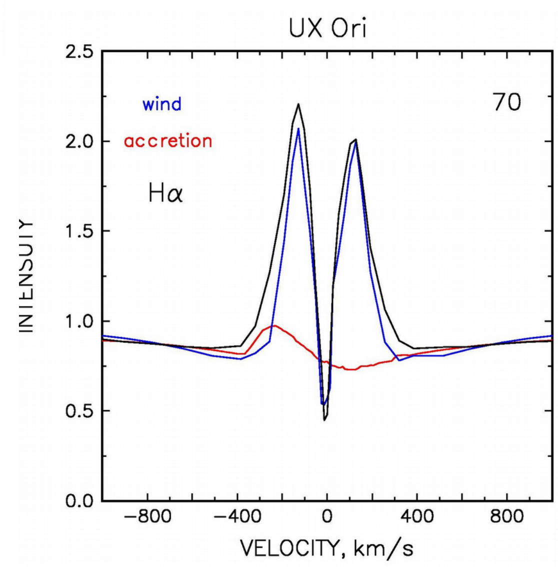
Grinin & Tambovtseva 2011

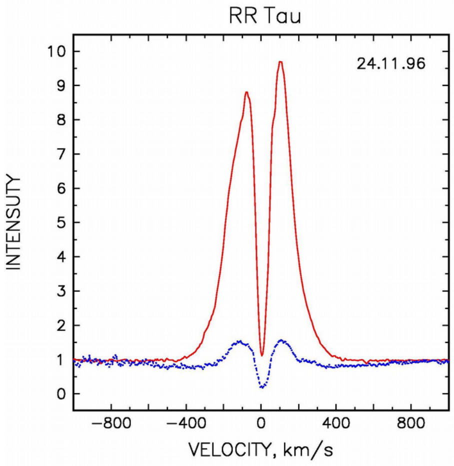


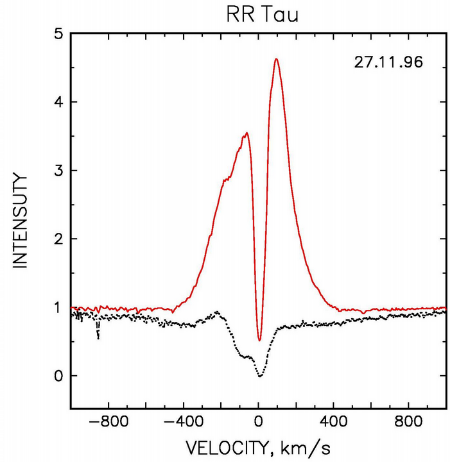
MA $\begin{cases} \dot{M}_{acc}=10^{-8} M_{SUN}/yr \\ r_c=1.5 R_{¿} \\ T(r)=T_0(r/R_{¿})^{-1/3} \\ T_0=8000\,K \end{cases}$

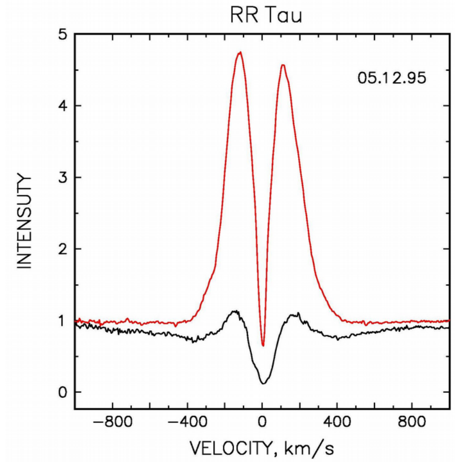
DW $\begin{cases} \dot{M}_w=2\times10^{-9} M_{SUN}/yr \\ \theta_1=45^{\circ} \\ w_1-w_N=2-10\,R_{¿} \\ T=10000\,K \end{cases}$

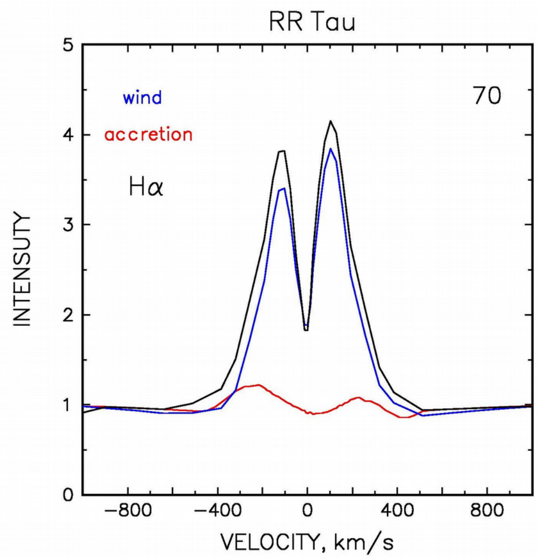
DW $\begin{cases} \theta_1=30^{\circ} \\ w_1-w_N=3-10\,R_{¿} \end{cases}$

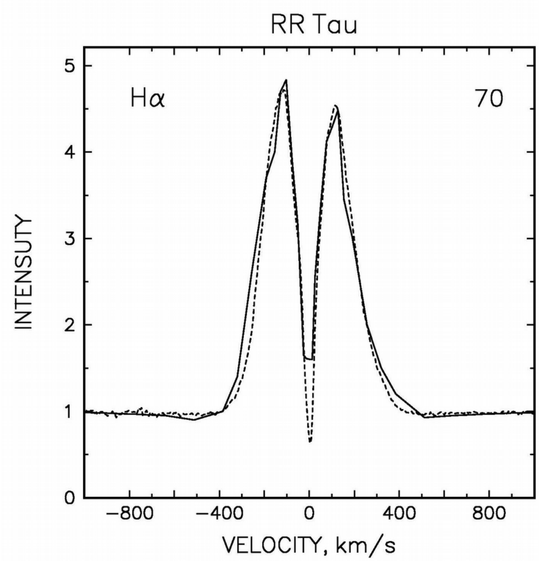












MA $\left\{ \begin{array}{c} \dot{M}_{acc}=10^{-7} M_{SUN}/yr \\ r_c=2R_{¿} \\ T_0=10000\,K \end{array} \right.$

$$\dot{M}_w=5\times10^{-9} M_{SUN}/yr$$
$$\theta_1=30^\circ$$
$$w_1-w_N=2-6\,R_{¿}$$

$$\dot{M}_w=1\times10^{-8} M_{SUN}/yr$$
$$\theta_1=30^\circ$$
$$w_1-w_N=2-20\,R_{¿}$$

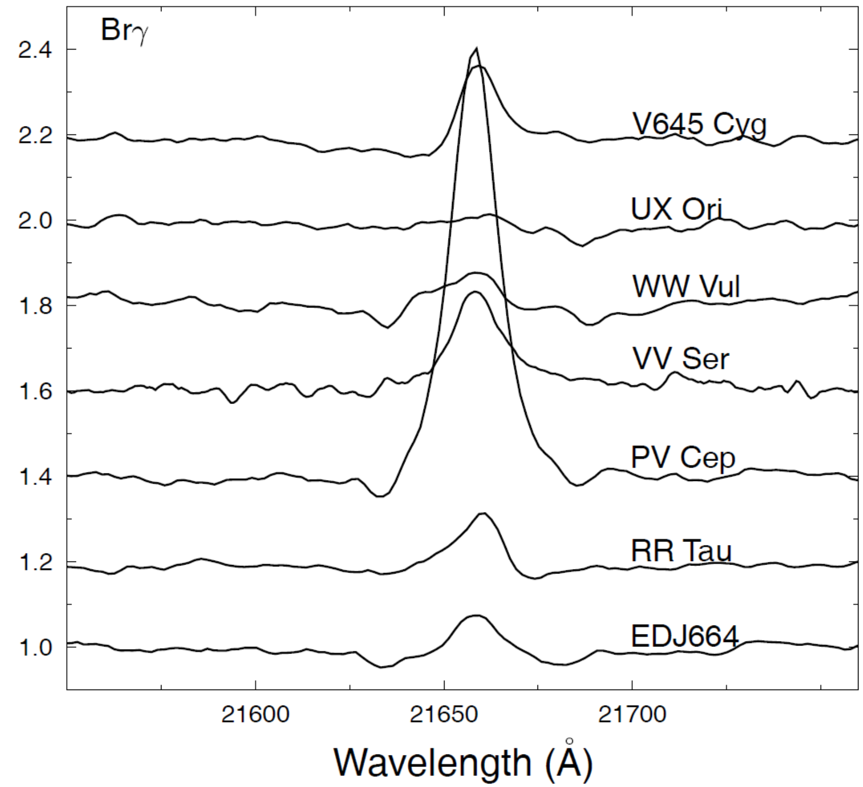
+ different kinematics

VV Ser, Sp B6 (Hernandez et al. 2004,
Montesinos et al. 2009)
or B7 (Reiter et al. 2018)
A0 (Mora et al. 2001)

Av ~ 3.4 (Rostopchina et al. 1999)
i = 60, 70°(Pontoppidan et al. 2007,
Lazareff et al. 2017)

observations:

interferometic (VLTI-AMBER) (R=1500)
spectroscopic (LBT-Lucifer) (R=6700)
(Garcia Lopez et al. 2016)



Magnetospheric accretion (MA)

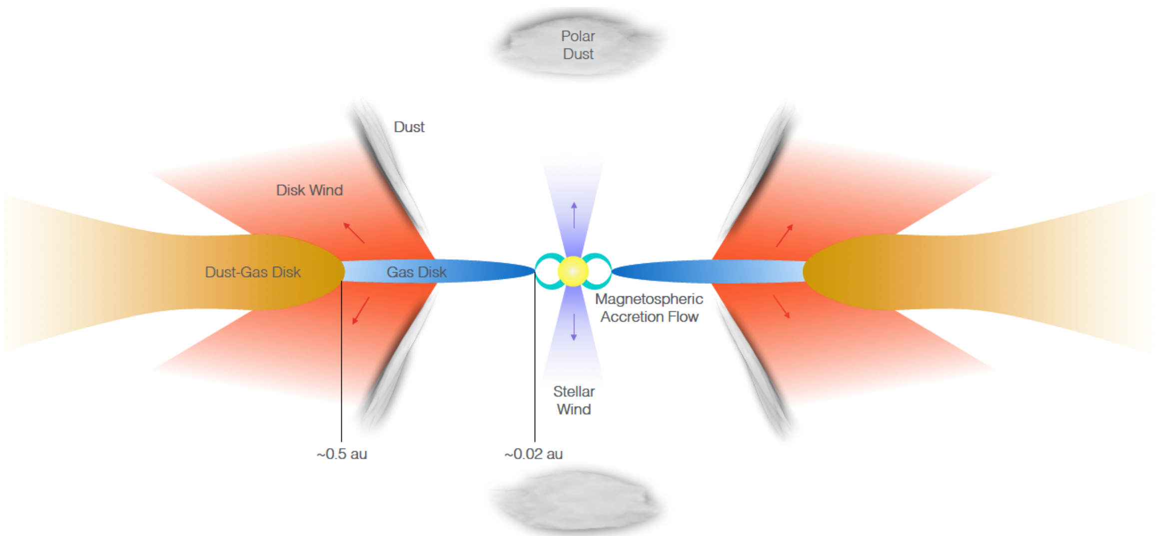
Polar wind (the Cranmer’s wind) (PW)

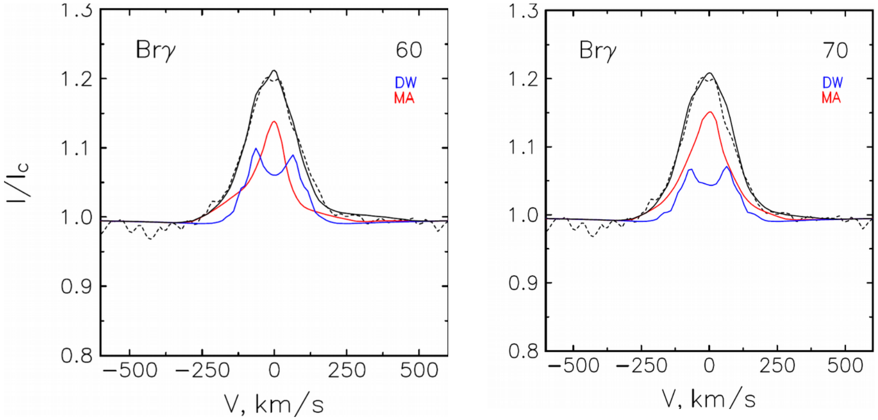
Radiation scattered by the CS dust

Magneto-centrifugal disk wind

and
Hybrid models:

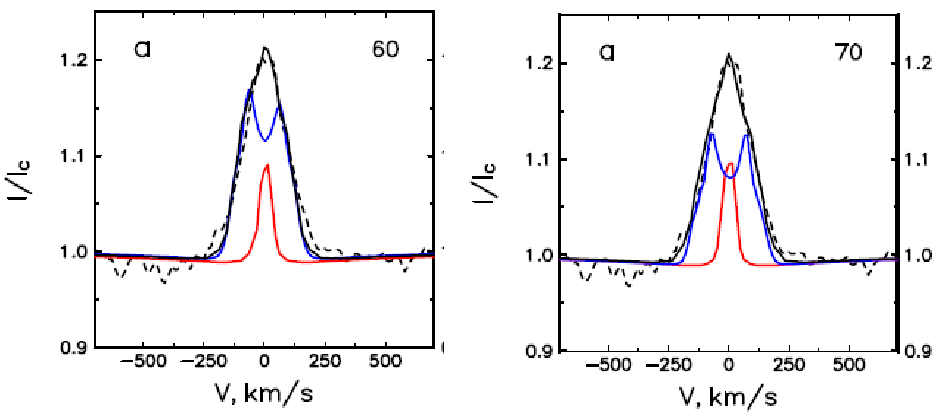
DW + MA
DW + PW
DW + scattered radiation





Disk wind (blue) + magnetospheric accretion (red)

$$\dot{M}_w / \dot{M}_{acc} \approx 0.1$$



Disk wind (blue) + polar wind (red)

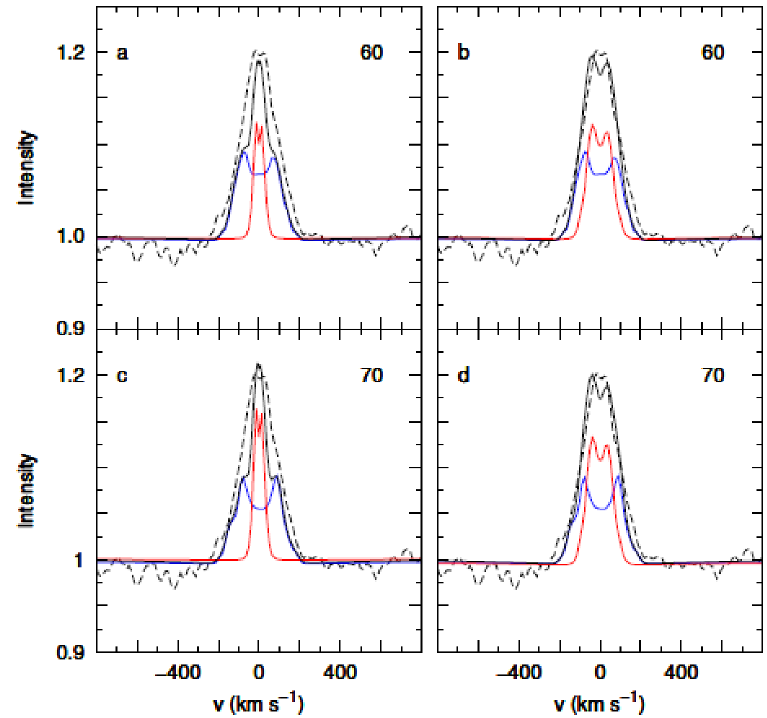
Disk wind

Resulting profile

Observed profile

$$\dot{M}_w / \dot{M}_{acc} \approx 0.01$$

Matt & Pudritz 2007
Cranmer 2008



Dust location: 0° 30°

Disk wind (blue) + scattered light (red)

$$I_{obs} = I_{dir} \exp(-\tau) + I_{sc} f_{sc}$$

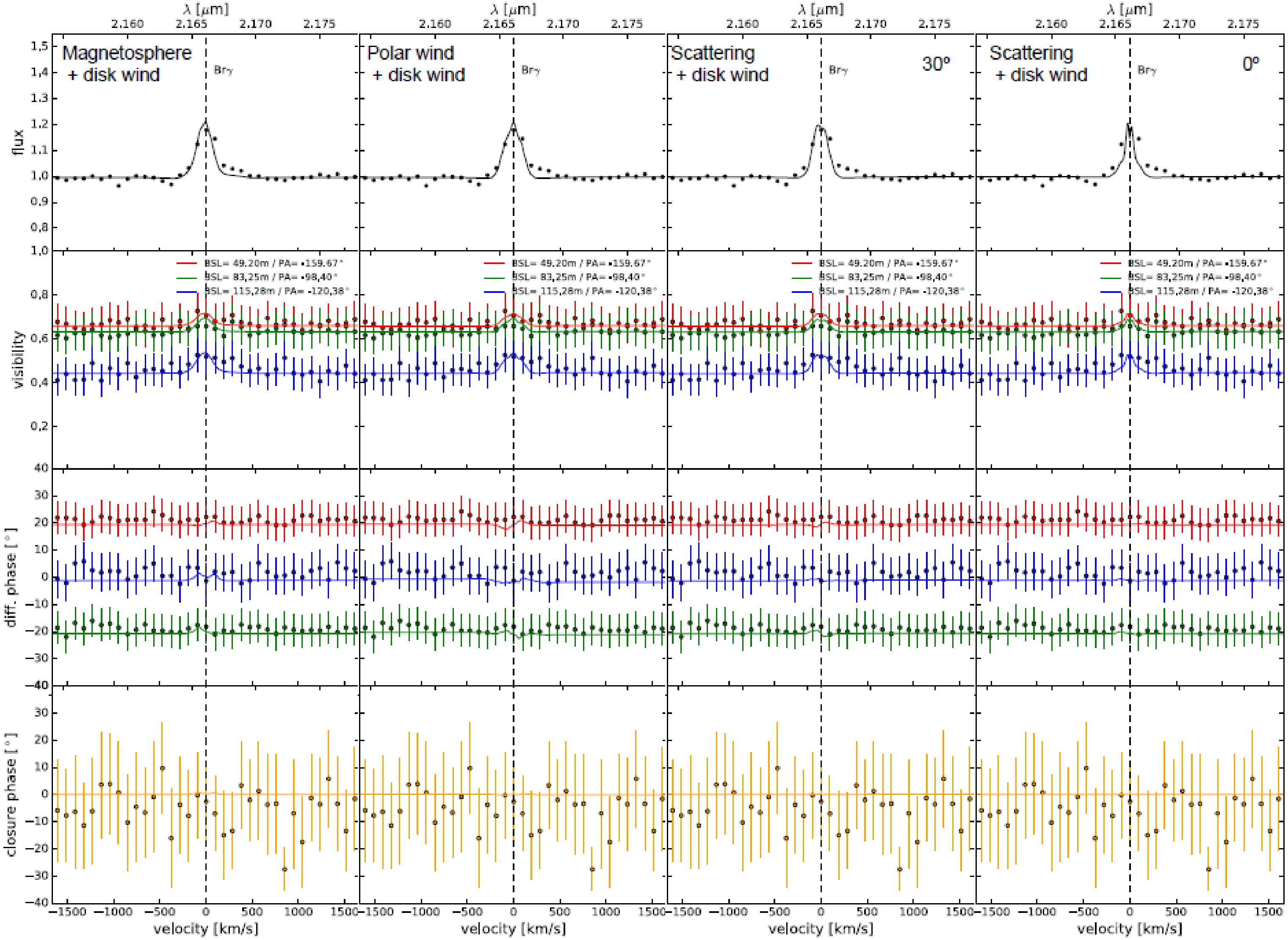
$$A_{Br} = 2.5 \log \frac{I}{I_0}$$

$$A \propto \lambda^{-1} \longrightarrow A_{Br\gamma}$$

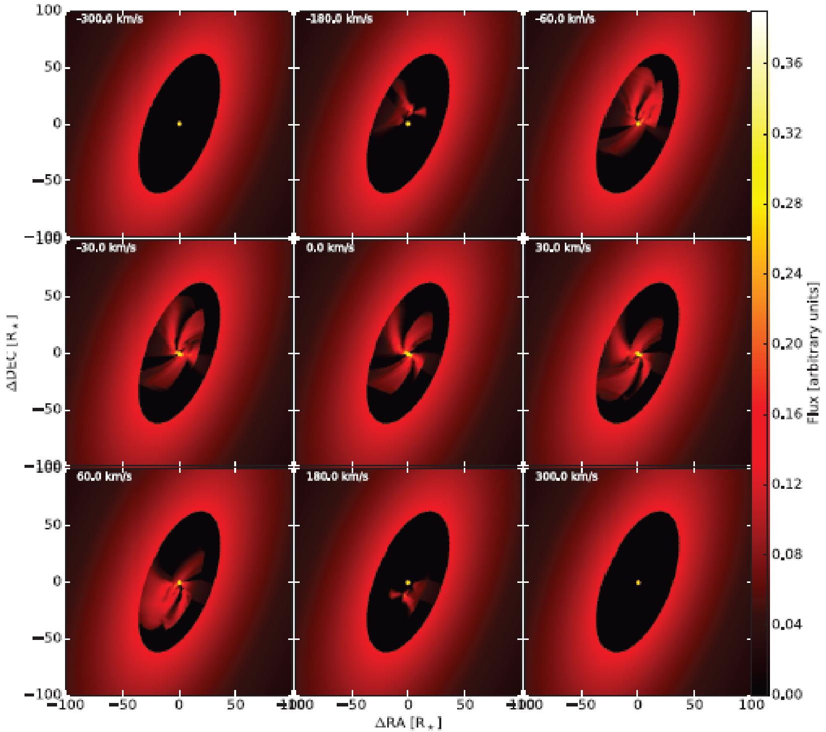
$$\log(I/I_0) \equiv \exp(-\tau)$$

f_{sc} $\longrightarrow$ from comparison of the calculated and observed line profiles

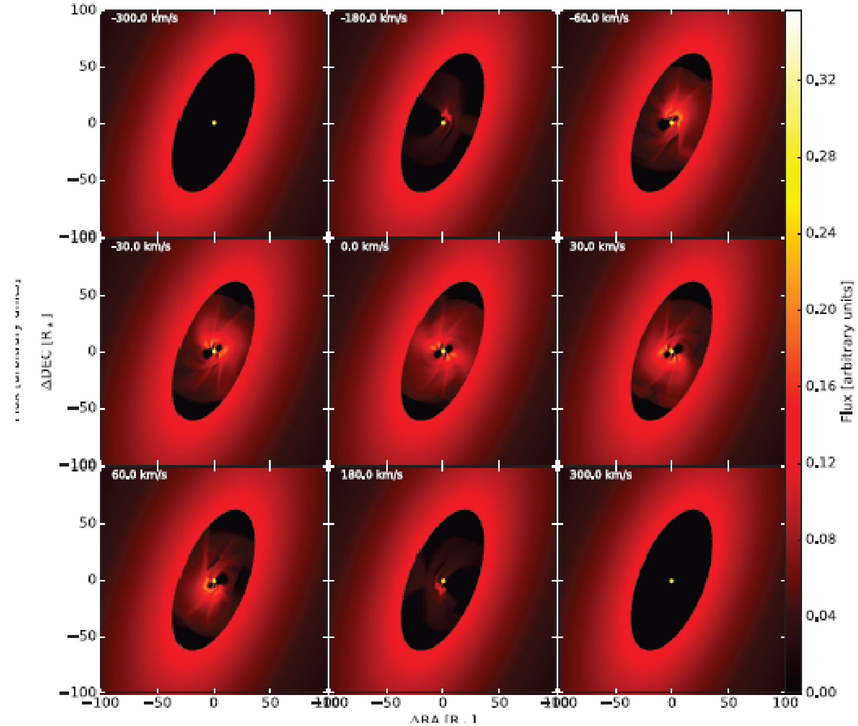
Appenzeller et al. 2005, Grinin et al. 2012



Tambovtseva, Kreplin, Grinin, Weigelt



Maps of the disk wind and polar wind seen at 70°



Maps of the disk wind seen at 70° and light scattered by the dust located along the cavity walls at 30°

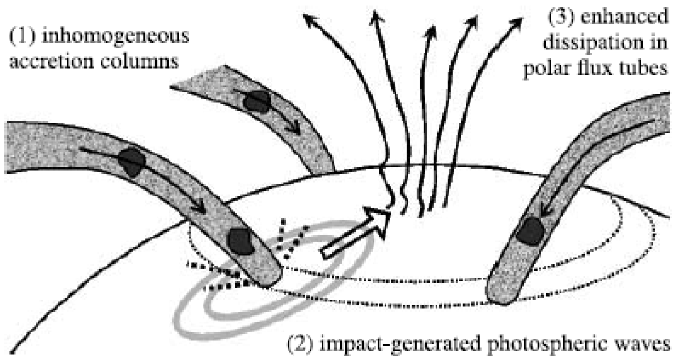
SUMMARY

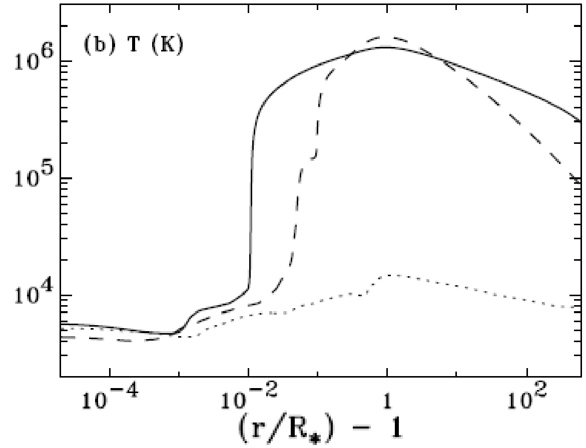
- Magnetospheres of UXORs are compact; emission from the disk wind region substantially contributes to the line emission. Estimates of $\dot{M}_{acc}$ only with magnetospheric accretion may be overstated
- The mass accretion rate from hydrogen emission line profiles is in the range $10^{-8}-10^{-7} M_{SUN}\, yr^{-1}$
- Spectroscopic observations has to be accompanied with photometric observations
- Modeling the emission spectra in UXORs can give important information not only about the gas distribution and motion in the nearest vicinity of stars but also information about a state, distribution and evolution of the dust in their protoplanetary disks

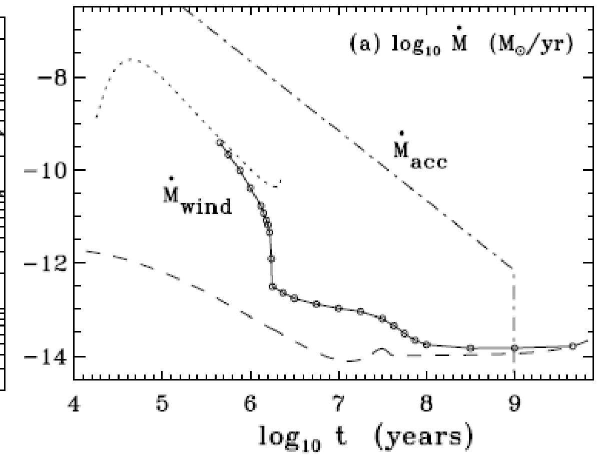
Hot polar wind in young stars = accretion driven wind

Matt & Pudritz (2007), Cranmer (2008)

Theoretical prediction







Sketch of the model

Physical mechanism:

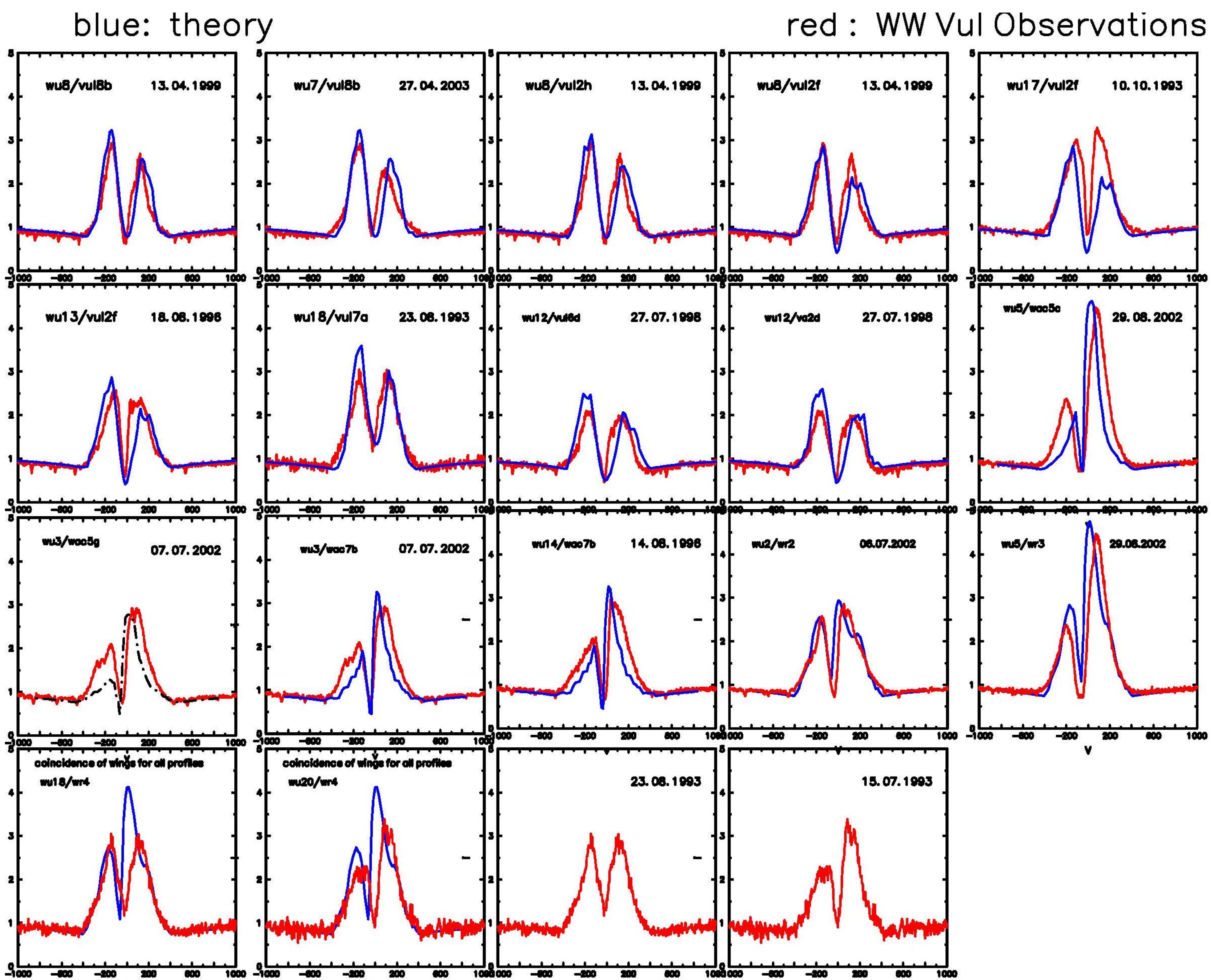
An accretion driven wind from the polar regions of TTSs.

A convection – driven MHD turbulence (a solar coronal heating) + another source of the wave energy that is driven by the impact of plasma in neighboring flux tubes undergoing magnetospheric accretion

Result:

Rapid heating the wind (T ~ 10^6 K)

Models with T = (10 000 - 15 000) K and the mass loss rate $10^{-9} M_{SUN}$ /yr (~ 0.01 of an accretion rate) are suitable for emission lines formation



blue: theory
red : WW Vul Observations
wu8/vul8b 13.04.1999
wu7/vul8b 27.04.2003
wu8/vul2h 13.04.1999
wu8/vul2f 13.04.1999
wu17/vul2f 10.10.1993
wu13/vul2f 18.08.1996
wu18/vul7a 23.08.1993
wu12/vul6d 27.07.1998
wu12/va2d 27.07.1998
wu5/wac5c 29.08.2002
wu3/wac5g 07.07.2002
wu3/wac7b 07.07.2002
wu14/wac7b 14.08.1996
wu2/wr2 08.07.2002
wu5/wr3 29.08.2002
coincidence of wings for all profiles
wu18/wr4
coincidence of wings for all profiles
wu20/wr4
23.08.1993
15.07.1993
v