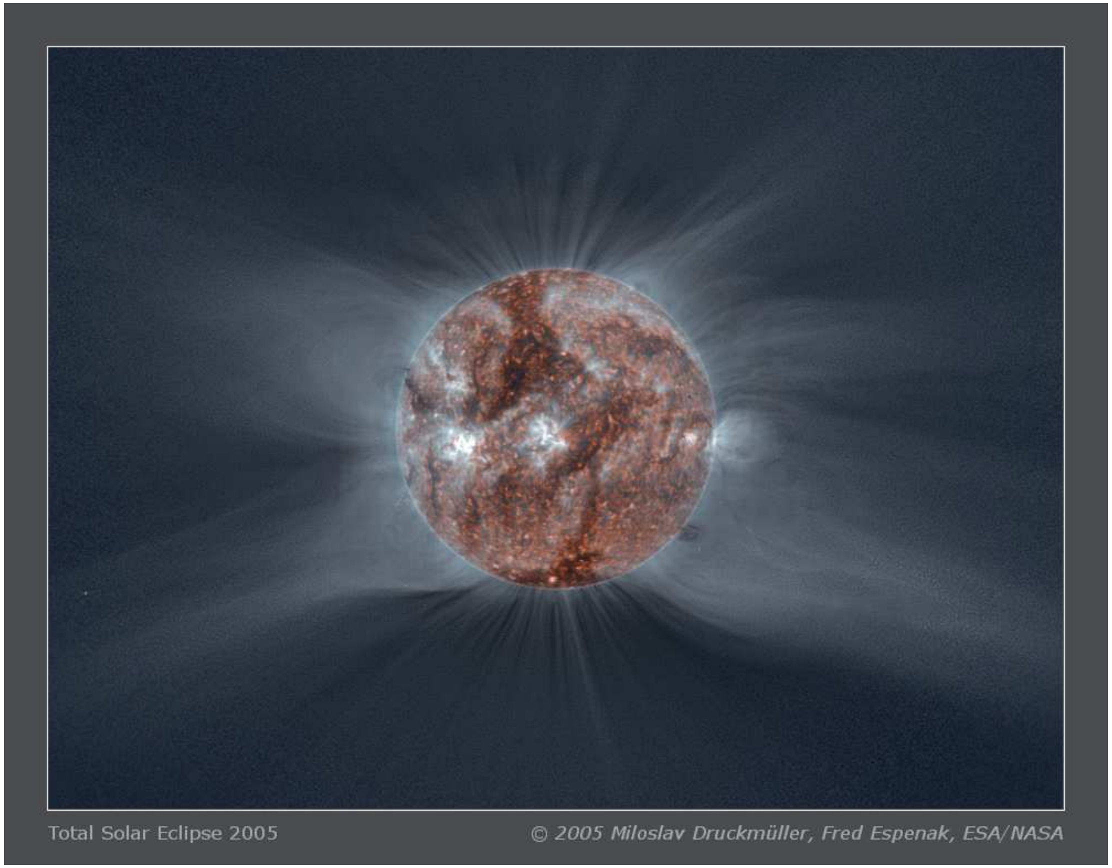
Influence of X-ray radiation on hot-star wind models

Jiří Krtička, Jiří Kubát



X-ray radiation

Properties of X-ray radiation

$\Rightarrow$ frequency: $\mathbf{3 \cdot 10^{16} - 3 \cdot 10^{19}}$ Hz

$\Rightarrow$ wavelength: $\mathbf{0{,}01 - 10}$ nm

$\Rightarrow$ energy: $\mathbf{0{,}1 - 100}$ keV

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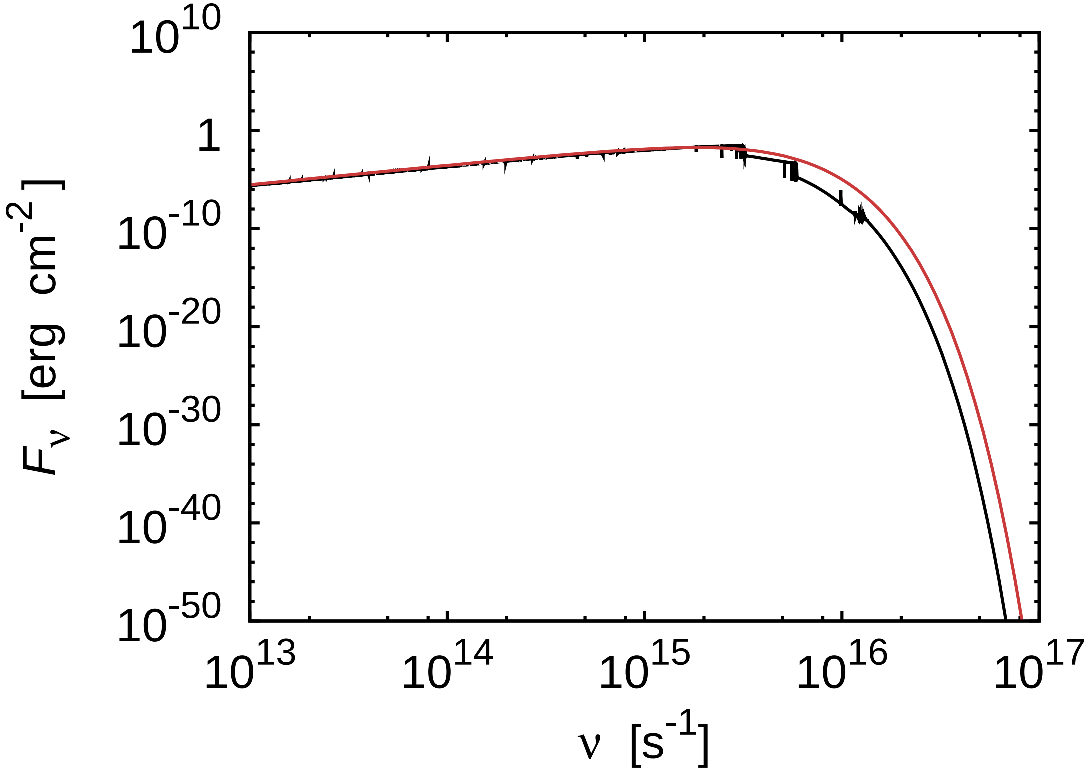
$\Rightarrow$ thermal velocities of protons: $\mathbf{200 - 5000}$ km s$^{\mathbf{-1}}$

Can hot stars be sources of X-ray radiation?

Flux from the spherically symmetric H-He model atmosphere $T_{\text{eff}} = 31\,400\,\text{K}$, $M = 15\,\text{M}_\odot$, $R = 4.9\,\text{R}_\odot$ (τ Sco, Kubát 2003)



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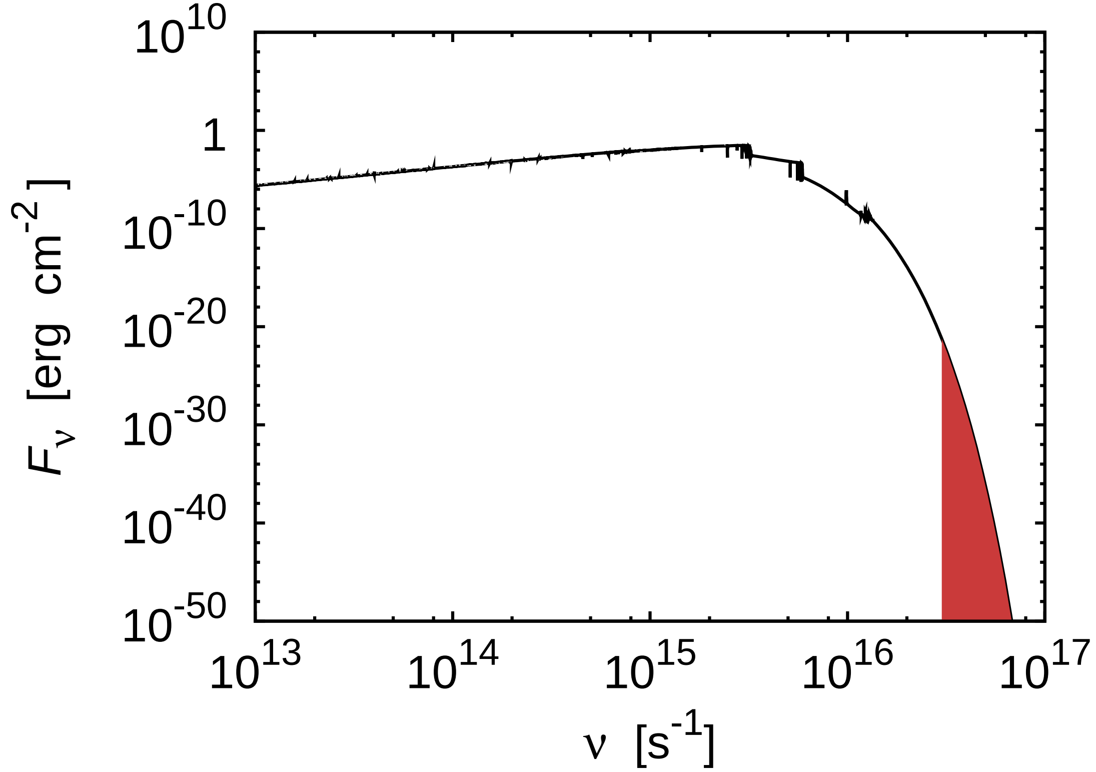

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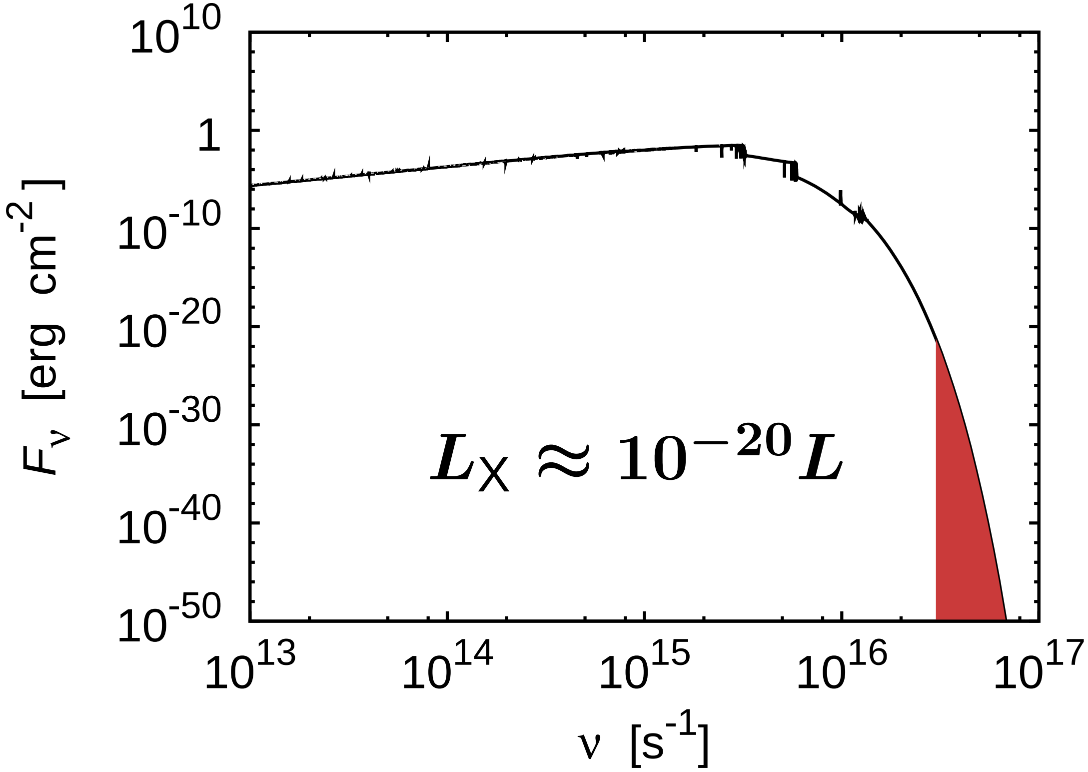
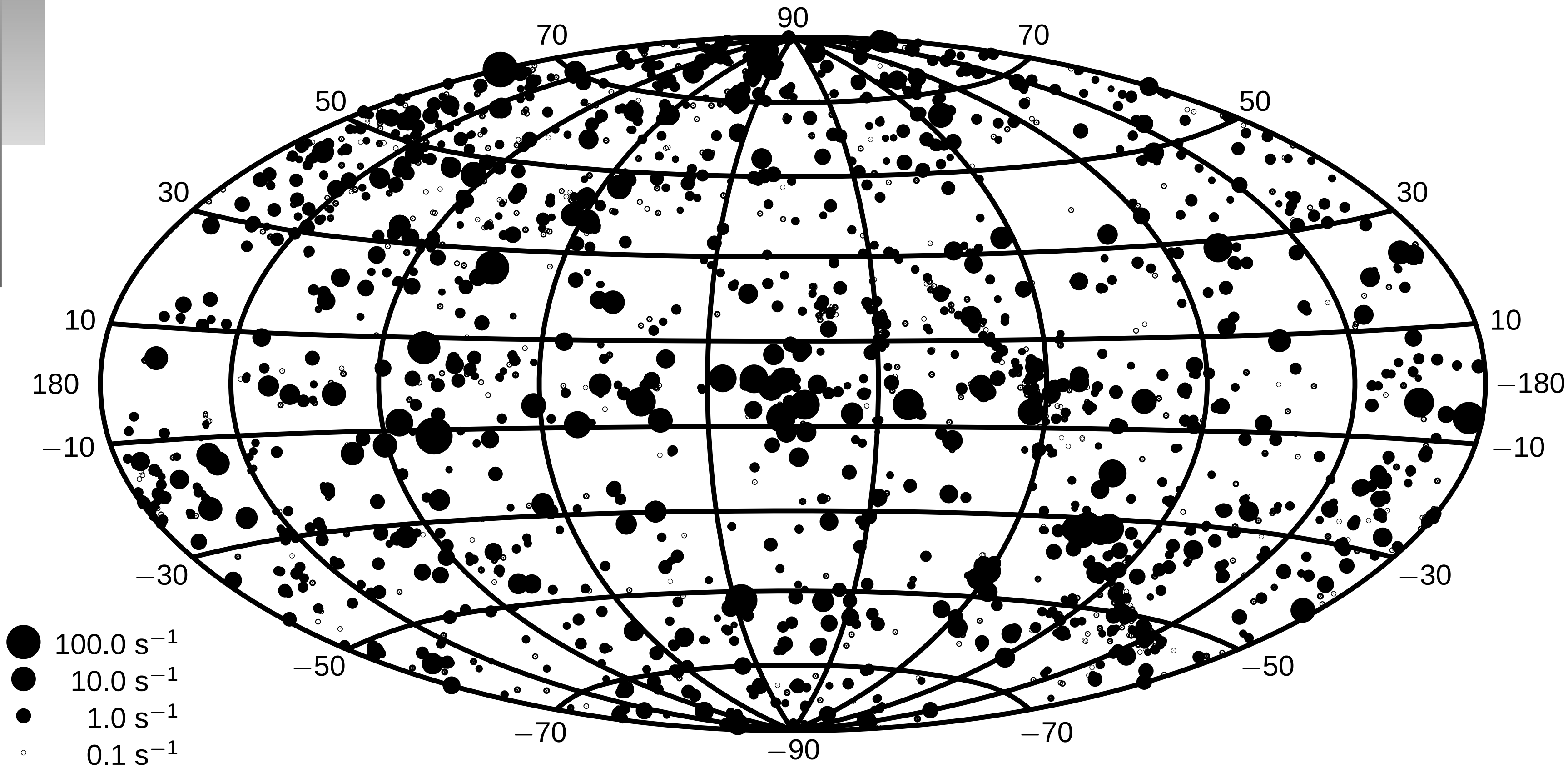


Can hot stars be sources of X-ray radiation?

⇒ X-ray flux emergent from the (static) hot star atmospheres negligible (with a possible exception of extremely hot white dwarfs)

⇒ hot stars should not emit any X-ray radiation

Point X-ray sources (ROSAT)



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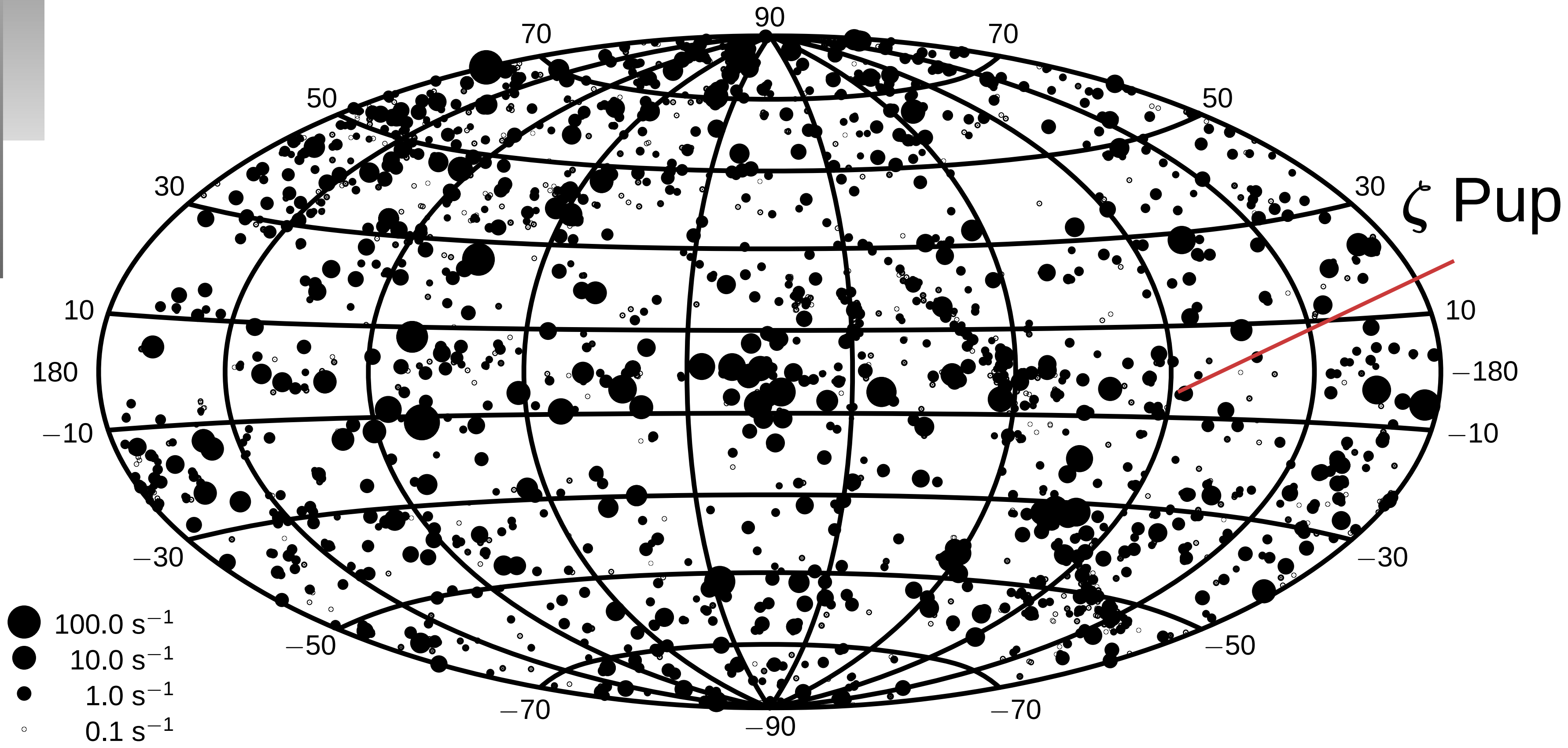

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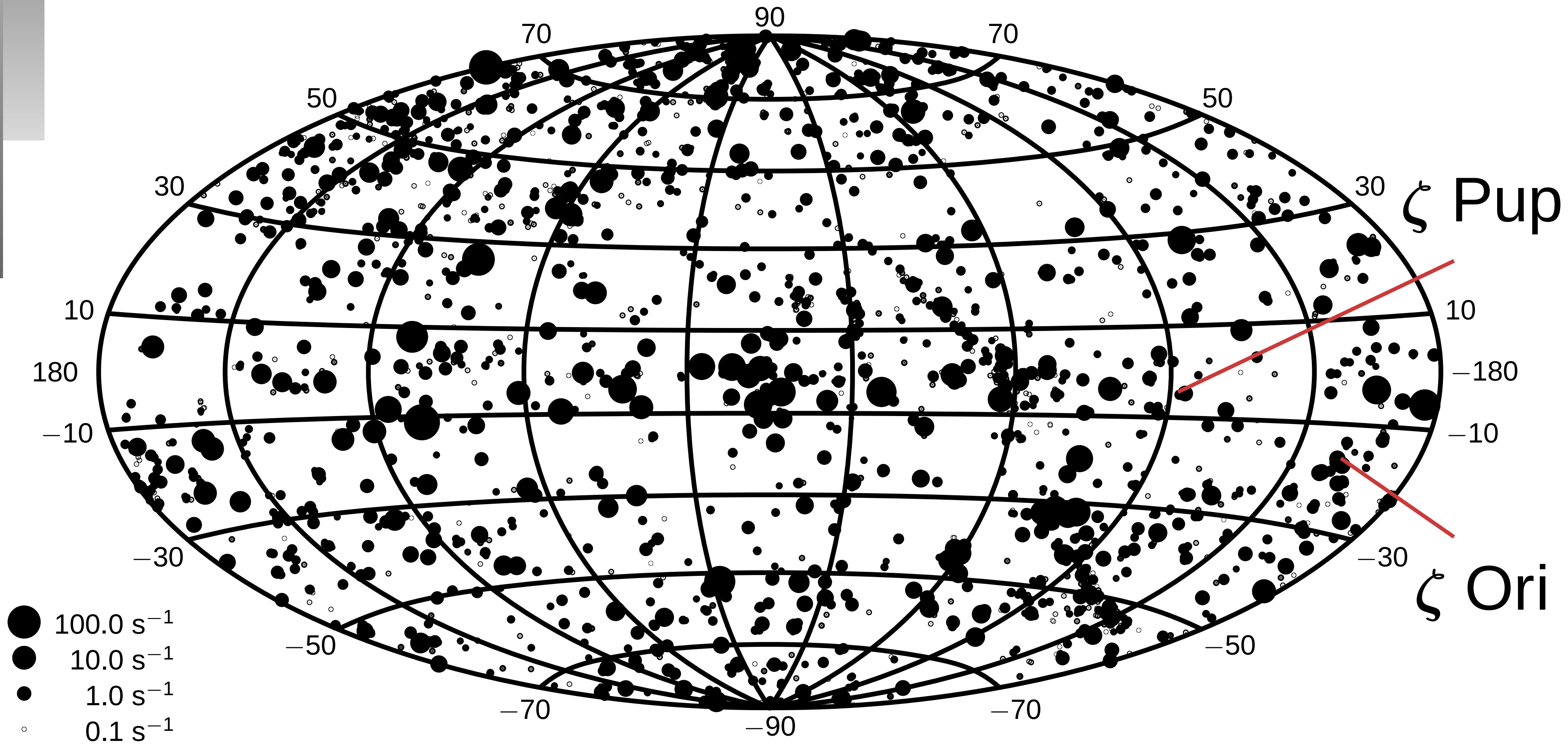

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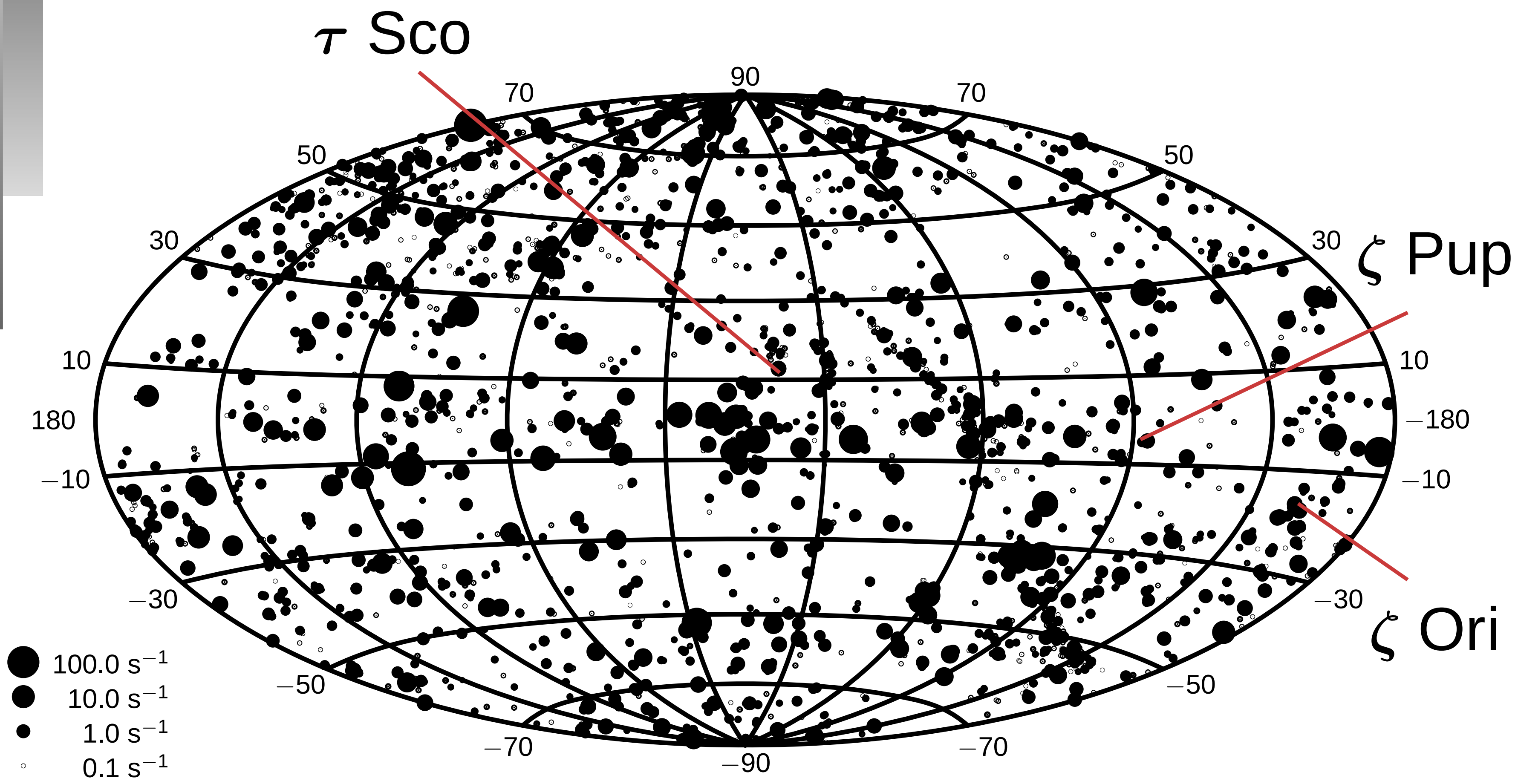

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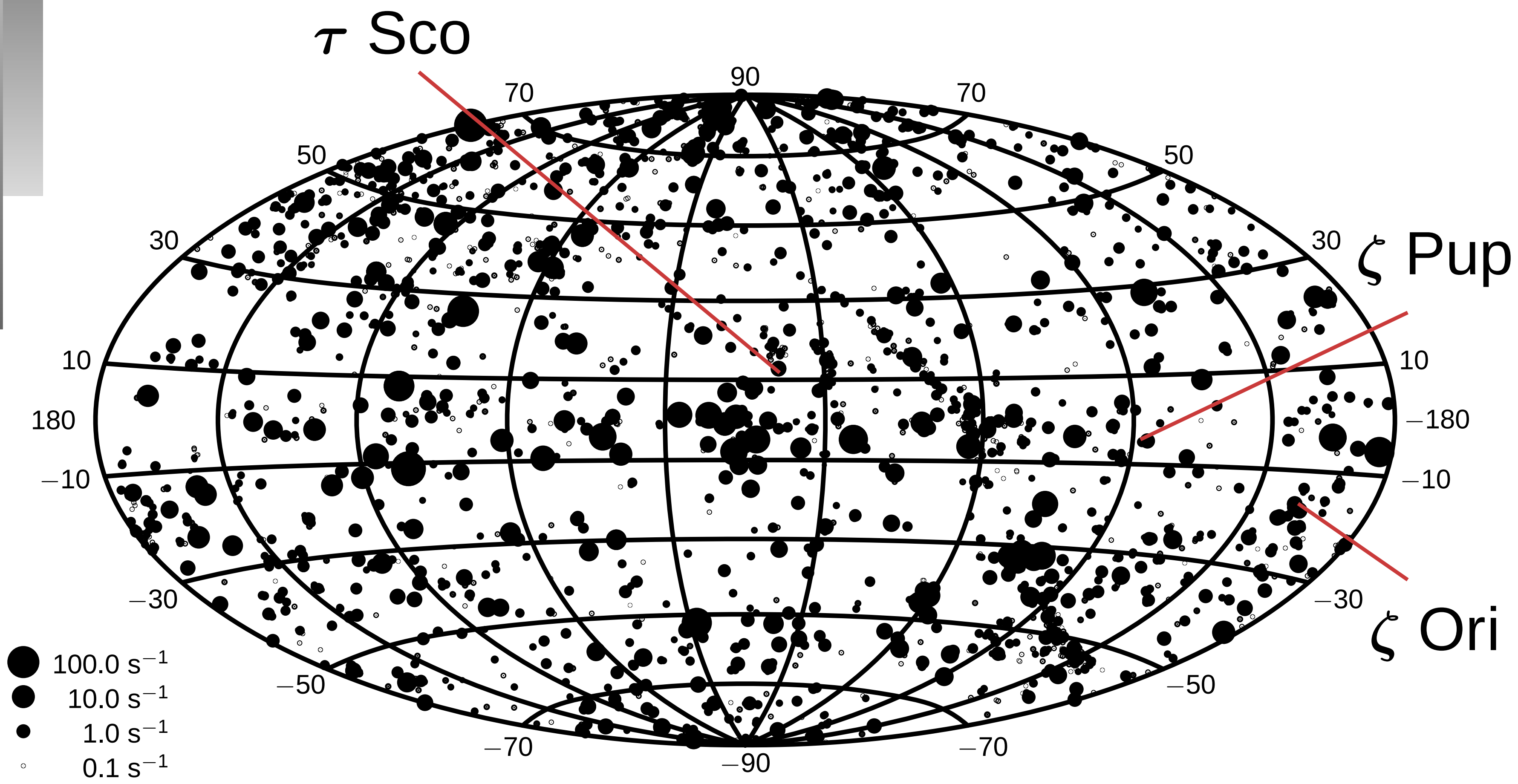
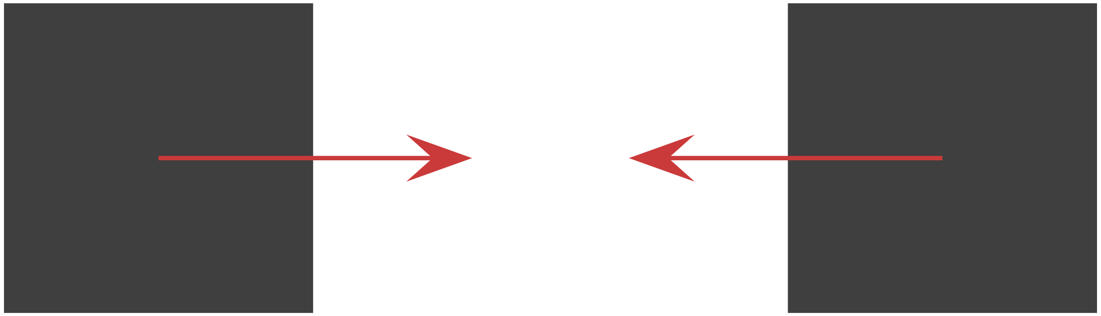


τ Sco: $L_X/L \approx 3 \cdot 10^{-7}$ (Berghöfer et al. 1996)

The simplest source of X-rays

$\Rightarrow$ hot stars have stellar wind (accelerated due to the line transitions of heavier elements) with typical velocities $\approx 1000\,\mathrm{km\,s^{-1}}$

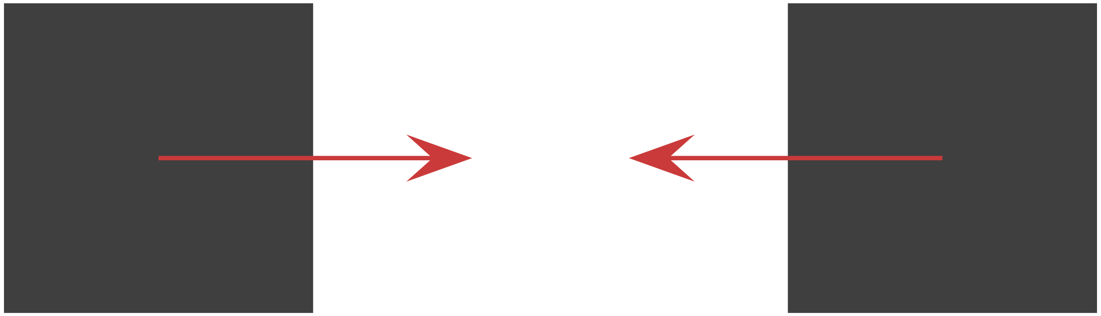
The simplest source of X-rays



$v_x = 1000\,\mathrm{km\,s^{-1}}$

$v_x = -1000\,\mathrm{km\,s^{-1}}$

The simplest source of X-rays

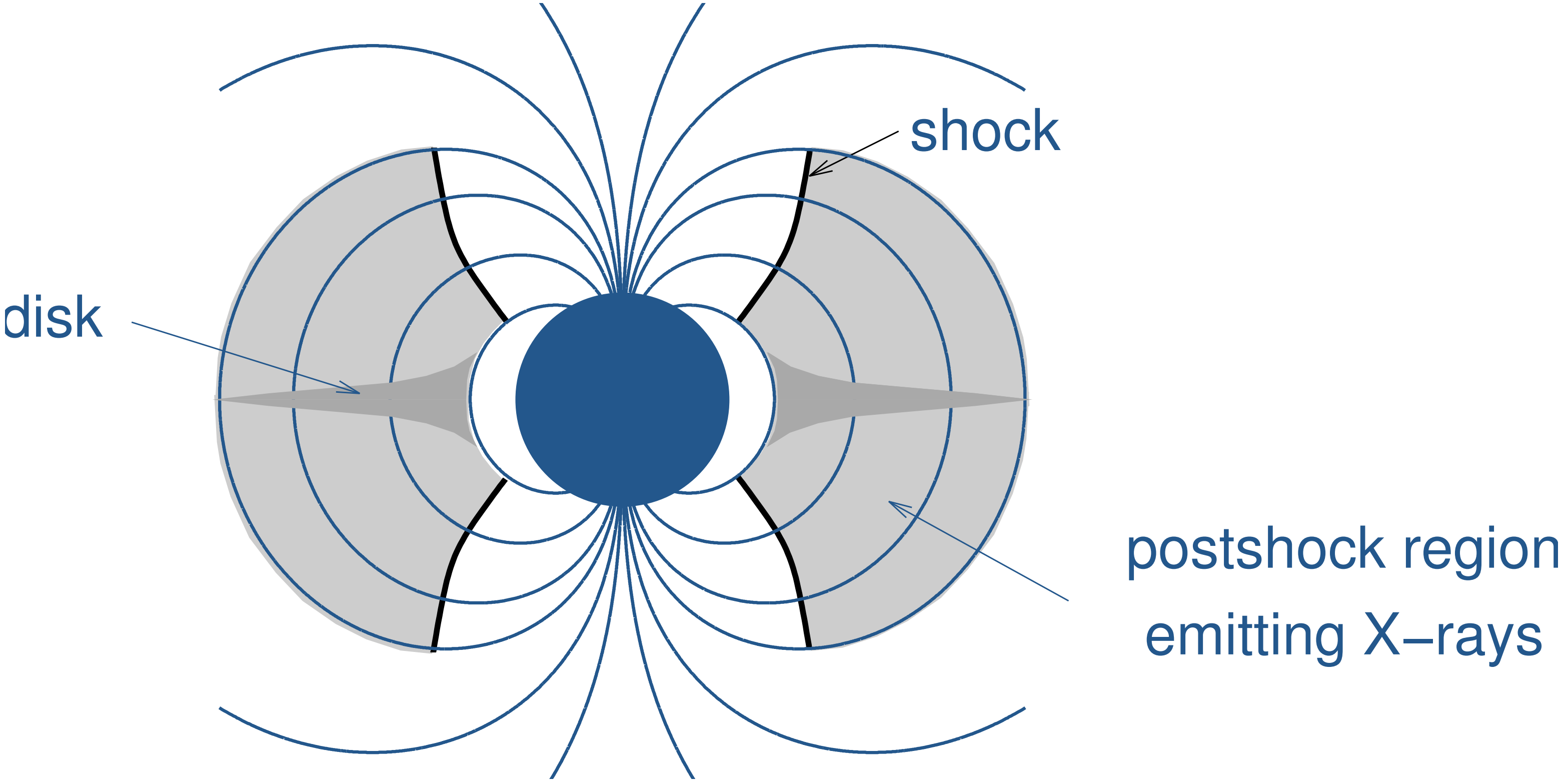


$v_x = 1000\,\mathrm{km\,s^{-1}}$ $v_x = -1000\,\mathrm{km\,s^{-1}}$

$T = 2 \cdot 10^7\,\mathrm{K}$

How can the individual streams of hot star wind collide?

⇒ influence of global (dipole) magnetic field (e.g., Babel & Montmerle 1997, ud-Doula & Owocki 2002)



How can the individual streams of hot star wind collide?

⇒ collisions of wind streams due to the binarity (e.g., Prilutskii & Usov 1976, Luo et al. 1990, Pittard 1998)

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$\Rightarrow$ influence of the wind instabilities

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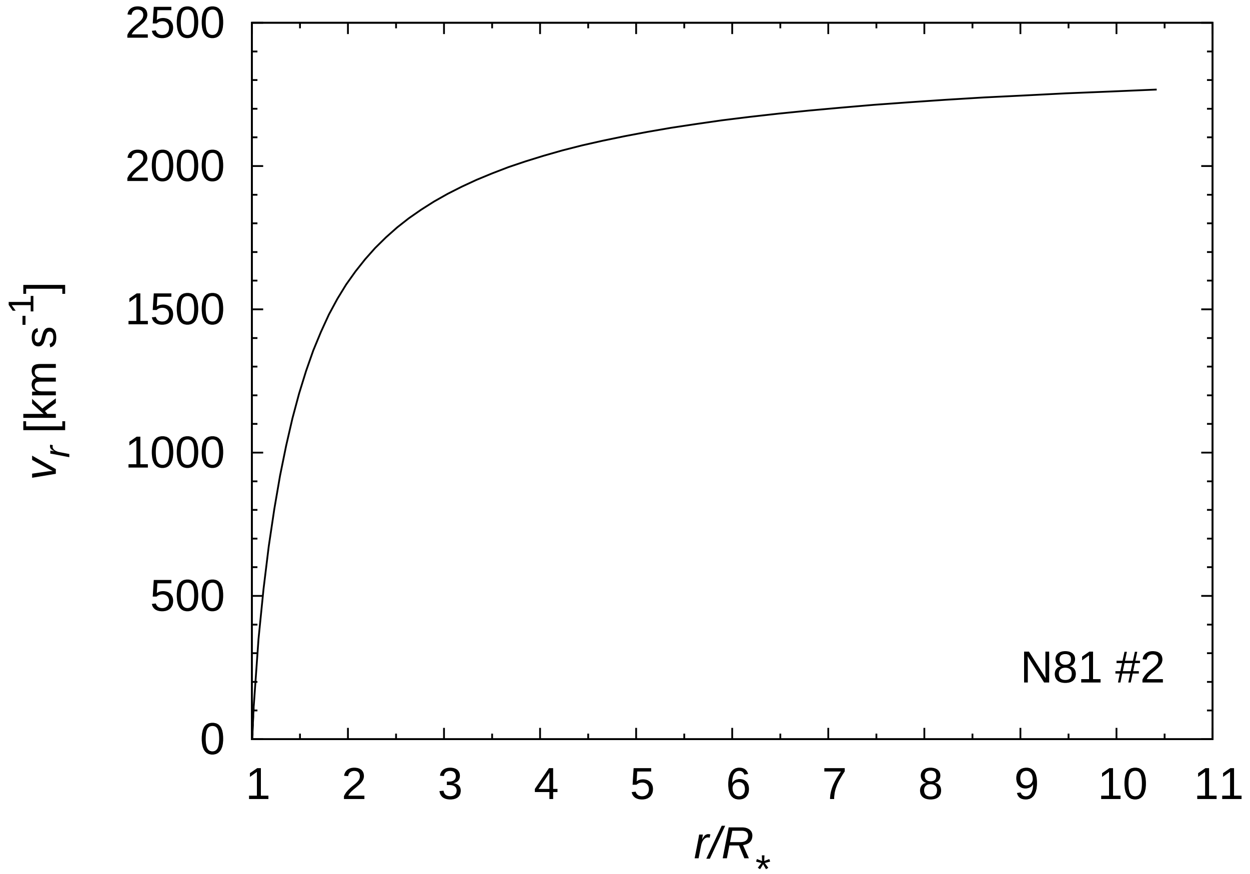

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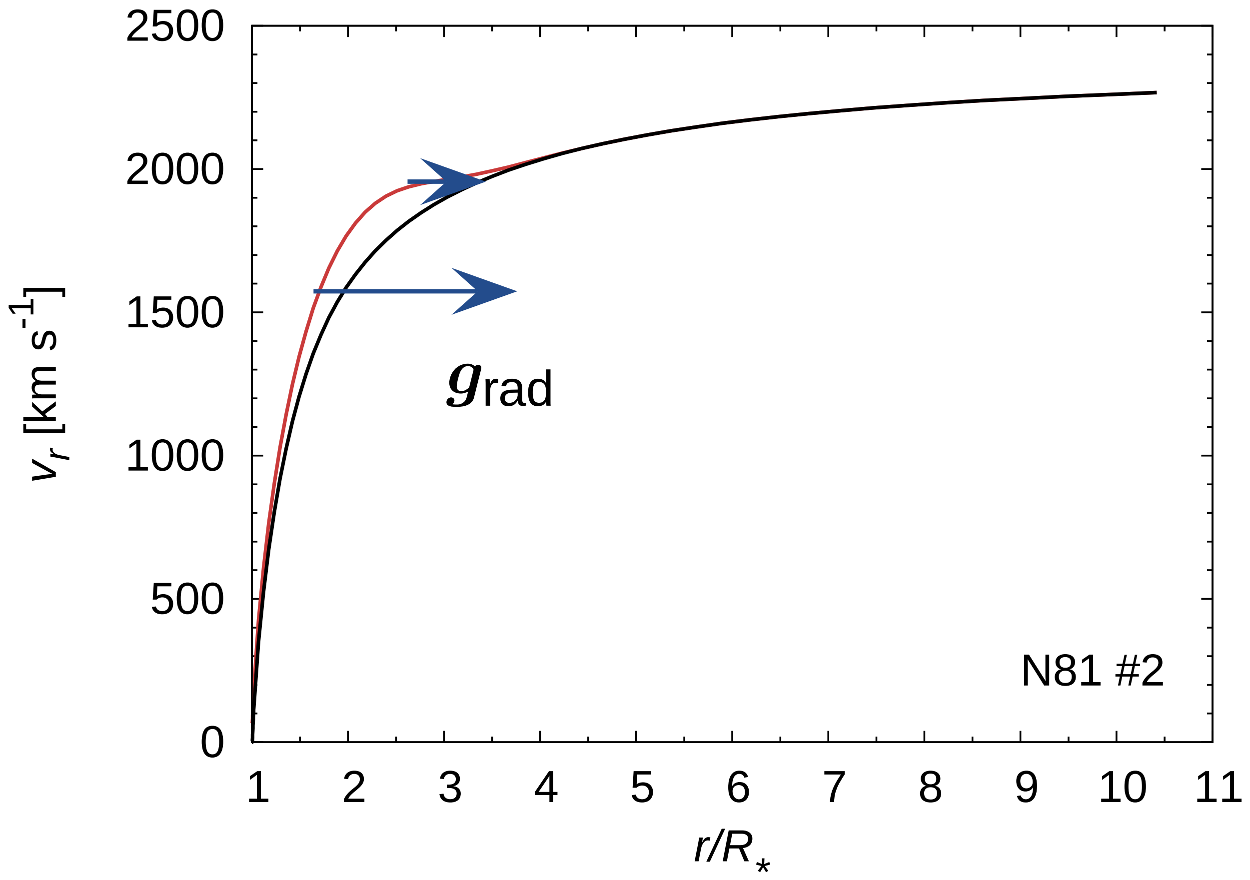
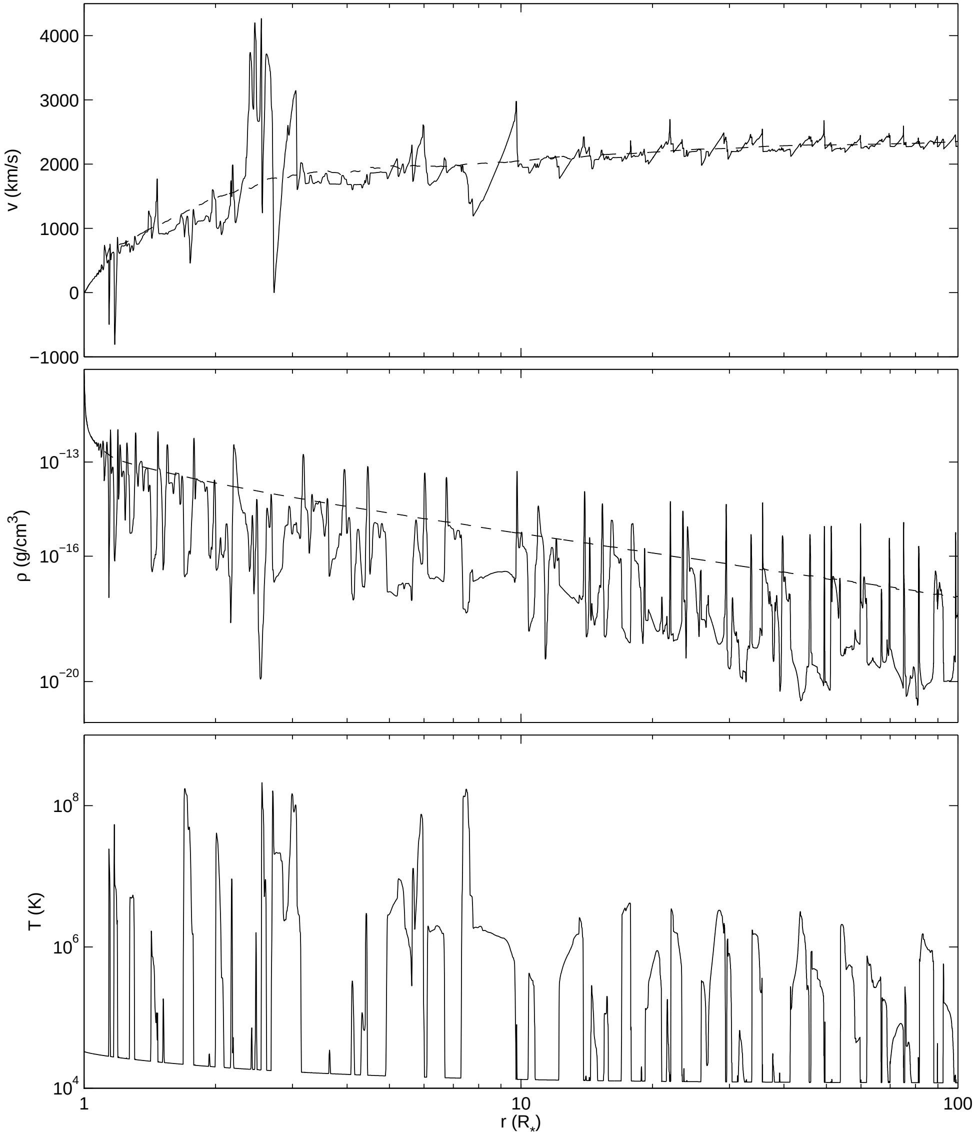
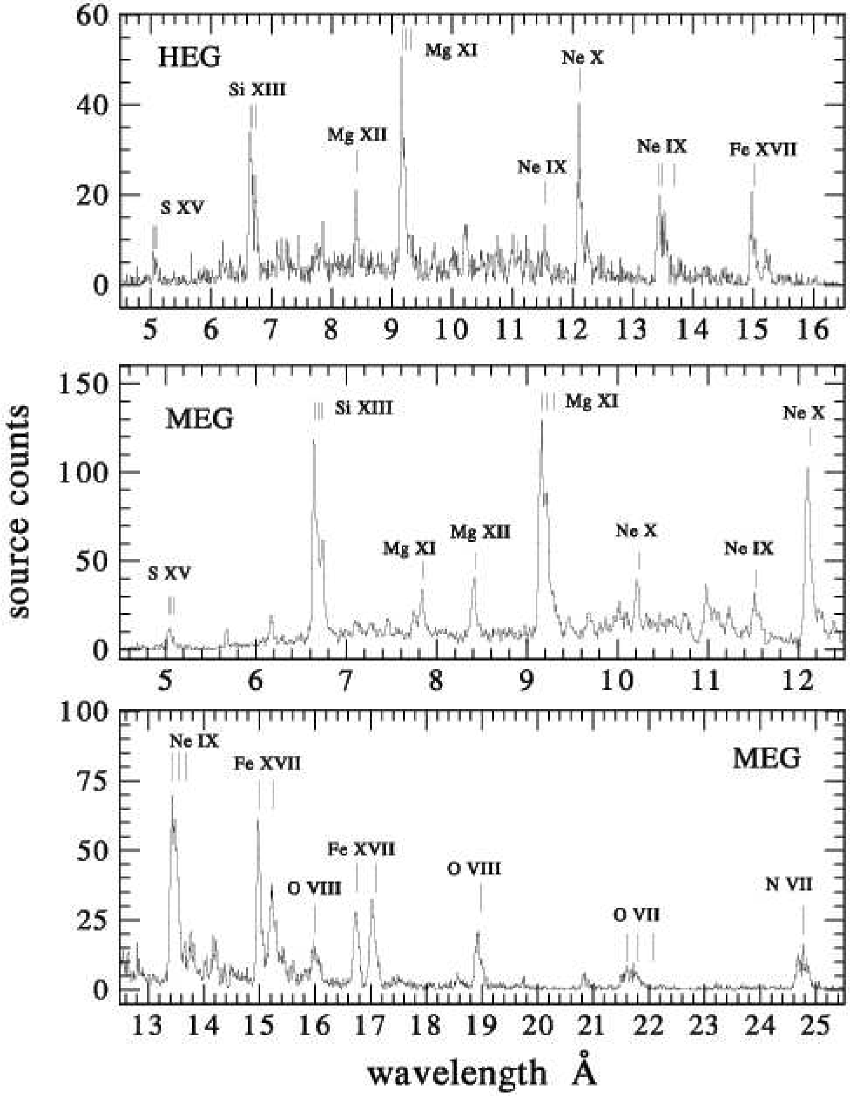


How can the individual streams of hot star wind collide?

$\Rightarrow$ numerical simulations (Runacres & Owocki 2002)

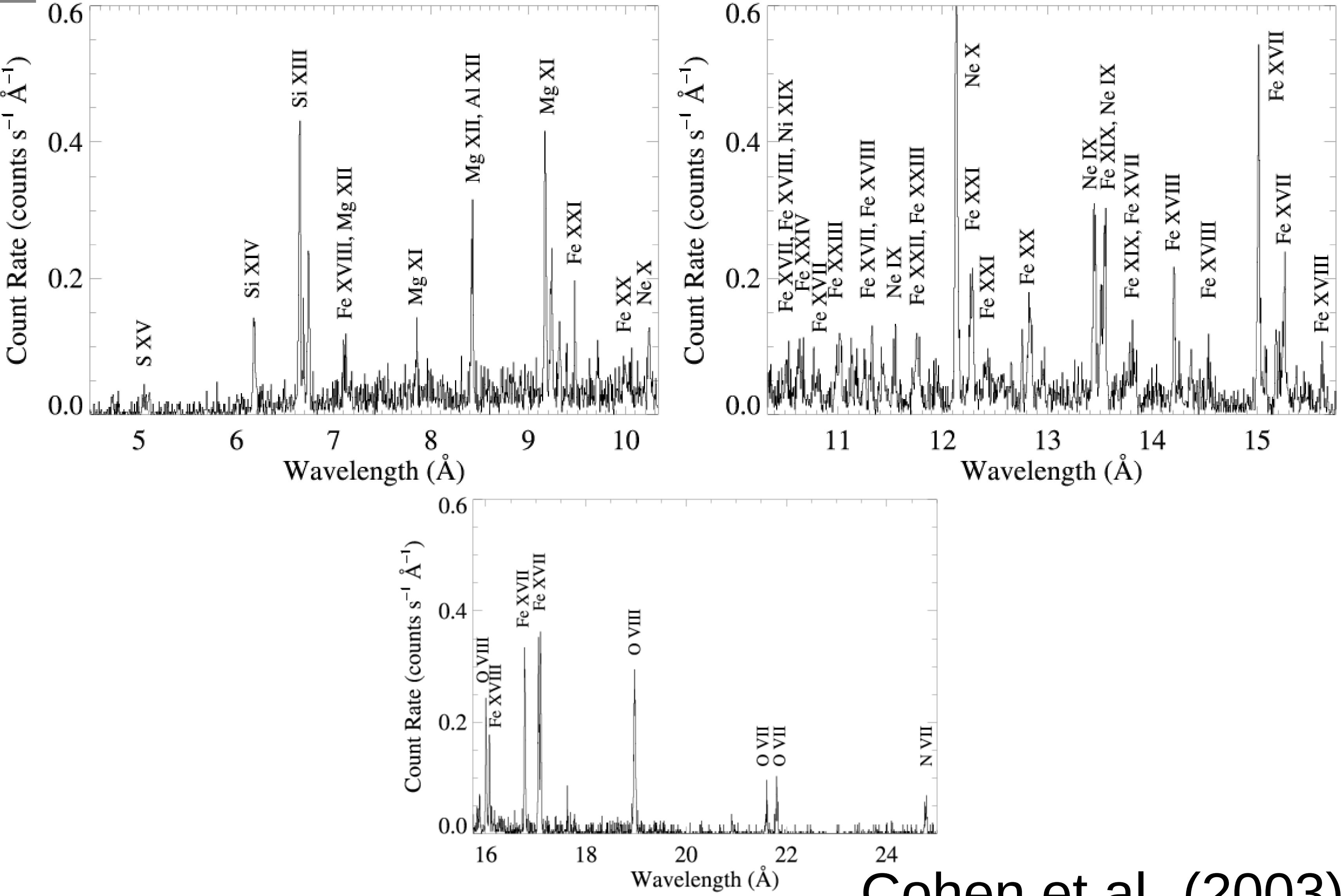


X-ray spectrum of ζ Pup (Chandra)



Cassinelli et al. (2001)

X-ray spectrum of τ Sco (Chandra)



Cohen et al. (2003)

X-ray spectrum of hot stars

- dominated by lines of highly ionized elements
- originate in the shocks in the stellar wind (small part of wind material)
- ambient cool wind is optically thick in continuum, but optically thin in lines (!)

Realistic models of hot star winds

	realistic model
hydro	2D/3D
	$\frac{\partial}{\partial t} \neq 0$
RTE	2D/3D
	CMF
state	NLTE

- very complicated problem: NLTE + RTE influence the radiative force (due to the lines) $\longrightarrow$ hydrodynamics
- hydrodynamics influences NLTE + RTE

Realistic models of hot star winds

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hydro	2D/3D
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state	NLTE

$\Rightarrow$ hydro simulations (e.g., Feldmeier et al. 1997, Runacres & Owocki 2002, Votruba et al. 2007)

$\Rightarrow$ enable to predict wind structure (clumping), emergent X-ray emission

$\Rightarrow$ do not provide *ab initio* wind parameters (e.g., mass-loss rate)

Realistic models of hot star winds

	realistic model
hydro	2D/3D
	$\frac{\partial}{\partial t} \neq \mathbf{0}$
RTE	2D/3D
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state	NLTE

- $\Rightarrow$ radiative transfer solution in moving media (e.g., Hillier & Miller 1998, Korčáková & Kubát 2005)
- $\Rightarrow$ enable to predict wind spectra
- $\Rightarrow$ do not provide *ab initio* wind parameters (e.g., mass-loss rate)

Realistic models of hot star winds

	realistic model
hydro	2D/3D
	$\frac{\partial}{\partial t} \neq 0$
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$\Rightarrow$ formidable task, beyond the possibilities of present computers (?)

$\Rightarrow$ selfconsistent wind models without any free parameters

$\Rightarrow$ provide mass-loss rates, velocity profiles, correct wind line profiles, X-ray emission, …

Realistic models of hot star winds

	realistic model	Krtička & Kubát (2004)
hydro	2D/3D	1D
	$\frac{\partial}{\partial t} \neq 0$	stationary
RTE	2D/3D	1D
	CMF	Sobolev
state	NLTE	NLTE

- $\Rightarrow$ selfconsistent wind models without any free parameters
- $\Rightarrow$ provide mass-loss rates, velocity profiles, but not the X-ray emission

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$\Rightarrow$ selfconsistent wind models without any free parameters

$\Rightarrow$ provide mass-loss rates, velocity profiles, but not the X-ray emission

$\Rightarrow$ what is the influence of wind inhomogeneities (clumping) and X-rays on the NLTE wind models?

Is this important?

Mass-loss rate determination:

- *theoretical mass-loss rates*: Pauldrach et al. (2001), Vink et al. (2001), Puls et al. (2003), Krtička & Kubát (2004) → enable ab initio prediction of mass-loss rates

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- *mass-loss derived from observations*: Bouret et al. (2003), Martins et al. (2005), Puls et al. (2006), Fullerton et al. (2006) → derived by analysis of observational data

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⇒ theoretical mass-loss rates *may* be $10\times$ higher than the predicted ones!

Influence of X-ray radiation on the wind structure

- ⇒ hot star wind emit X-ray radiation
- ⇒ X-ray radiation influences the wind ionization balance (MacFarlane et al. 1994, Pauldrach et al. 2001)
- ⇒ may the modified ionization balance influence wind parameters (wind mass-loss rate, terminal velocity)?

NLTE wind models

(Krtička & Kubát 2004)

- spherically symmetric stationary wind models
- radiative force calculated using the solution of the statistical equilibrium equations
- wind density, velocity and temperature structure derived from hydrodynamical equations
- enable to predict $\dot{M}$, v_∞, but not L_x

Procedure of the model calculation

radiative transfer equation

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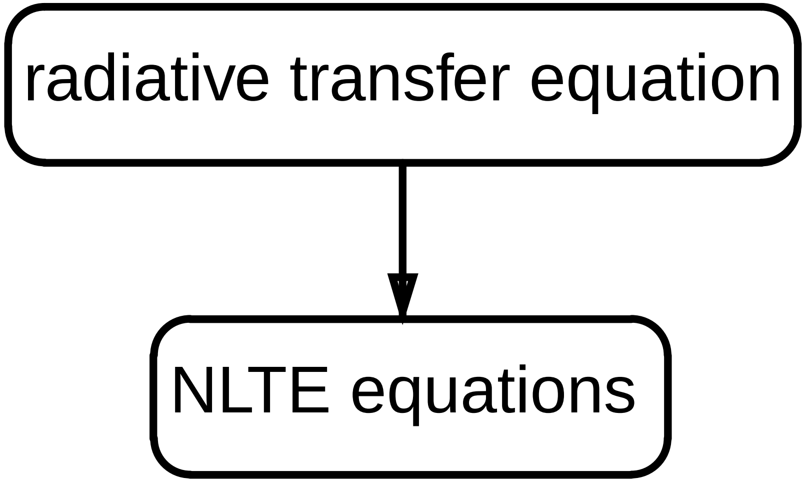

radiative transfer equation

NLTE equations

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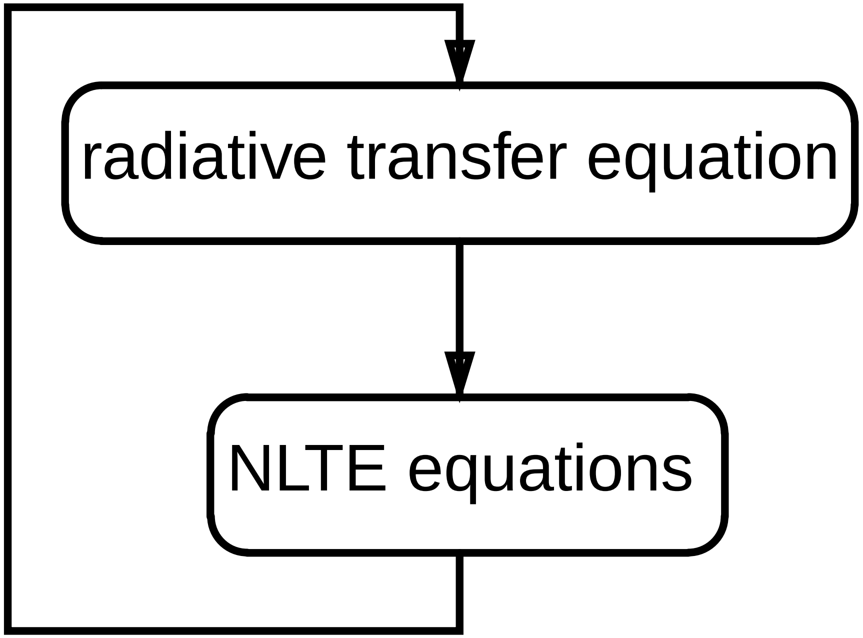

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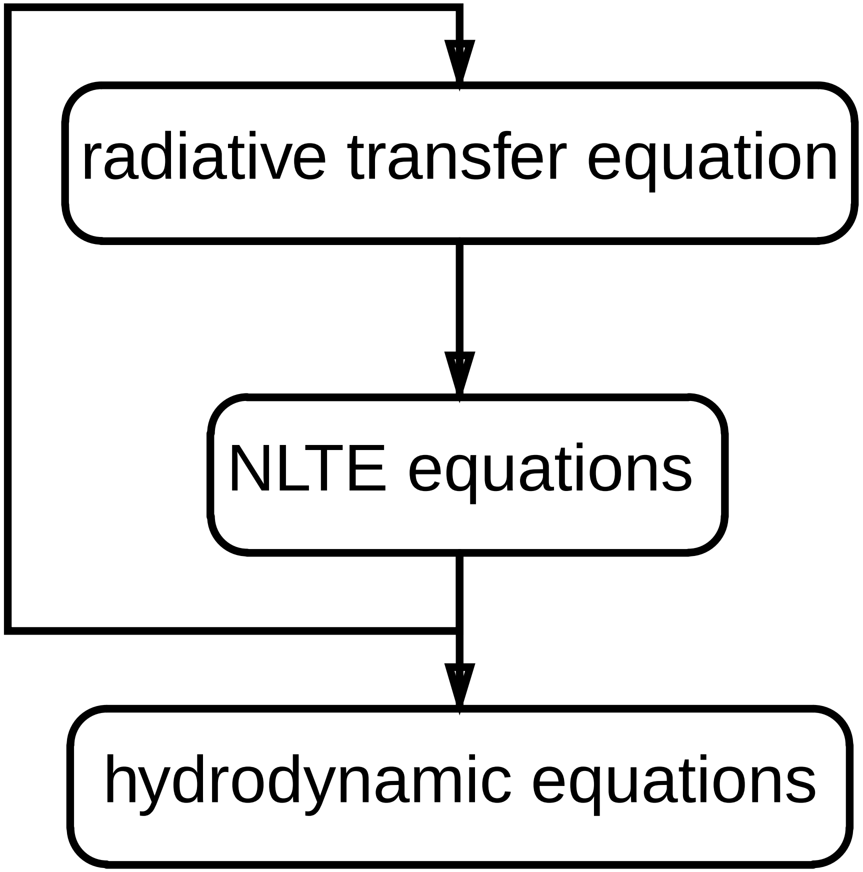

radiative transfer equation

NLTE equations

hydrodynamic equations

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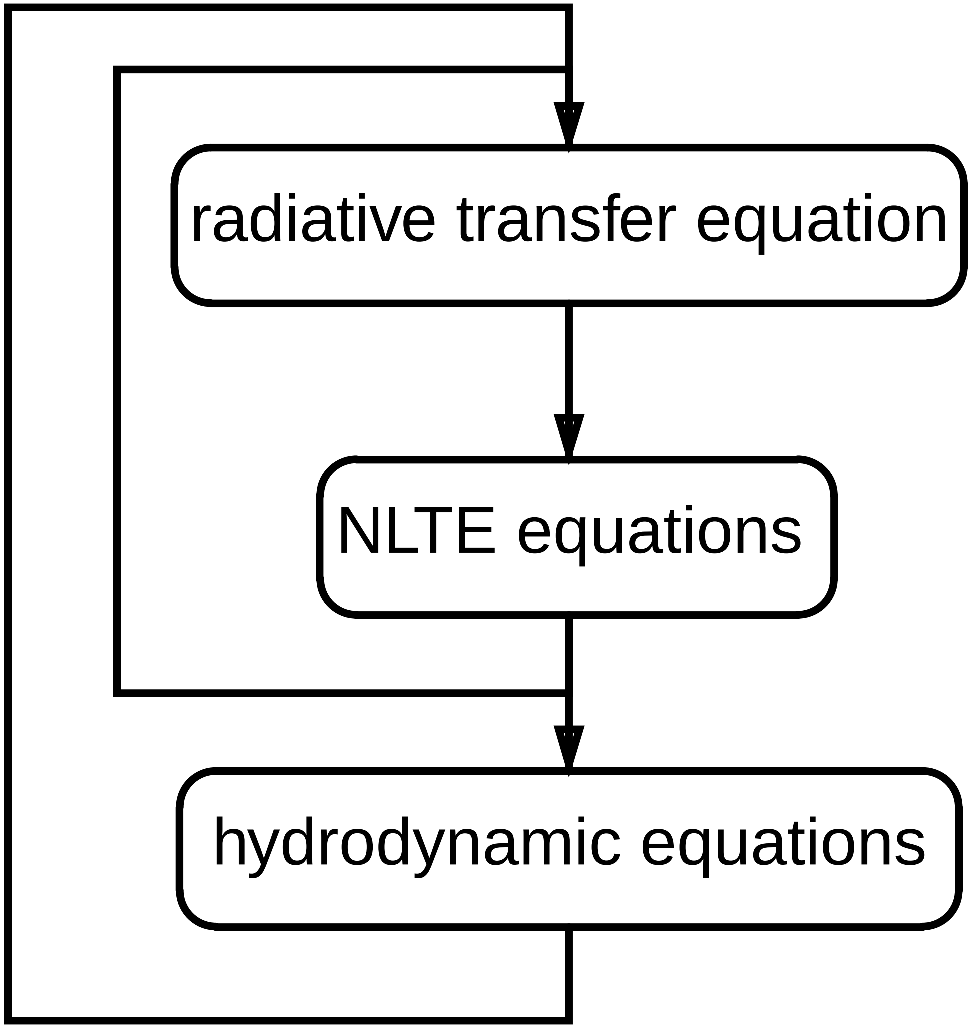

radiative transfer equation

NLTE equations

hydrodynamic equations

Continuum radiative transfer equation

$$\mu\frac{\partial I(r,\nu,\mu)}{\partial r}+\frac{1-\mu^2}{r}\frac{\partial I(r,\nu,\mu)}{\partial\mu}=\eta-\chi I(r,\nu,\mu),$$

- neglect of the wind movement
- $I(r,\nu,\mu)$ is the specific intensity
- $\mu=\cos\theta$, θ is the angle, ν is the frequency
- $\chi(r,\nu,\mu)$, $\eta(r,\nu,\mu)$ are absorption and emission coefficients
- solution using Feautrier method

Line radiative transfer equation

Solution using the Sobolev approximation

$$\bar{J}_{ij} = (1-\beta)S_{ij} + \beta_c I_c,$$

- $\bar{J}_{ij} = \int_0^\infty \mathrm{d}\nu \int_{-1}^{1} \mathrm{d}\mu \phi_{ij}(\nu) I(r,\nu,\mu)$ is the mean intensity, $\phi_{ij}(\nu)$ is the line profile,
- I_c is the stellar specific intensity, $\beta = \frac{1}{2}\int_{-1}^{1} \mathrm{d}\mu \frac{1-e^{-\tau_\mu}}{\tau_\mu}$, $\beta_c = \frac{1}{2}\int_{\mu_*}^{1} d\mu \frac{1-e^{-\tau_\mu}}{\tau_\mu}$, $\mu_* = \left(1 - R_*^2/r^2\right)^{1/2}$,
- source function $S_{ij} = \eta_{ij}/\chi_{ij}$.

Statistical equilibrium equations

Number density of atoms (ions) N_i in the state i is given by

$$\sum_{j\neq i} N_j P_{ji} - N_i \sum_{j\neq i} P_{ij} = 0.$$

- P_{ij} are rates of transition from i to j
- P_{ij} is the sum of the radiative excitation and deexcitation rates, radiative ionization and recombination rates and corresponding collisional processes

Included ionization states

H I-II	He I-III	C I-IV	N I-IV
O I-IV	Ne I-IV	Na I-III	Mg II-IV
Al I-V	Si II-V	S II-V	Ar III-IV
Ca II-IV	Fe II-V	Ni II-V	

- model atoms are taken mostly from TLUSTY code (Hubeny & Lanz 1992, 1995)
- the original set is extended using data from Opacity Project and Iron Project

Inclusion of the X-ray radiation

- hot stars emit X-ray radiation (e.g., Berghöfer et al. 1996)
- X-ray radiation is the result of the presence of the wind instabilities (Owocki et al. 1988, Feldmeier et al. 1997)

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- X-ray radiation is the result of the presence of the wind instabilities (Owocki et al. 1988, Feldmeier et al. 1997)
- approximate inclusion of the X-ray radiation (Pauldrach et al. 1994)

Inclusion of the X-ray radiation

- part of the stellar wind heated to a very high temperature T_X has the density

$$f_\mathrm{X}\rho$$

(f_X is a fraction of hot material, ρ is the density of ambient wind)

Inclusion of the X-ray radiation

- part of the stellar wind heated to a very high temperature T_X has the density

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- shock temperature T_X given by the Rankine-Hugoniot condition

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- the shock velocity difference is

$$u_\mathrm{X} = u_\mathrm{rel} v_r$$

v_r is the radial wind velocity

Inclusion of the X-ray radiation

- part of the stellar wind heated to a very high temperature T_{X} has the density

$$f_{\mathrm{X}}\rho$$

- shock temperature T_{X} given by the Rankine-Hugoniot condition
- the shock velocity difference is

$$u_{\mathrm{X}} = u_{\mathrm{rel}} v_r$$

- f_{X} and u_{rel} are free parameters

Inclusion of the X-ray radiation

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$$f_{\mathrm{X}}\rho$$

- shock temperature T_{X} given by the Rankine-Hugoniot condition
- the shock velocity difference is

$$u_{\mathrm{X}} = u_{\mathrm{rel}} v_r$$

- the shock emissivity is $\eta_{\mathrm{X}}(\nu) = n_{\mathrm{e,X}}^2 \, \Lambda_\nu(T_{\mathrm{X}}) / \, (4\pi)$ where $n_{\mathrm{e,X}}$ is the electron number density, $\Lambda_\nu(T_{\mathrm{X}})$ calculated after Raymond & Smith (1977)

Auger ionization

- presence of the X-ray radiation

⇒ Auger ionization may modify the ionization balance (Cassinelli & Olson 1979, Olson & Castor 1981, MacFarlane et al. 1994, Pauldrach et al. 1994)

⇒ inclusion of the Auger ionization into the models

Auger ionization

- Auger ionization term in the statistical equilibrium equations

$$\sum_{j>i} N_i A_{ij}^{\text{Auger}}$$

- Auger ionization rate A_{ij}^{Auger} is

$$A_{ij}^{\text{Auger}} = a_{\text{ion}(i)\text{ion}(j)} A_{\text{ion}(i)}^{\text{Auger}}$$

$a_{\text{ion}(i)\text{ion}(j)}$ is probability of a given process, $A_{\text{ion}(i)}$ is the inner shell ionization cross-section

Auger ionization

- Auger ionization term in the statistical equilibrium equations

$$\sum_{j>i} \boldsymbol{N_i A_{ij}^{\text{Auger}}}$$

- ionization cross-section are taken from Verner & Yakovlev (1995), probabilities are from Kaastra & Mewe (1993)

Hydrodynamic equations

- continuity equation

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\rho v_r\right) = 0 \Rightarrow \dot{M} = 4\pi r^2 \rho v_r = \text{const.}$$

  - ρ is the wind density
  - v_r is the radial velocity

Hydrodynamic equations

- equation of motion

$$v_r \frac{\mathrm{d}v_r}{\mathrm{d}r} = g^{\text{rad}} - g - \frac{1}{\rho}\frac{\mathrm{d}}{\mathrm{d}r}\left(a^2\rho\right)$$

  - ◆ g is the gravity acceleration
  - ◆ a is the isothermal sound speed
  - ◆ $g^{\text{rad}} = g^{\text{rad}}_{\text{lines}} + g^{\text{rad}}_{\text{el}}$ is the radiative acceleration

$$g^{\text{rad}}_{\text{lines}} = \frac{8\pi}{\rho c^2}\frac{v_r}{r}\sum_{\text{lines}} \nu H_c \int_{\mu_c}^{1} \mathrm{d}\mu\, \mu \left(1 + \sigma\mu^2\right)\left(1 - e^{-\tau_\mu}\right)$$

Hydrodynamic equations

- energy equation

$$\frac{3}{2} v_r \rho \frac{\mathrm{d}a^2}{\mathrm{d}r} + \frac{a^2 \rho}{r^2} \frac{\mathrm{d}}{\mathrm{d}r} \left(r^2 v_r \right) = Q^{\mathrm{rad}}$$

  - Q^{rad} is the radiative heating/cooling calculated using the thermal balance of electrons method (Kubát et al. 1999)

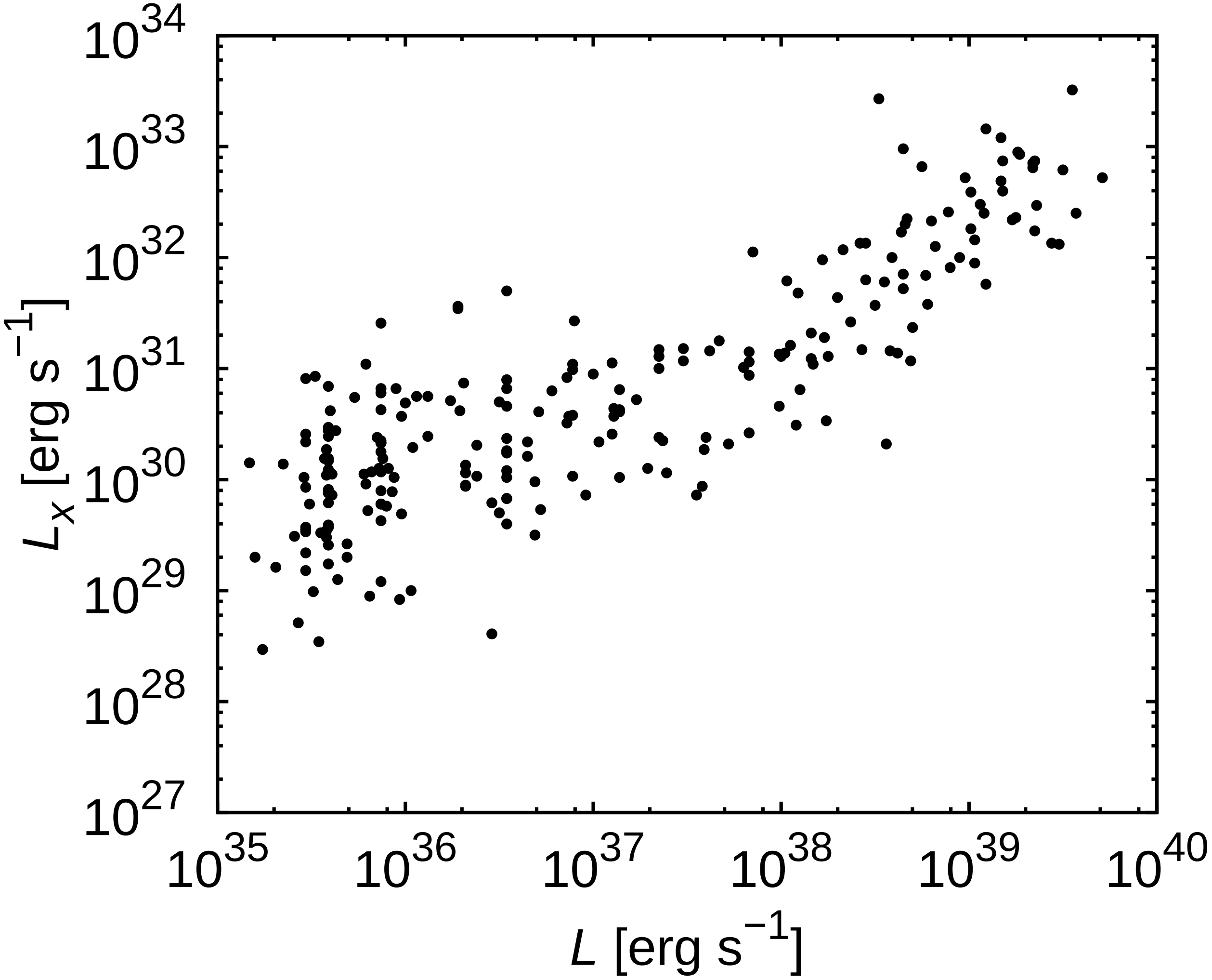
Studied stars

- hot O stars
- parameters taken from Lamers et al. (1995), Repolust et al. (2004), Markova et al. (2004), Martins et al. (2005)
- X-ray flux measured by the satellites ROSAT (Berghöfer a kol. 1996), Einstein (Chlebowski & Garmany 1991), Chandra (Evans a kol. 2003)

Studied stars

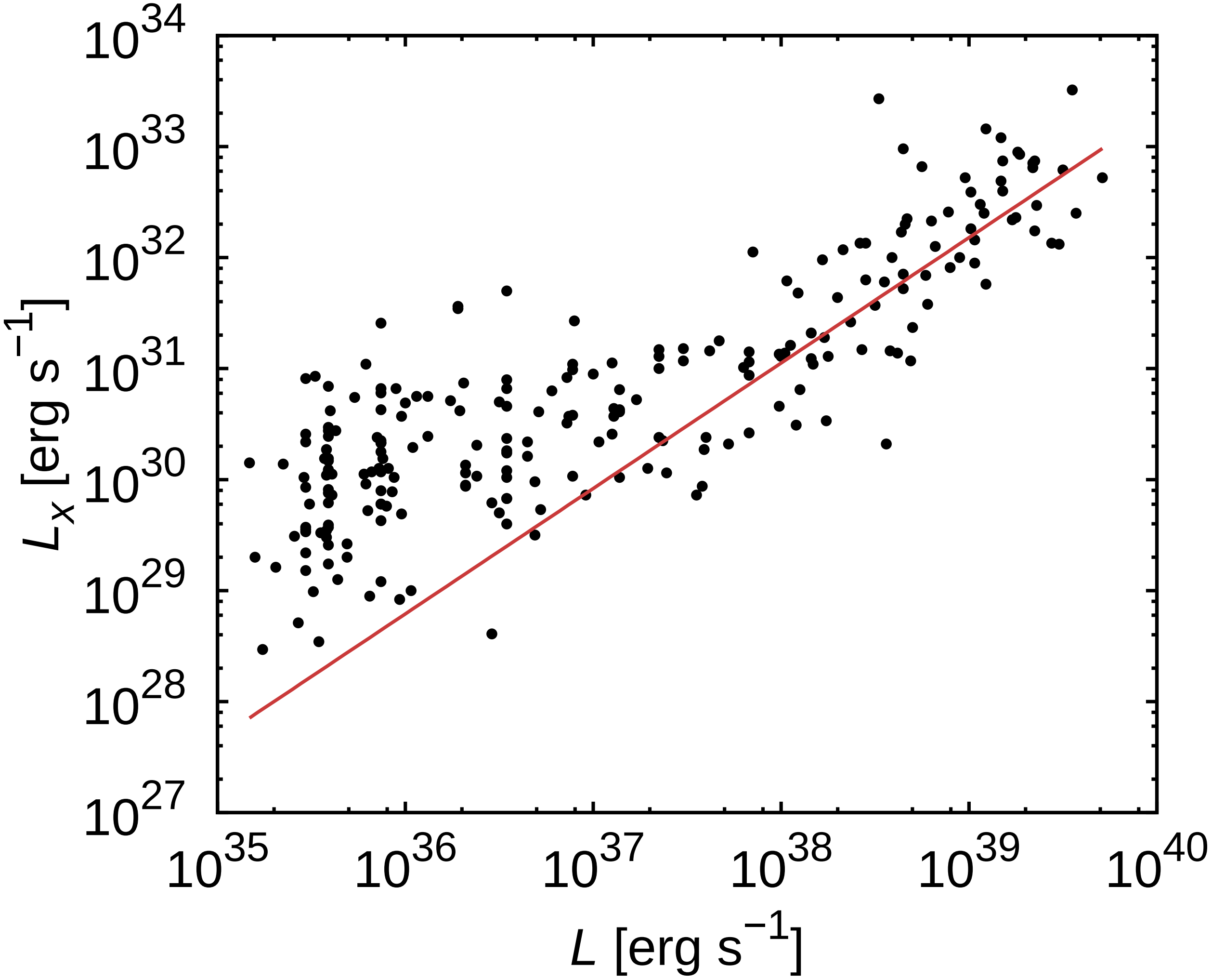
Star	HD	Sp. type	R_* [$R_\odot$]	M [$M_\odot$]	$T_{\rm eff}$ [K]
	93204	O5V	11.9	41	40 000
	54662	O7III	11.9	38	38 600
λ Cep	210839	O6Iab	19.6	51	38 200
	42088	O6.5V	9.6	31	38 000
15 Mon	47839	O7Ve	9.9	32	37 500
63 Oph	162978	O8III	16.0	40	37 100
λ Ori A	36861	O8 III	12.3	30	36 000
	152590	O7.5V	6.4	22	36 000
ξ Per	24912	O7.5IIIe	14.0	36	35 000
68 Cyg	203064	O8e	15.7	38	34 500
μ Col	38666	O9.5V	6.6	19	33 000
	46202	O9V	8.4	21	33 000
19 Cep	209975	O9Ib	22.9	47	32 000
ζ Oph	149757	O9V	8.9	21	32 000
ι Ori	37043	O9III	21.6	41	31 400
α Cam	30614	O9.5Ia	27.6	43	30 900

L_X – L relationship



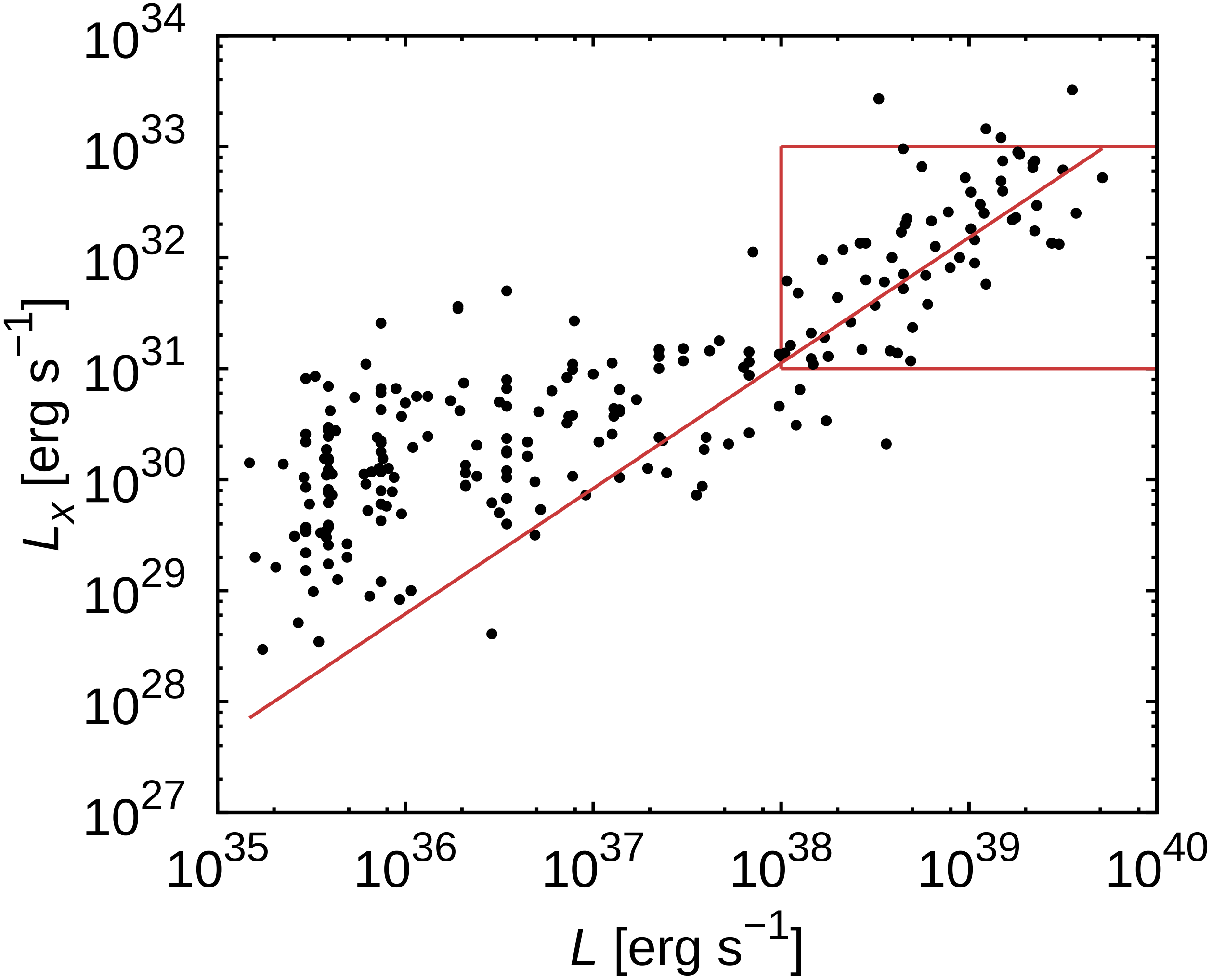
ROSAT (Berghöfer et al. 1996)

L_X – L relationship



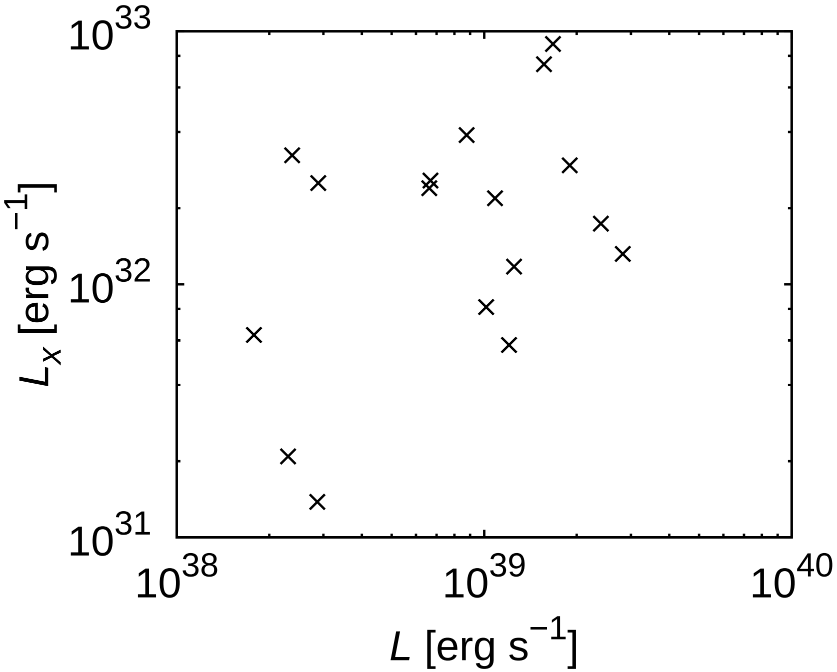
$$L_\mathrm{X} \approx 10^{-7} L$$

L_X – L relationship



L_{X} – L relationship

selected stars:

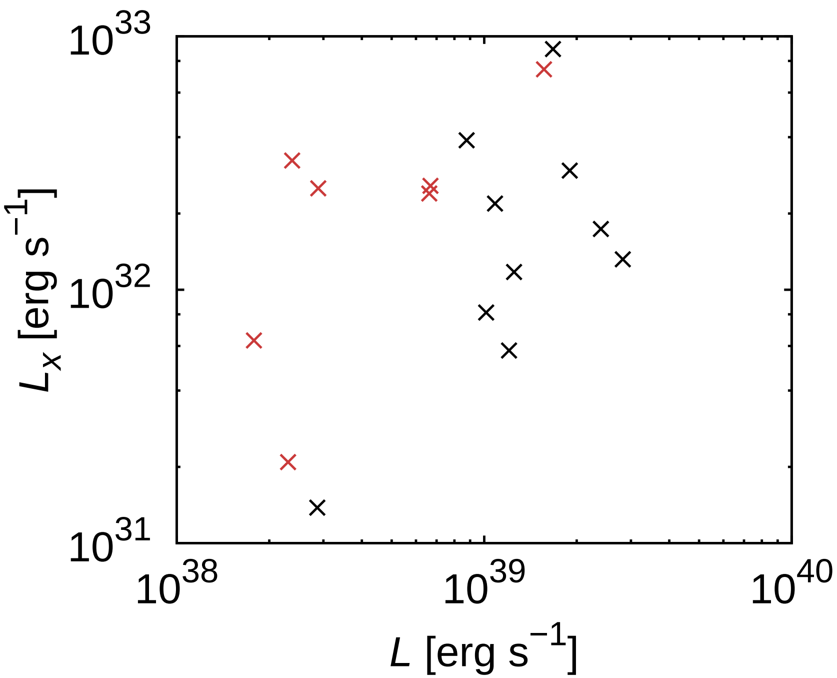


- for most stars $f_{\mathrm{X}} \approx 10^{-3} - 10^{-2}$, $u_{\mathrm{rel}} = 0.3$

⇒ X-ray emission can be expained by the wind instabilities

$L_{\rm X}$ – L relationship

selected stars:

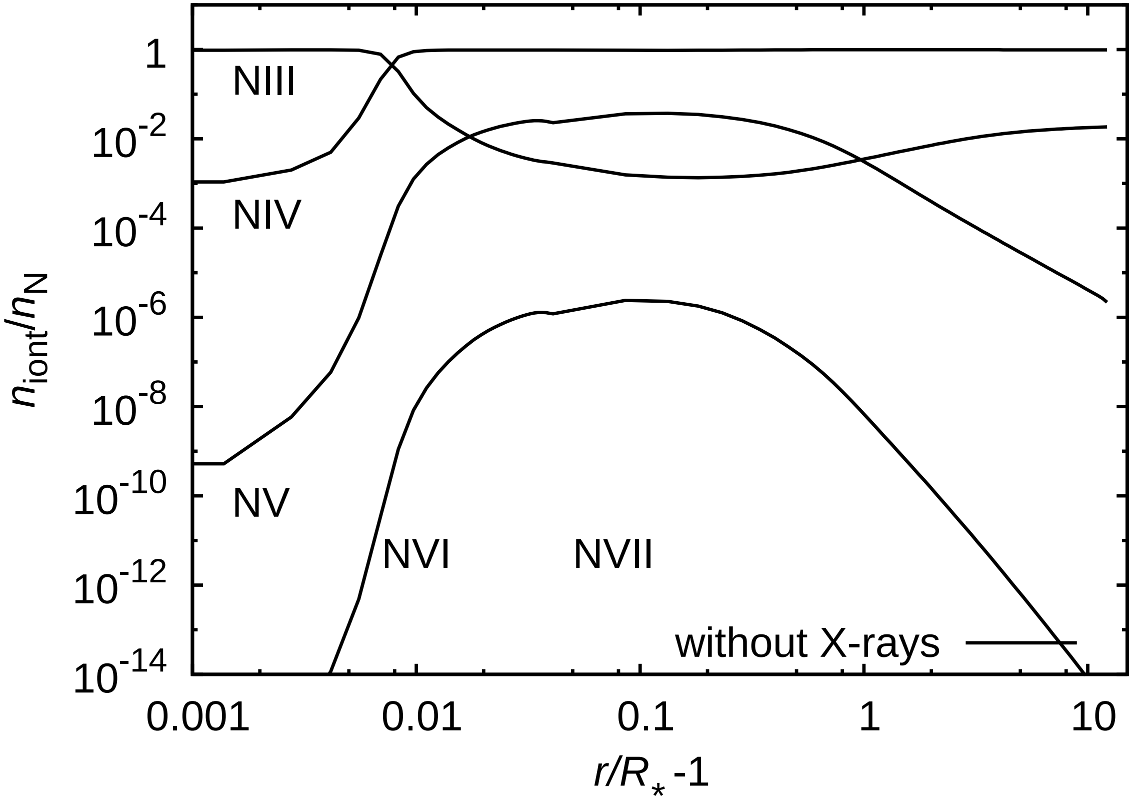


- for some stars $f_{\rm X} \gtrsim 0.1$

$\Rightarrow$ another processes (binarity, magnetic fields)?

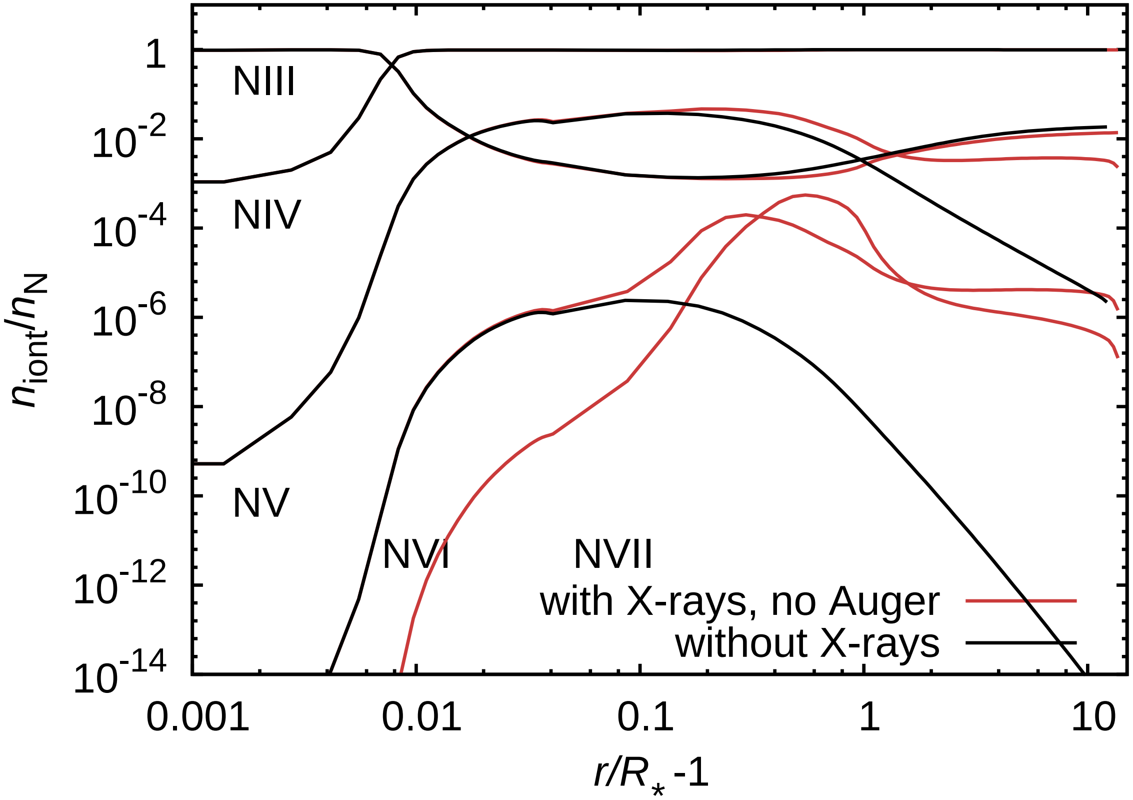
Influence of X-ray on the wind ionization state

- star HD 210839, $T_{\text{eff}} = 38\,200\,\text{K}$



Influence of X-ray on the wind ionization state

- star HD 210839, $T_{\mathrm{eff}} = 38\,200\,\mathrm{K}$



⇒ enhanced N V ionization fraction just due to direct ionization

Influence of X-ray on the wind ionization state

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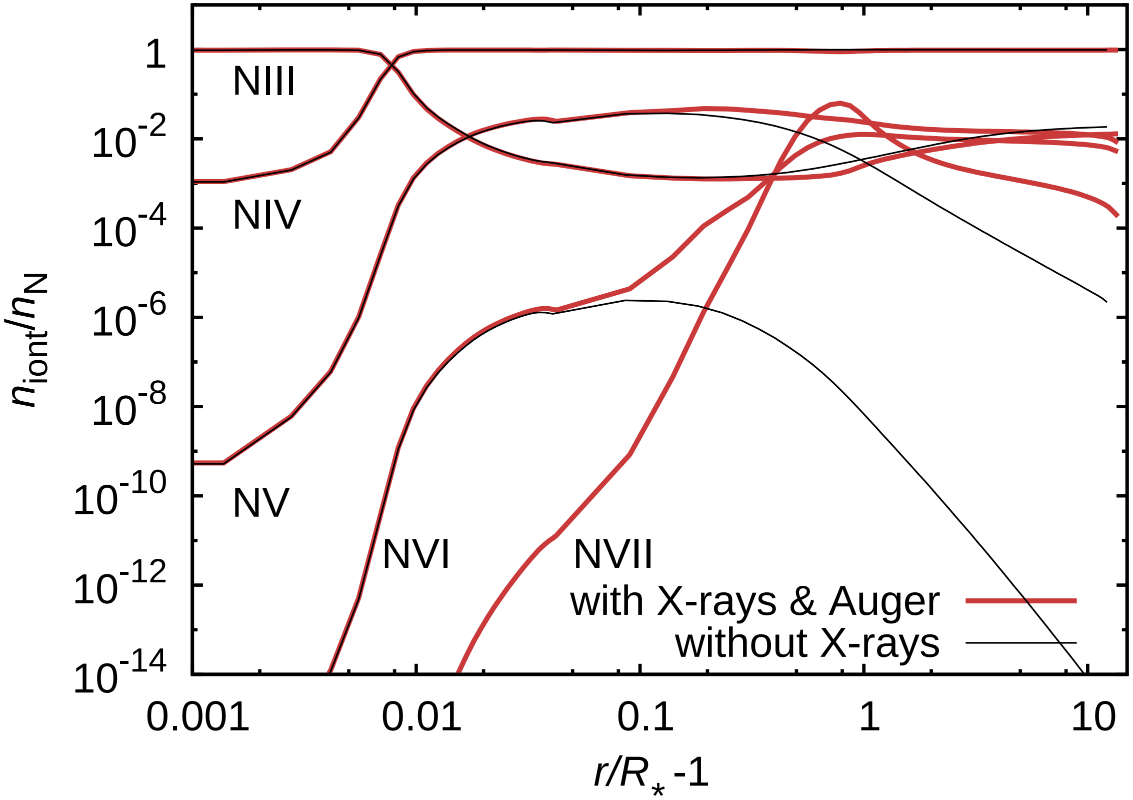
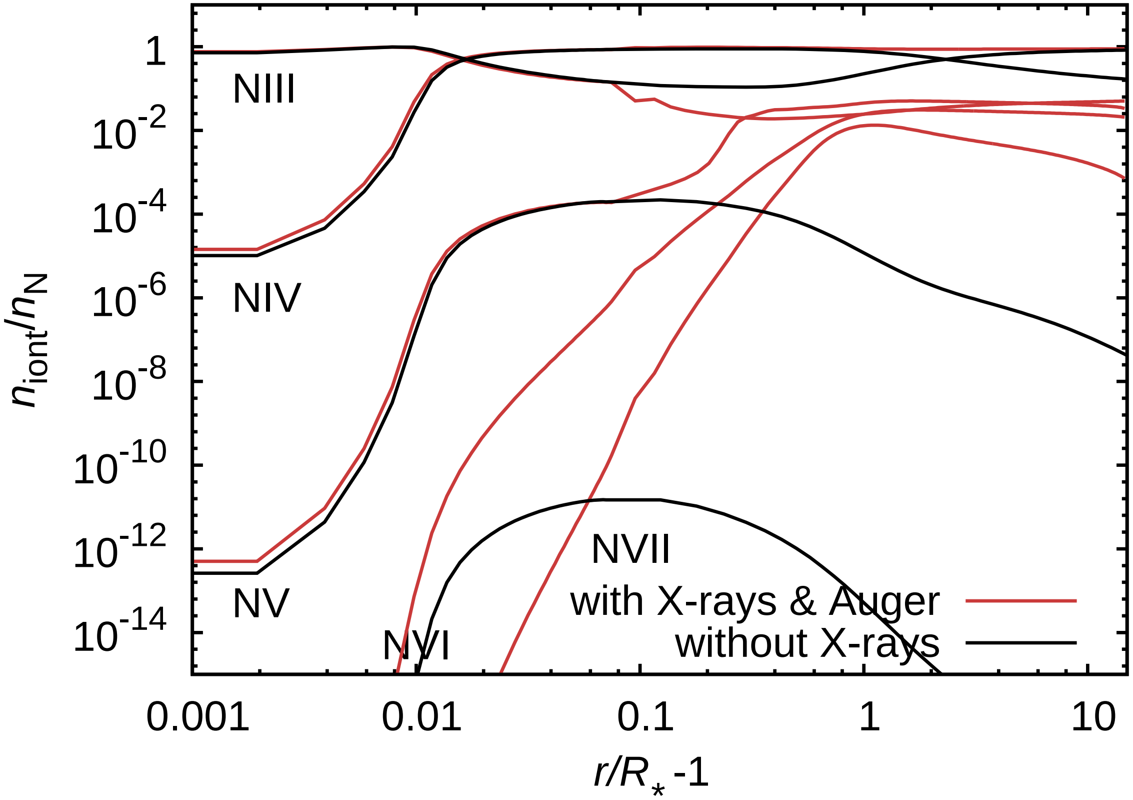
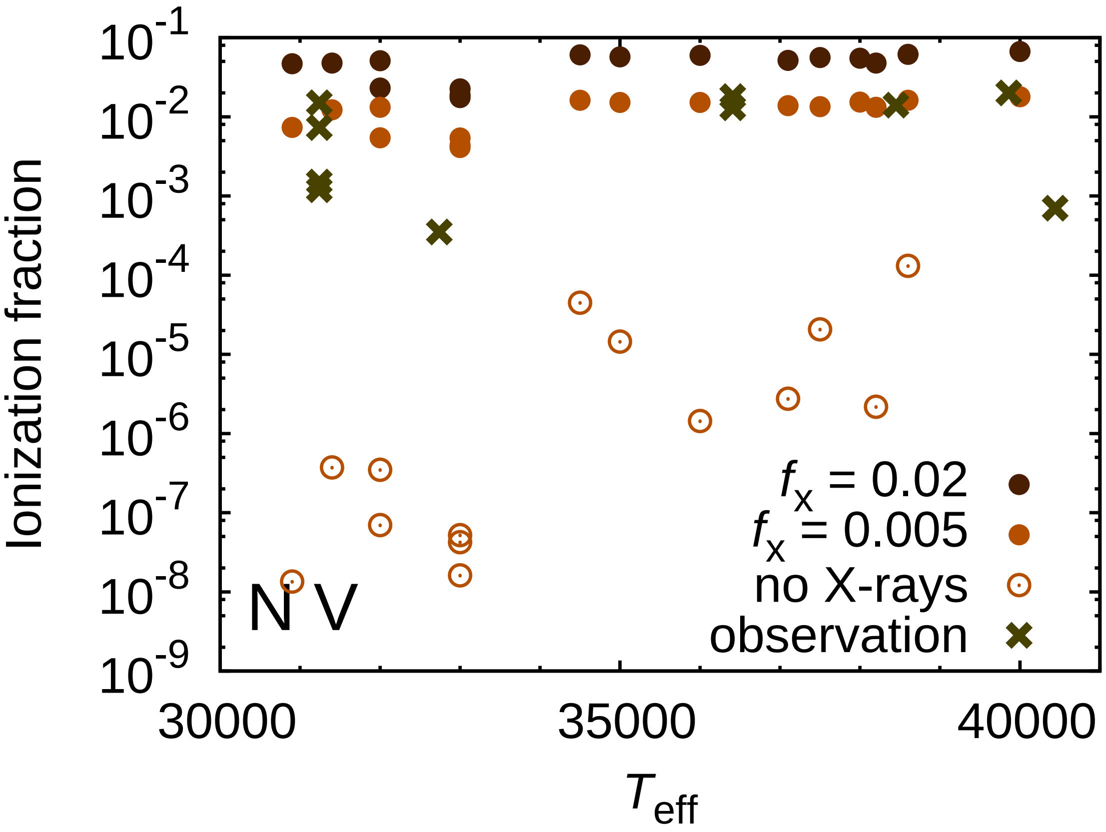


Influence of X-ray on the wind ionization state

- star HD 30614, $T_{\mathrm{eff}} = 30\,900\,\mathrm{K}$

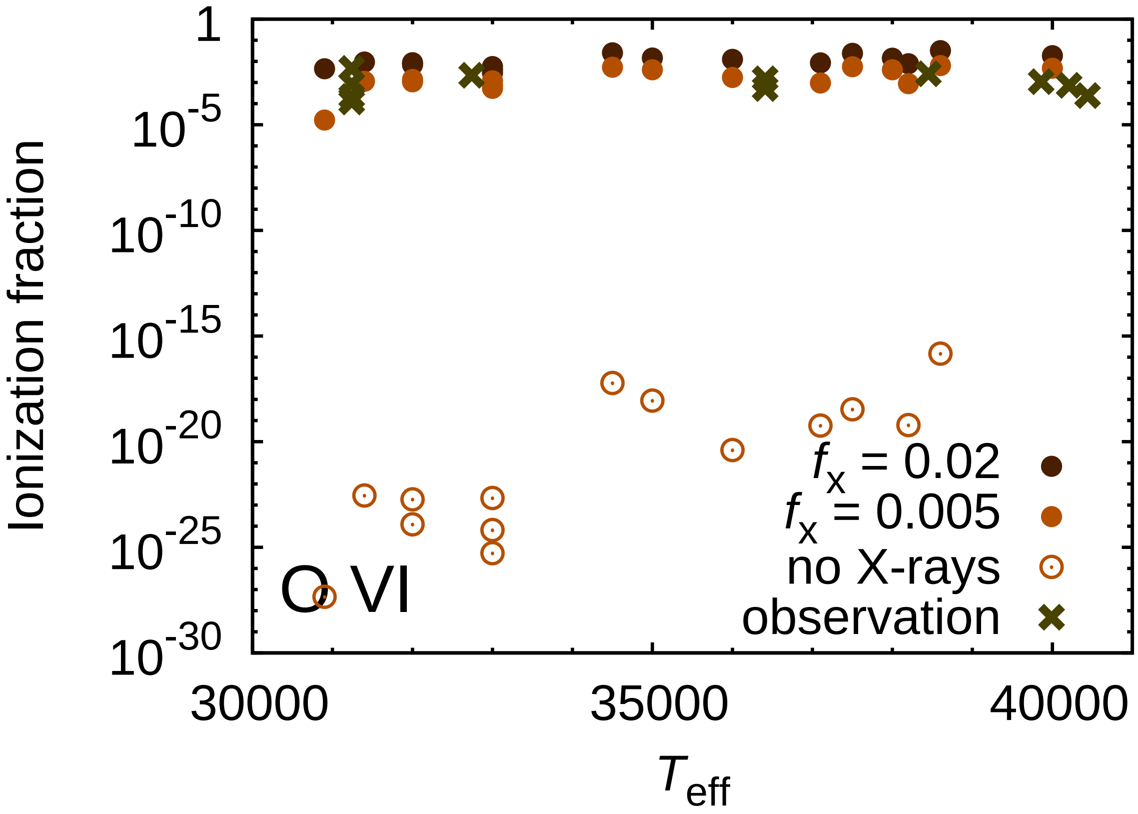


Infuence of X-rays on the ionization fractions for $v \approx v_\infty$



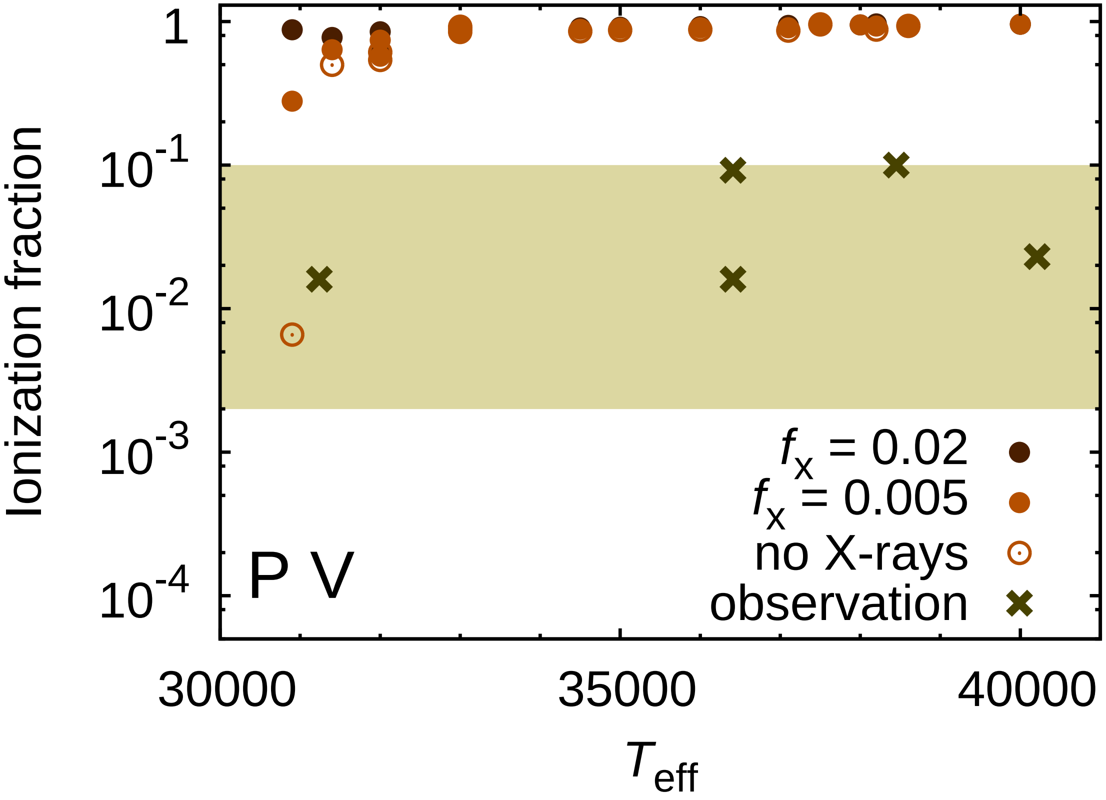
$\Rightarrow$ much better agreement between observations (Massa et al. 2003) and theory with inclusion of X-rays

Infuence of X-rays on the ionization fractions for $v \approx v_\infty$



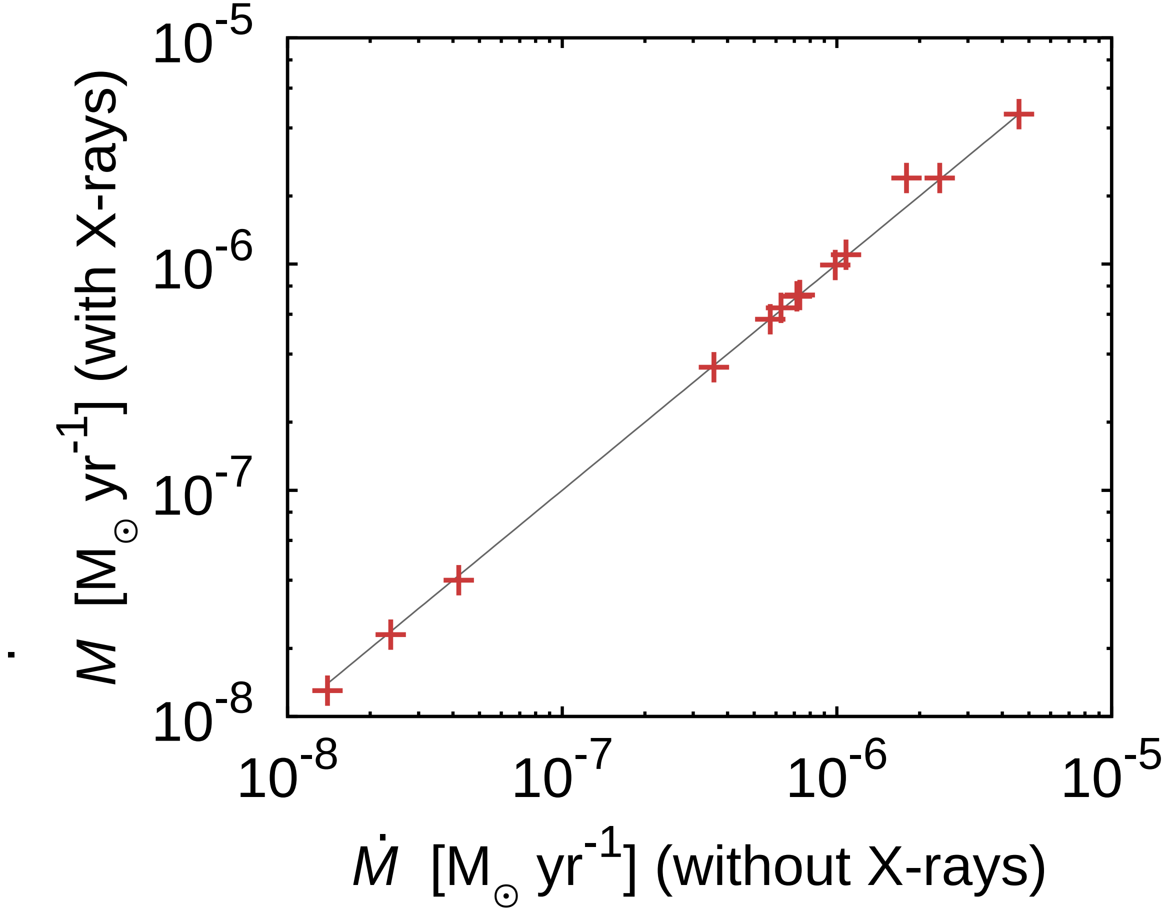
⇒ much better agreement between observations (Massa et al. 2003) and theory with inclusion of X-rays

Infuence of X-rays on the ionization fractions for $v \approx v_\infty$



⇒ still significant discrepancy between observations (Massa et al. 2003, Fullerton 2006) and theory

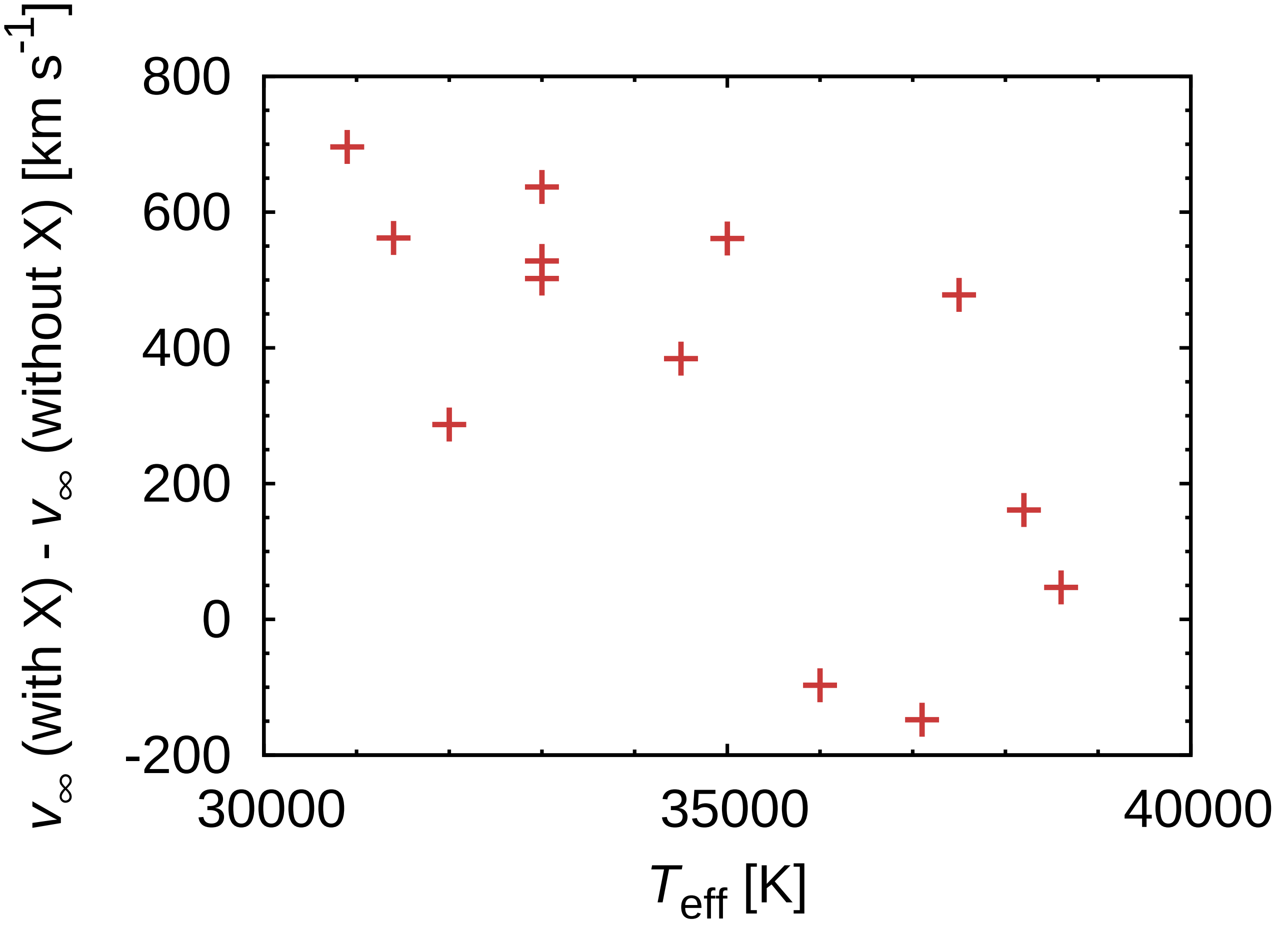
Influence of X-rays emission on the wind mass-loss rate



⇒ X-rays influence the ionization state only in the outer wind regions

⇒ influence of X-rays on the mass-loss rate negligible

Influence of X-rays emission on the wind terminal velocity



⇒ X-rays may influence the terminal velocity, especially for cooler stars

Conclusions

- hot stars have X-ray emission due to wind instabilities
- X-rays influence the wind ionization state and the terminal velocity
- incluse of X-rays improve the agreement between the observations and theory, but some problems still remain