X-ray emission from massive stars: lessons learned and remaining mysteries

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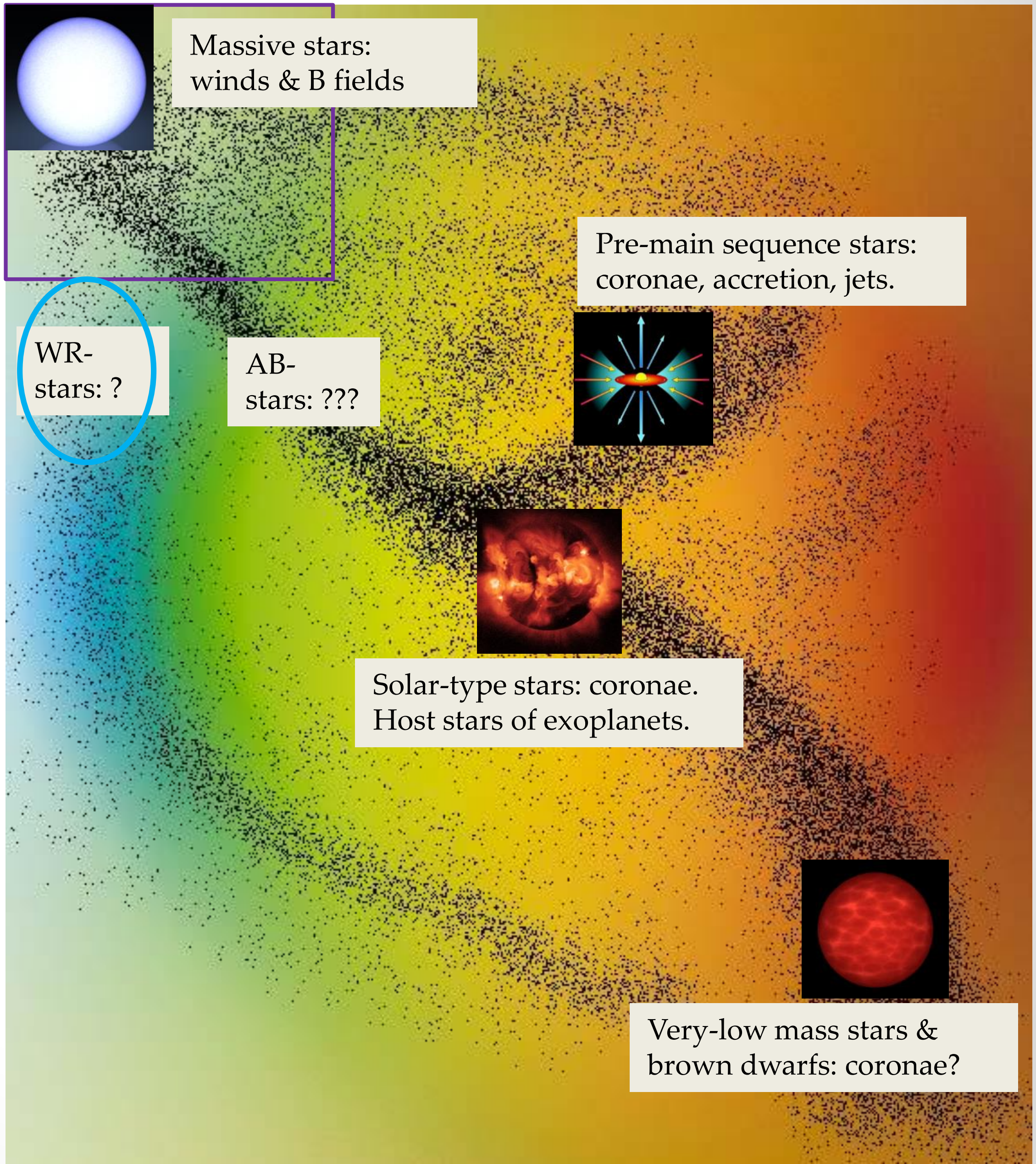
X-ray emission from normal stars

X-ray emission is observed over wide parts of the HRD.

The mechanisms at work are different for massive and low-mass stars.



Massive stars: winds & B fields

Pre-main sequence stars: coronae, accretion, jets.

WR-stars: ?

AB-stars: ???

Solar-type stars: coronae. Host stars of exoplanets.

Very-low mass stars & brown dwarfs: coronae?

Massive stars

OB and Wolf-Rayet stars feature powerful line-driven stellar winds that impact their surroundings.

These winds have considerable structure:

- Small-scale clumps
- Large-scale co-rotating interaction regions or magnetically confined winds.

Be/Oe stars feature equatorial Keplerian decretion disks

The circumstellar environment is a key ingredient in the generation of the X-ray emission.

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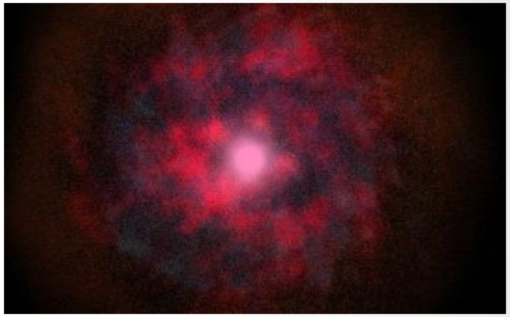
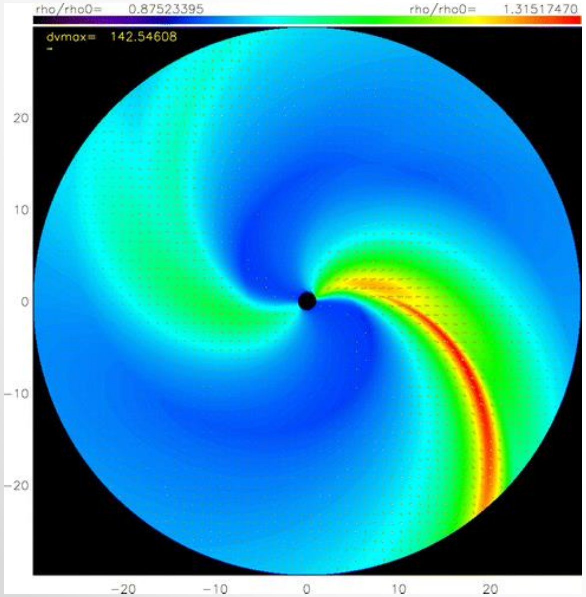


Nazé et al. 2013, ApJ 763, 143

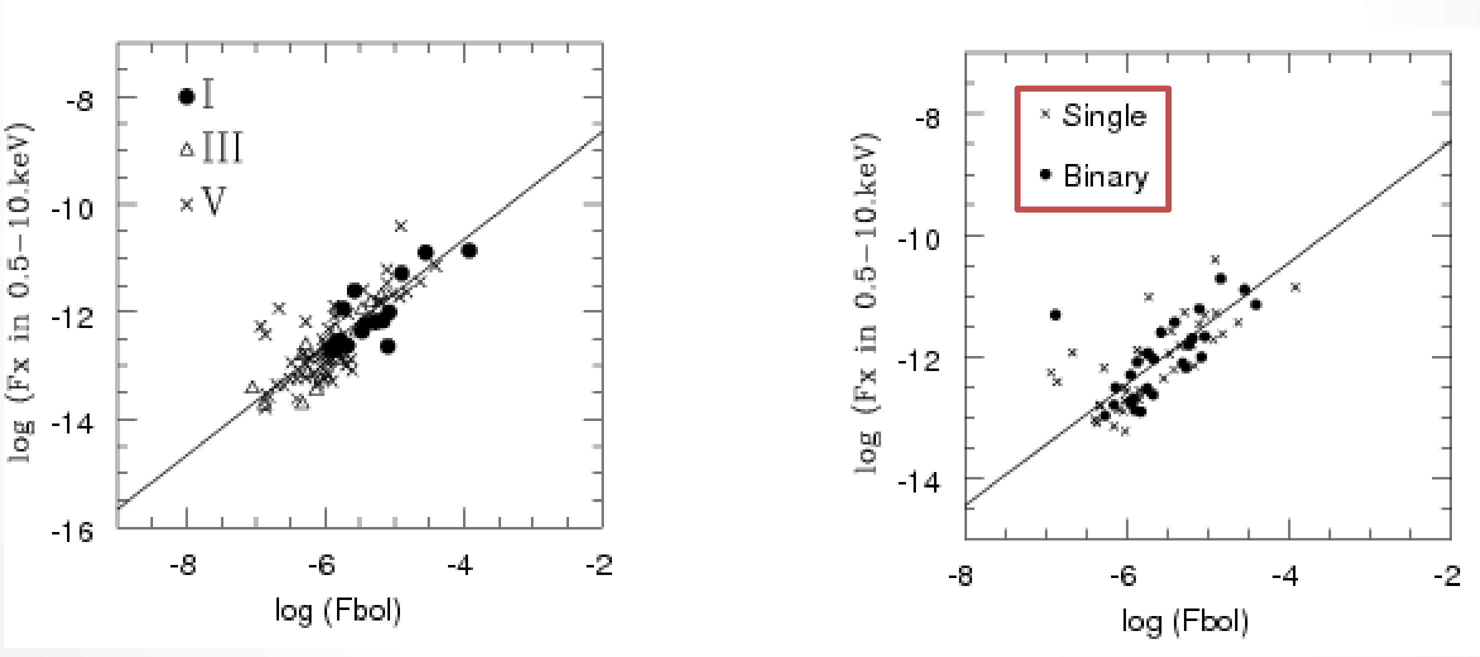


Lobel & Blomme 2008, ApJ 678, 408

X-rays from single massive stars

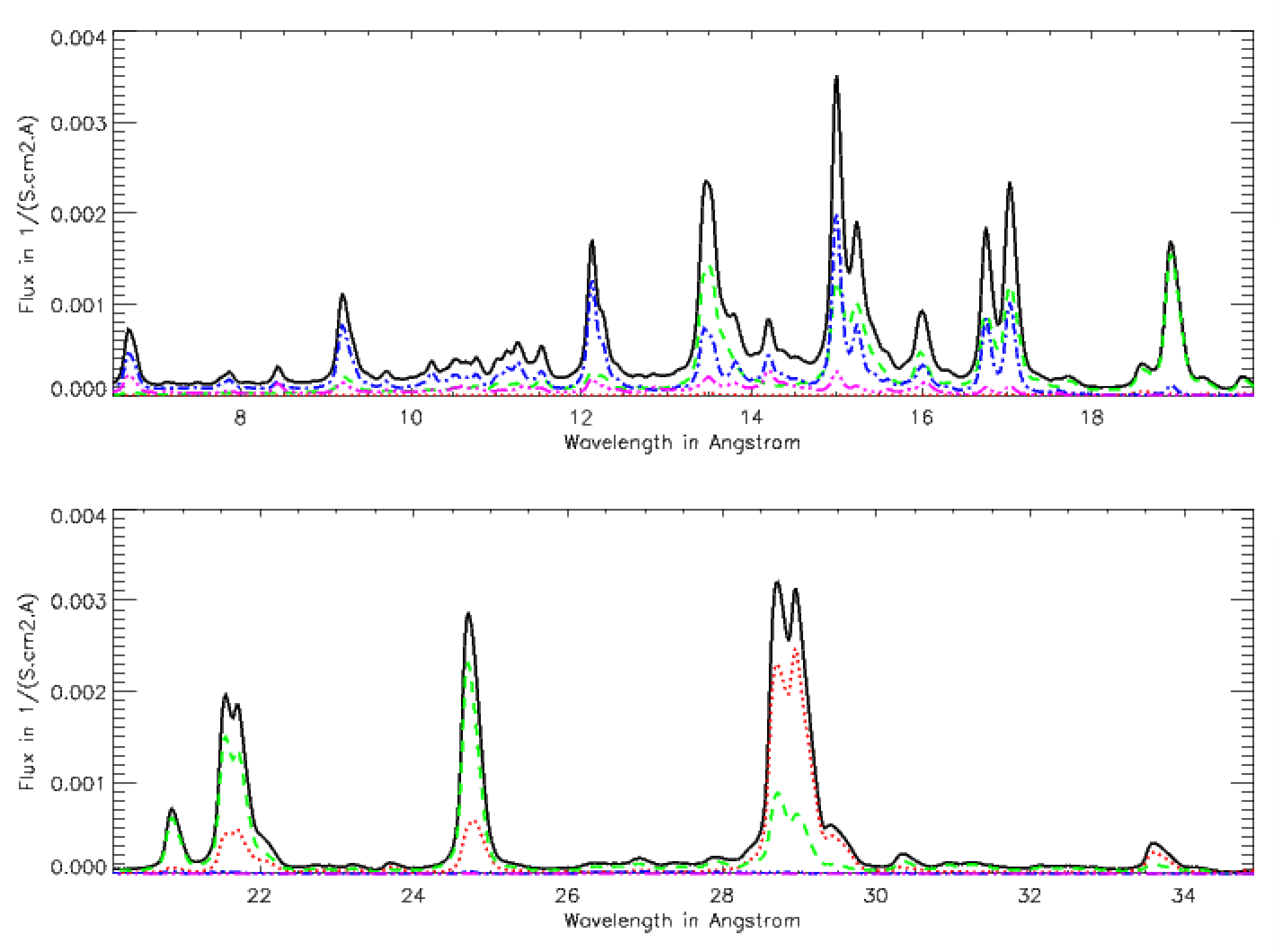
The line de-shadowing instability of OB star winds leads to wind embedded shocks that are the likely causes of the intrinsic X-ray emission (Owocki et al. 1988, ApJ 335, 914; Feldmeier et al. 1997, A&A 322, 878; Owocki et al. 2013, MNRAS 429, 3379).

X-ray luminosity of non-magnetic OB star scales linearly with bolometric luminosity $L_X/L_{bol} \approx 10^{-7}$ (Chlebowski et al. 1989, ApJ 341, 427; Berghöfer et al. 1997, A&A 322, 167; Nazé 2009, A&A 506, 1055). Emission is thermal and soft ($kT < 1$ keV).



Nazé 2009, A&A 506, 1055

High-resolution X-ray spectra of OB stars are dominated by broad emission lines which imply plasma components over a range of temperatures.



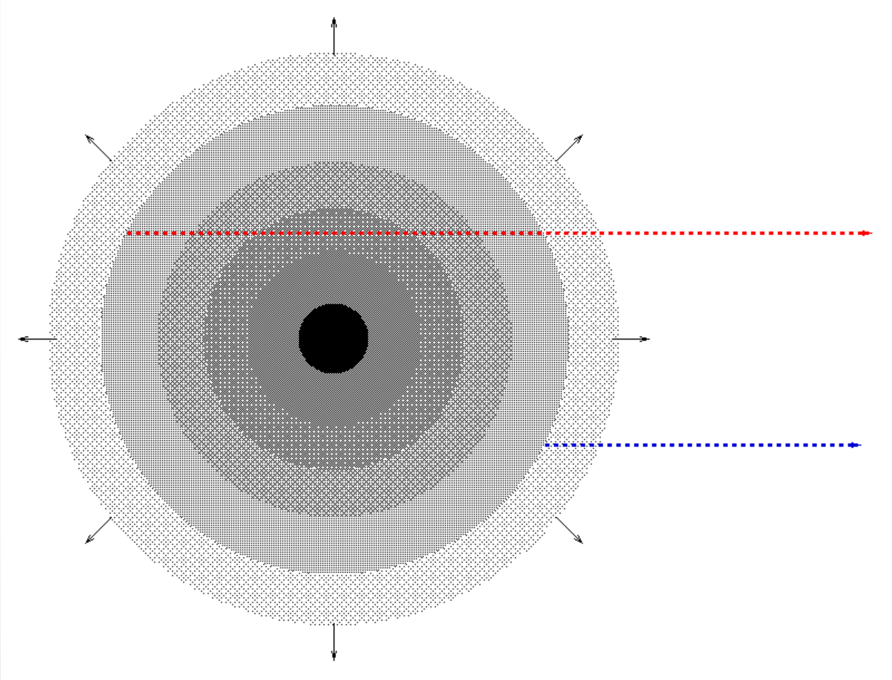
Hervé et al. 2013, A&A 551, A83

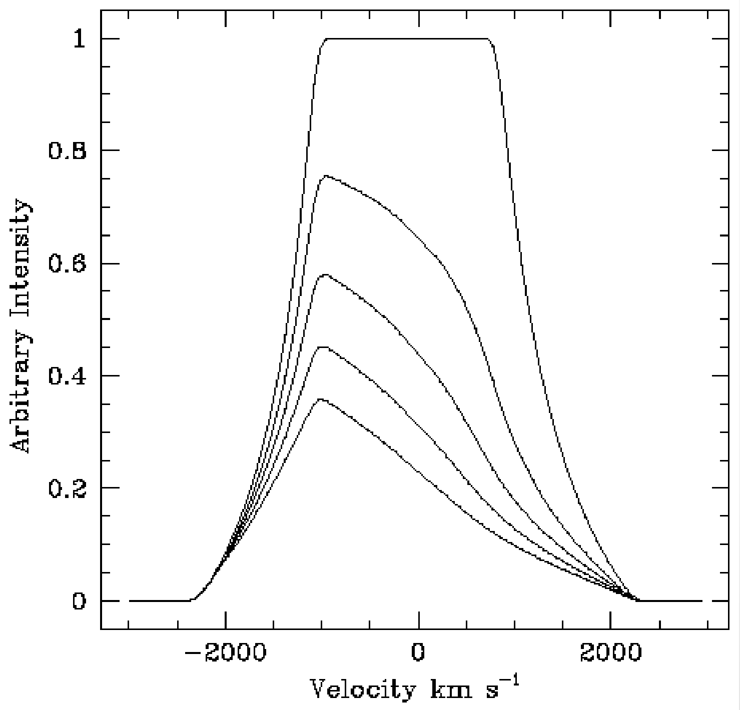
Standard model: shock-heated plasma distributed throughout the cool stellar wind and moving with the latter.

X-ray emission line profiles = combination of broadening due to the wind’s velocity and absorption by the cool wind material (MacFarlane et al. 1991 ApJ 380, 564 ; Owocki & Cohen 2001, ApJ 559, 1108; Owocki & Cohen 2006, ApJ 648, 565).

Line shape mostly ruled by a single parameter $\tau_* \equiv \dfrac{\kappa \dot{M}}{4\pi v_\infty R_*}$

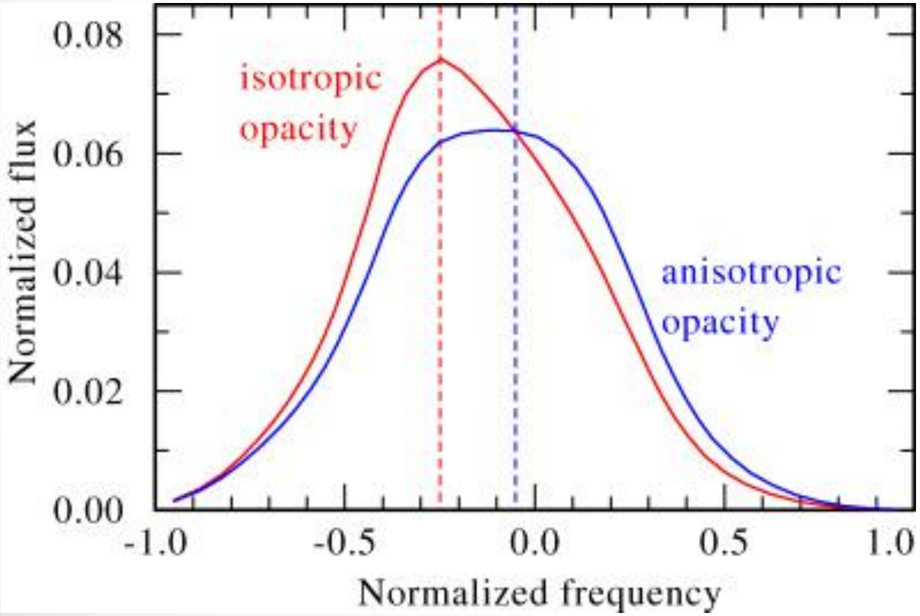
where κ is the wavelength-dependent opacity.



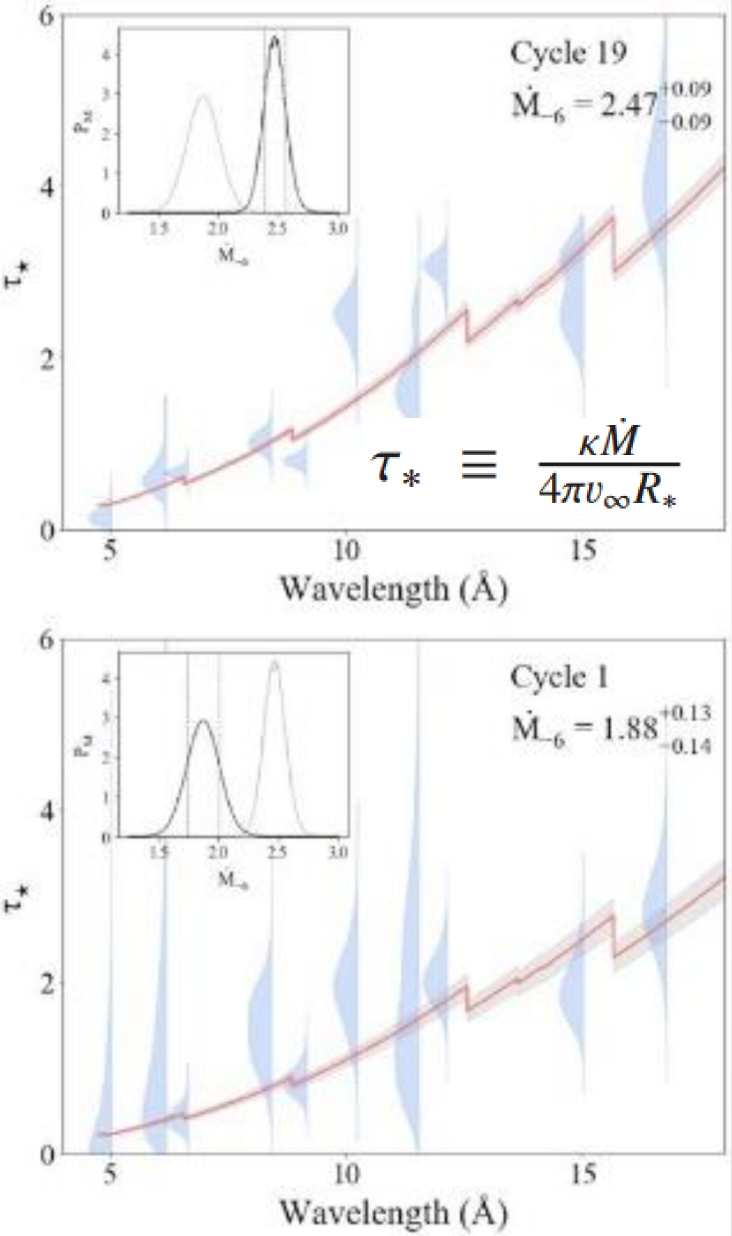


Determination of τ_* allows evaluation of the mass-loss rate (Cohen et al. 2014, MNRAS 439, 908; Cohen et al. 2020, MNRAS 444, 3729).

BUT reality might be more complicated: parameter degeneracy between mass-loss rate, distribution, geometry and optical depth of the fragments of cool wind (Feldmeier et al. 2003, A&A 403, 217; Oskinova et al. 2006, MNRAS 372, 313).



Oskinova et al. 2006, MNRAS 372, 313

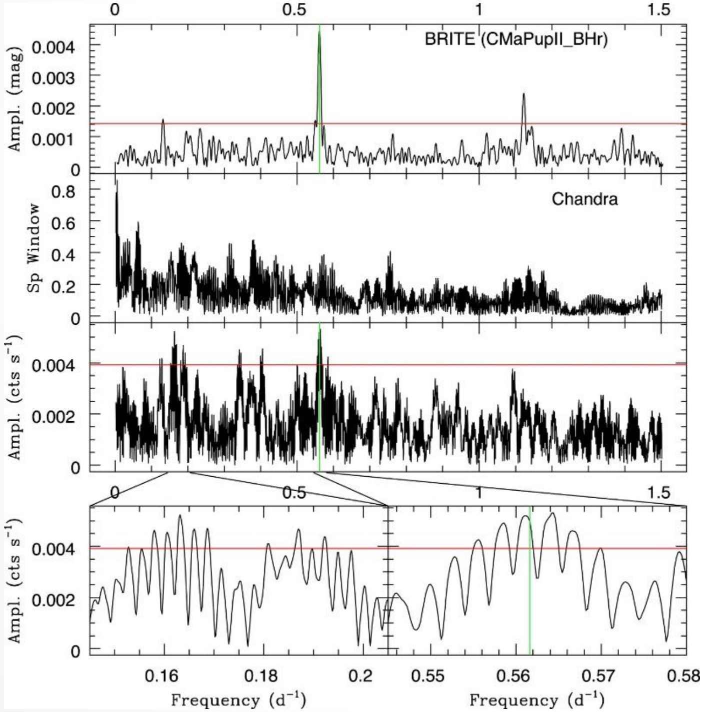


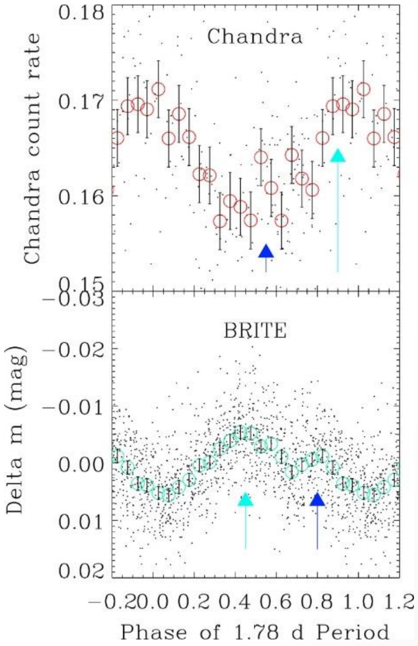
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi v_\infty R_*}$$

Cohen et al. 2020, MNRAS 444, 3729

Lack of strong short-term (minutes to hours) X-ray variability implies large number (> 10^5) of clumps (Nazé et al. 2013, ApJ 763, 143).

Increasing number of stars displaying pseudo-periodic modulations of their X-ray emission (Rauw et al. 2015, A&A 580, A59; Nazé et al. 2018, A&A 609, A81; Massa et al. 2019, ApJ 873, 81; Nichols et al. 2021, ApJ 906, 89). Most spectacular case: ζ Pup (O4 Ief) with 1.78 d periodicity seen in optical photometry.





ζ Pup, Nichols et al. 2021, ApJ 906, 89

What is the role of large-scale structures in the X-ray emission/absorption?

X-rays from single Wolf-Rayet stars

Does LDI also operate in winds of single WR stars?

No L_X/L_{bol} relation for WR stars (Wessolowski 1996, MPE Rep. 263, 75; Ignace & Oskinova 1999, A&A 348, L45, Oskinova 2005, MNRAS 361, 679)

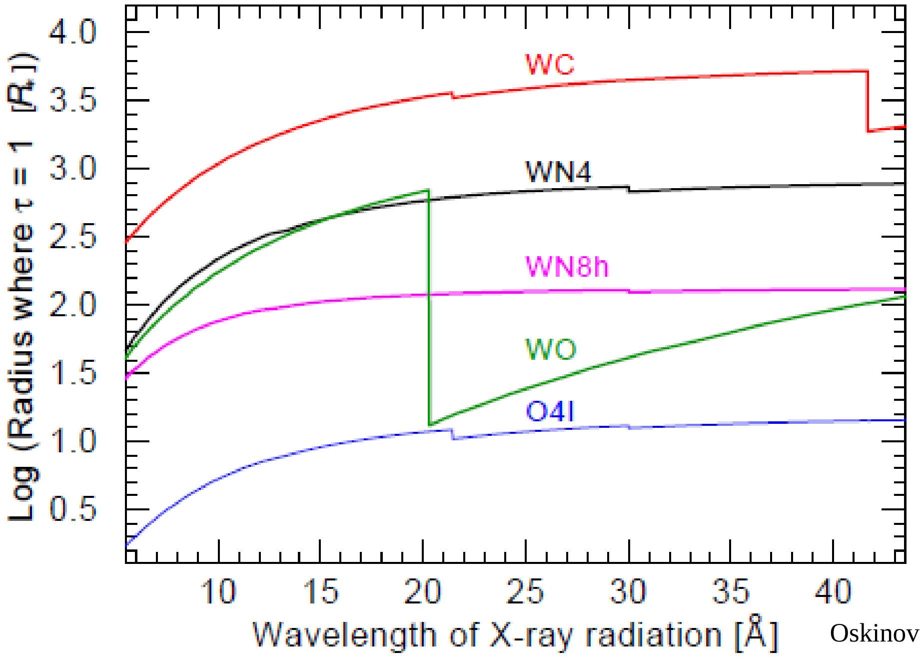
WNE stars: $L_X \sim$ a few times 10^{32} erg/s (e.g. Huenemoerder et al. 2015, ApJ 815, 29)

WNL stars: X-ray faint or dark (Gosset et al. 2005, A&A 429, 685; Skinner et al. 2012, AJ 143, 116)

WC stars: X-ray faint or dark (Rauw et al. 2015, ApJS 221, 1)

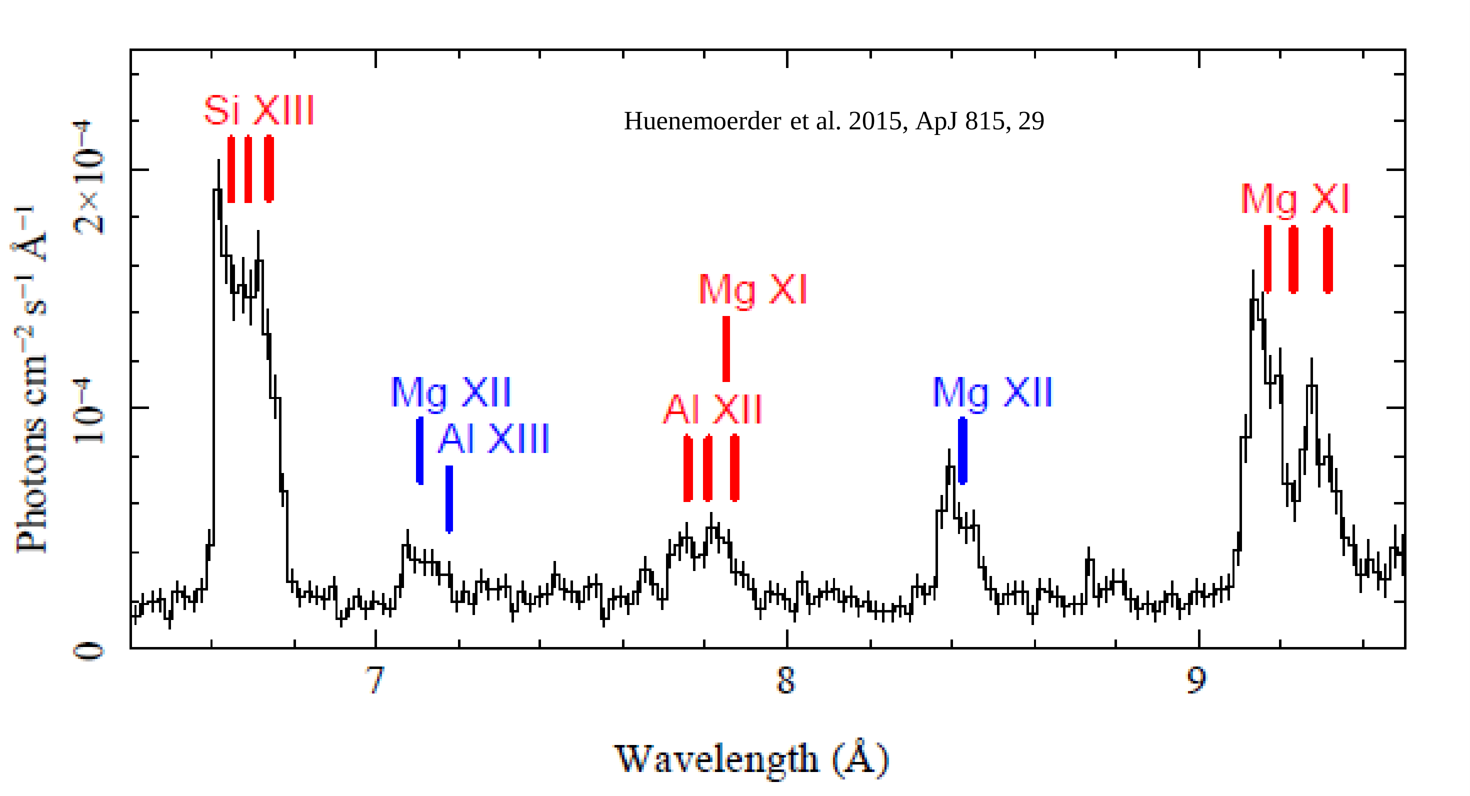
WO stars: $L_X \sim 10^{31}$ erg/s (Oskinova et al. 2009, ApJ 693, L44)

WR winds: huge optical depth, but cannot explain everything…



Oskinova 2016, arXiv:1607.03658)

WR6 (WN4): lines arise far out in the wind, from smallest possible radius around $\tau = 1$ (Huenemoerder et al. 2015, ApJ 815, 29)



Possible scenario (Gayley 2016, Adv. Sp. Res. 58, 719) : fast winds (WNE and WO stars) advect LDI shock-heated plasma out beyond $\tau = 1$ before it cools.

Magnetically confined wind shocks

Impact of large-scale B fields quantified by confinement parameter:

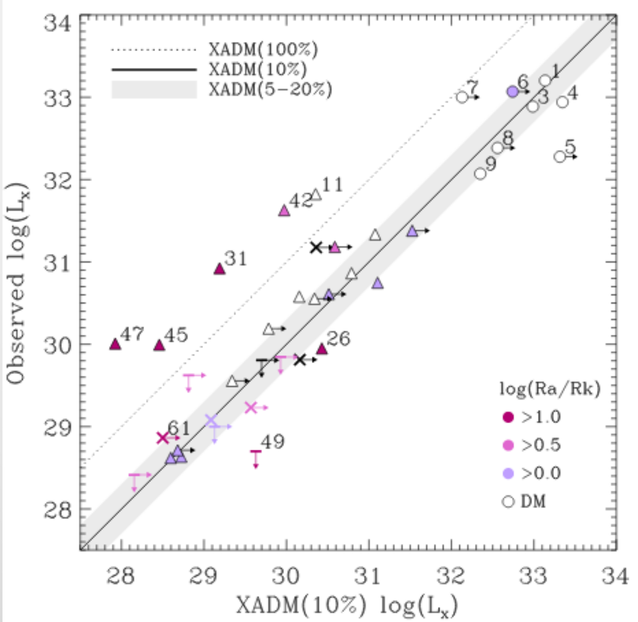
$$\eta_* \equiv \frac{B_{\rm eq}^2 R_*^2}{\dot{M}_{B=0} V_\infty}$$

(ud-Doula & Owocki 2002, ApJ 576, 413).

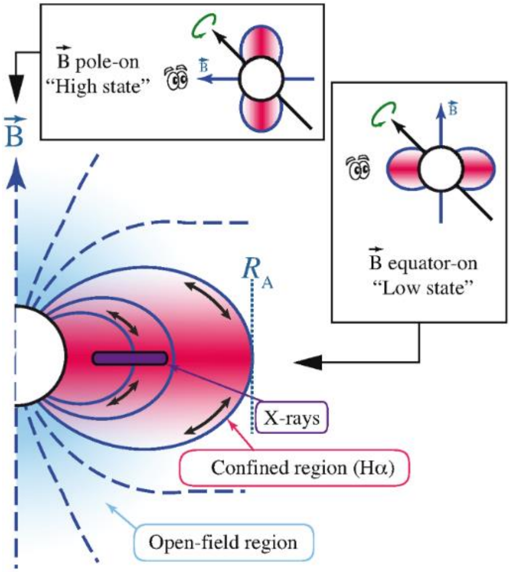
B fields with $\eta_* \geq 10$ confine the winds producing X-ray emission from shock-heated plasma (Babel & Montmerle 1997, A&A 323, 121; ud-Doula et al. 2014, MNRAS 441, 3600; Nazé et al. 2014, ApJS 215, 10; Owocki et al. 2016, MNRAS 462, 3830; ud-Doula & Nazé 2016, Adv. Sp. Res. 58, 680)

Oblique rotator configuration leads to rotational modulation of observed X-ray emission (Gagné et al. 1997, ApJ 478, L87; Petit et al. 2015, MNRAS 453, 3288)

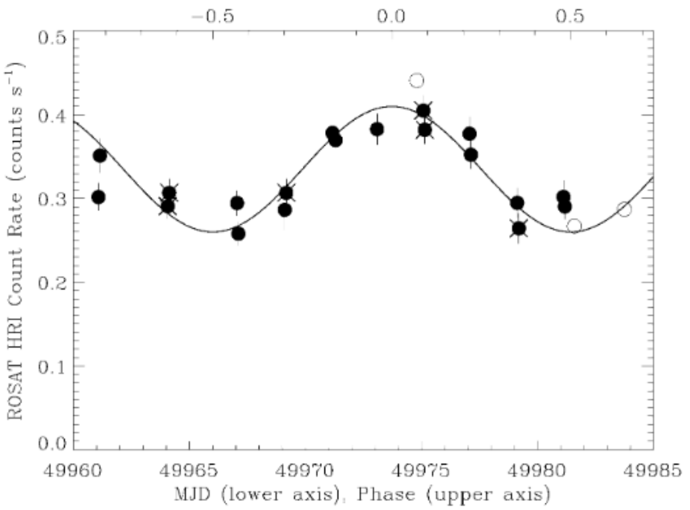
For more details see the reviews by Asif ud-Doula and Matt Shultz



Nazé et al. 2014, ApJS 215, 10



Petit et al. 2015, MNRAS 453, 3288

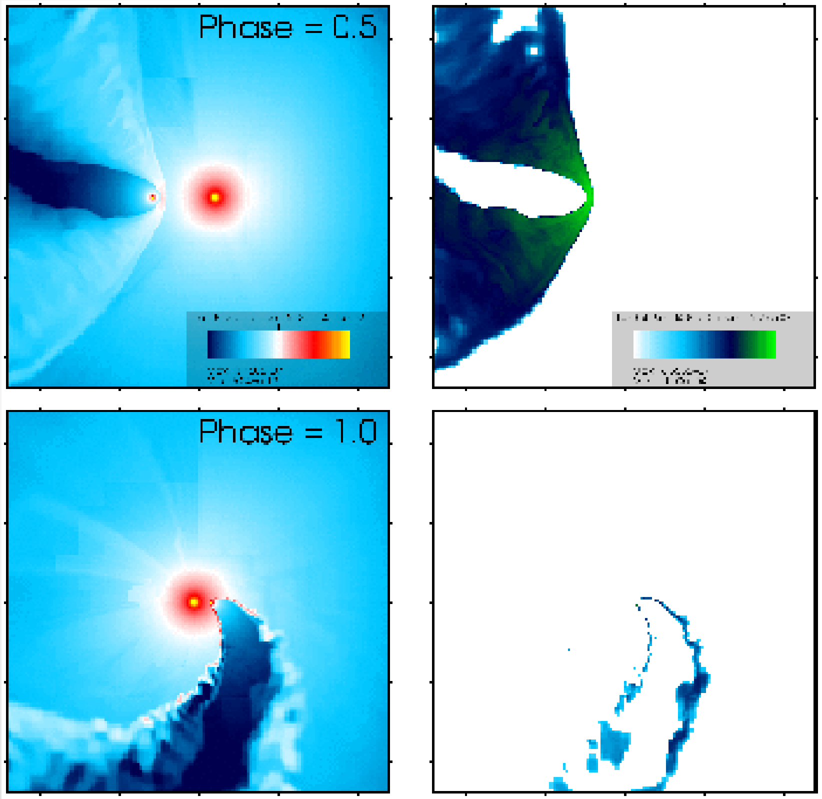


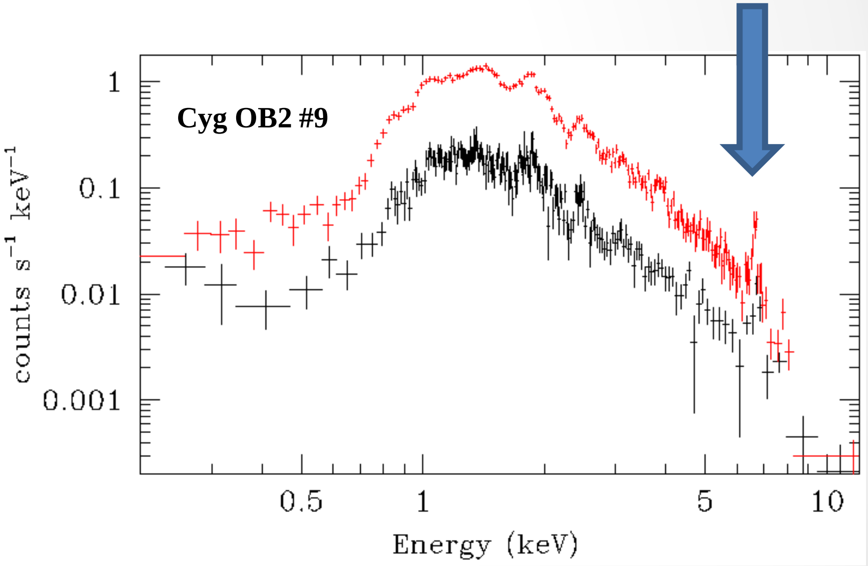
Gagné et al. 1997, ApJ 478, L87

Interacting winds in massive binaries

Some massive binaries host wind collision regions that produce additional X-ray emission (Stevens et al. 1992, ApJ 386, 265; Rauw & Nazé 2016, Adv. Sp. Res. 58, 761).

O + O and WR + O binaries are expected to be bright (Pollock 1987, ApJ 320, 283) and hard X-ray sources (as revealed by strong Fe xxv / Fe xxvi lines).



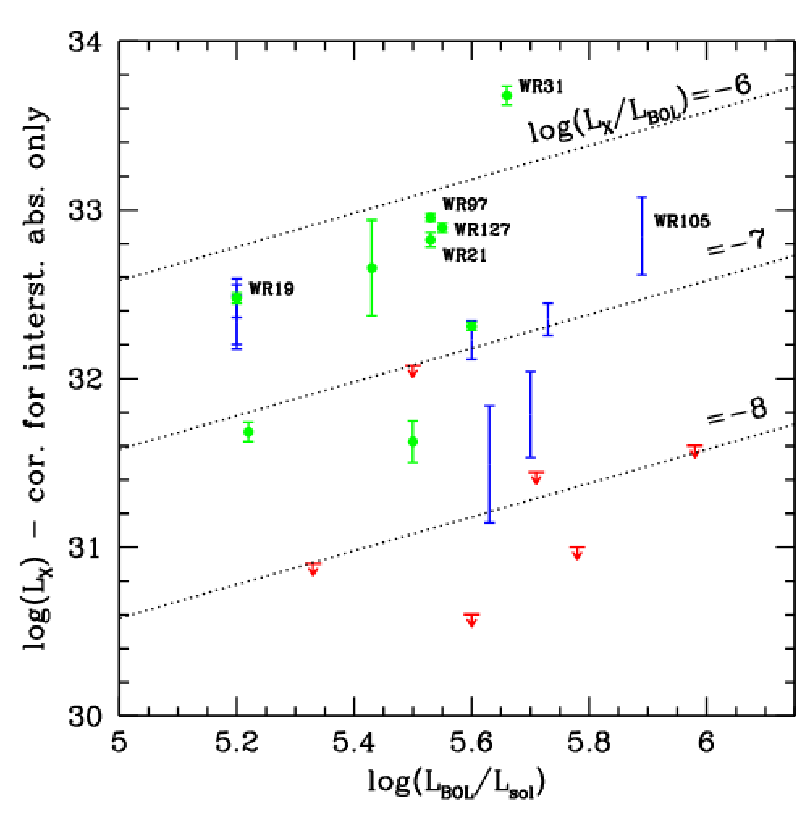


Rauw & Nazé, 2016 Adv Sp Res, 58, 761

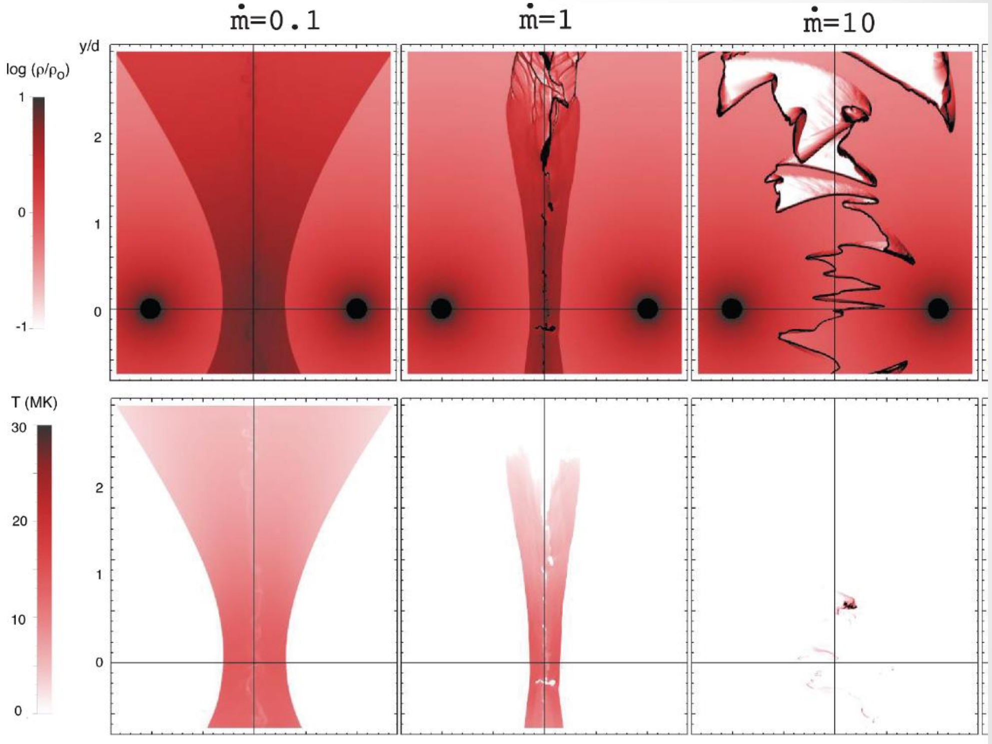
Parkin & Gosset 2011, A&A 530, A119

BUT, not all massive binaries are X-ray overluminous (e.g. Skinner et al. 2019, Astr. Nach. 340, 50; Nazé et al. 2021, MNRAS 501, 4214) AND many display a soft emission.

Importance of radiative cooling and ensuing thin shell instabilities (Kee et al. 2014, MNRAS 438, 3557) → reduction by factor ~50 of X-ray flux.



Nazé et al., 2021 MNRAS, 501, 4214

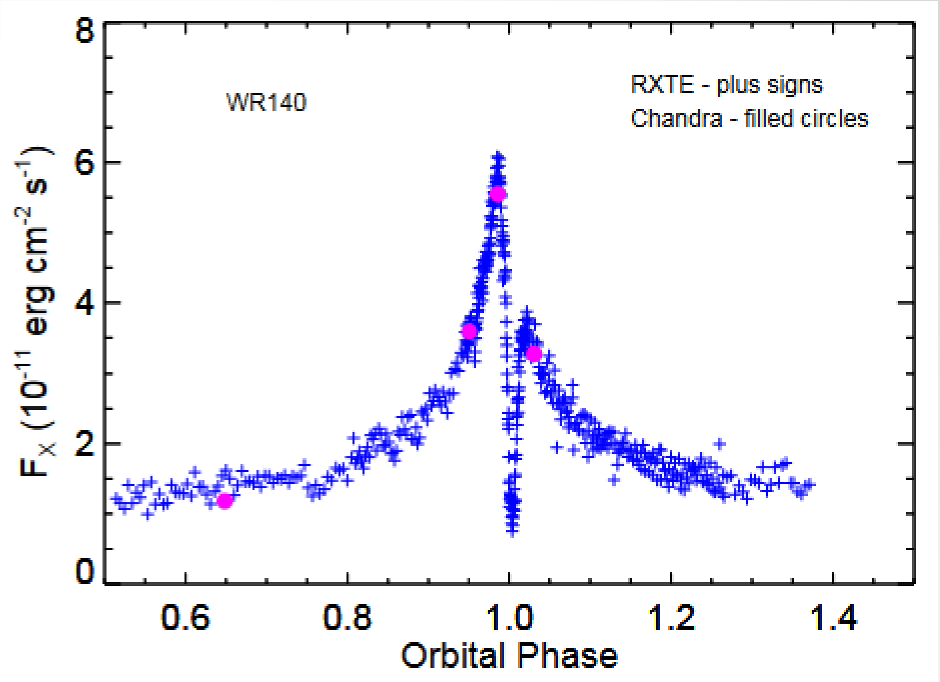


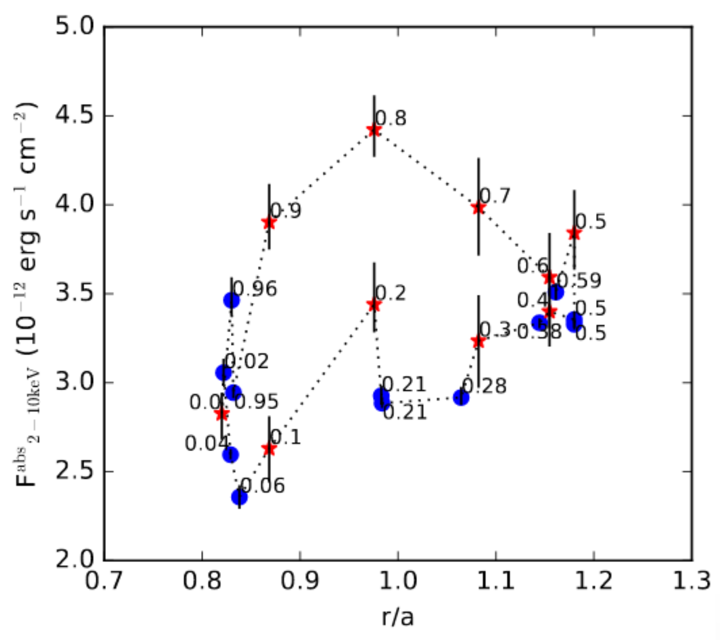
Kee et al. 2014, MNRAS 438, 3557

Colliding winds → orbital variability of X-ray flux due to changing line-of-sight absorption and/or changing orbital separation (Pittard & Parkin 2010, MNRAS 403, 1657; Gosset & Nazé 2016, A&A 590, A113; Pollock et al. 2018, MNRAS 474, 3228).

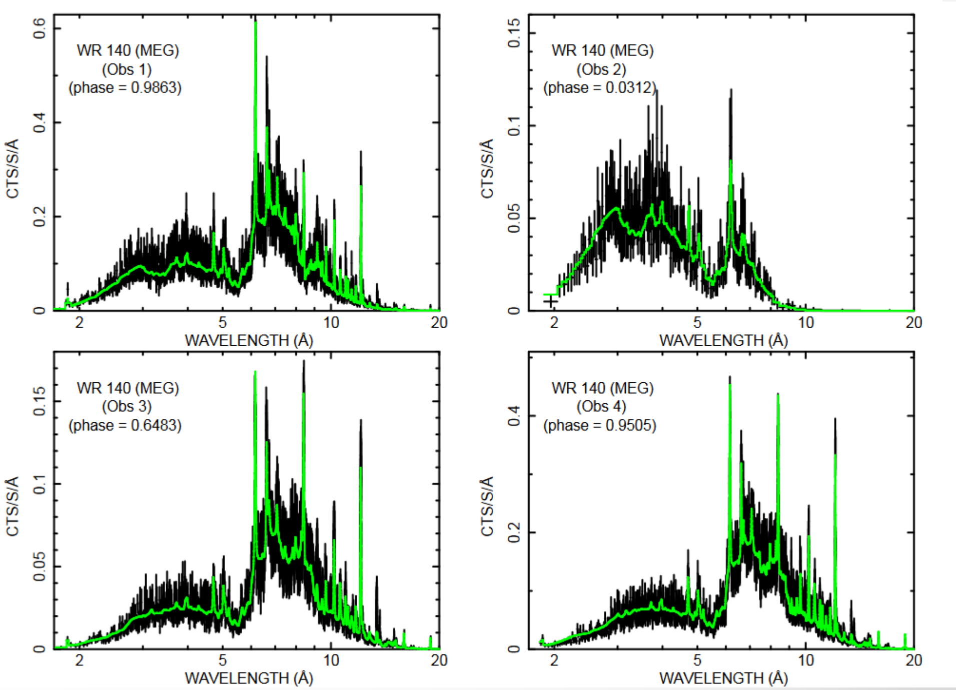
Prominent case: WR140 (WC7pd + O4-5, P=7.9 yrs, e=0.896; Zhekov 2021, MNRAS 500, 4837)

“Hysteresis” effect in (short-period) eccentric systems (Mossoux et al. 2020, A&A 636, A109).





Mossoux et al. 2020, A&A, 636, A109



Zhekov 2021, MNRAS 500, 4837

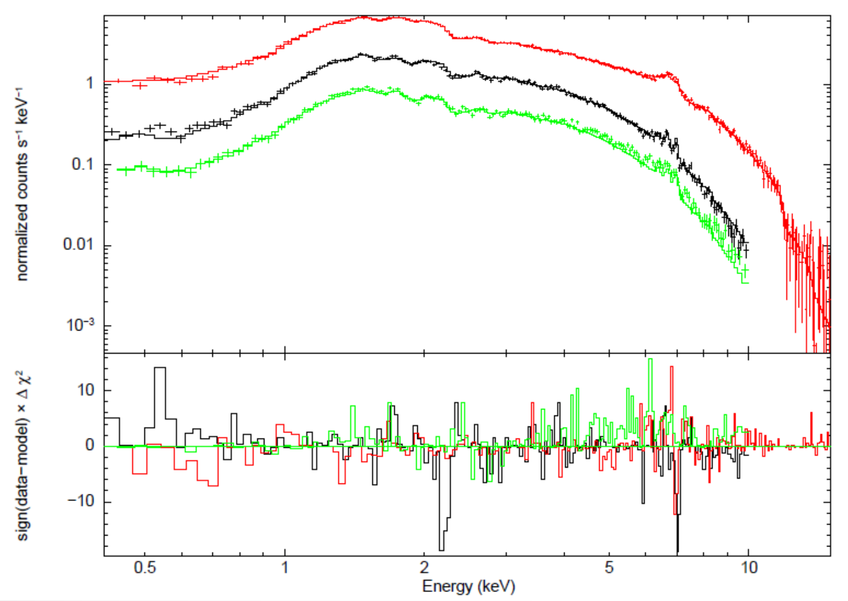
γ Cas stars

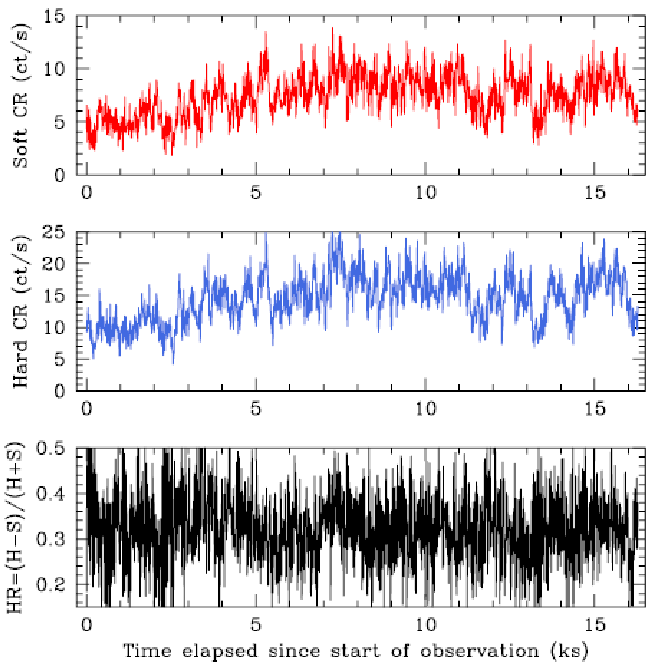
γ Cassiopeia stars are Be stars displaying unusually strong and hard thermal X-ray emission and undergo rapid shot-like variability (Smith et al. 2016, AdSpR 58, 782):

- 10 L_X (OB stars) < L_X (γ Cas) < 0.1 L_X (Be HMXBs)
- Thermal X-rays with kT ~ 10 keV.
- Fluorescent Fe Kα line arising from Be disk material.

Currently about two dozens γ Cas stars are known (Nazé et al. 2020, MNRAS 493, 2511).

Where does the X-ray emission of γ Cas stars come from?

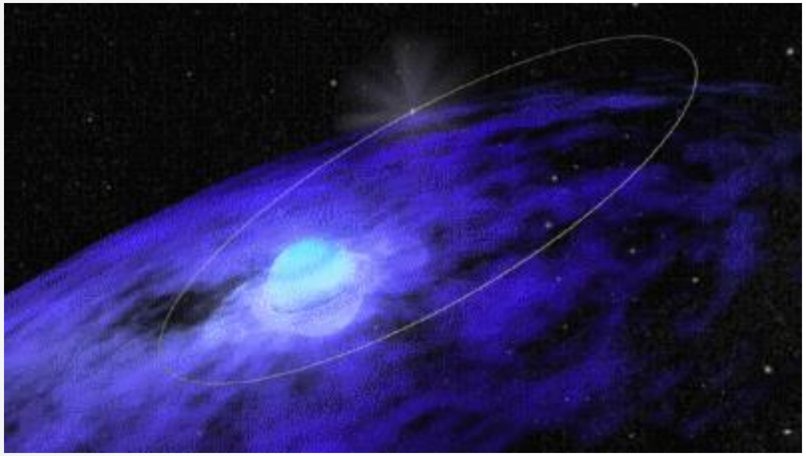




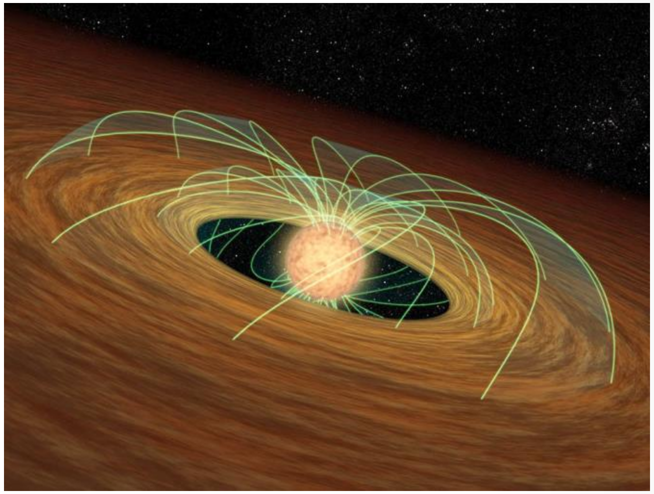
Rauw et al. 2021, in preparation

Two main scenarios:

Accretion onto a compact companion (WD or NS in low-efficiency accretion regime, Tsujimoto et al. 2018, PASJ 70, 109; Postnov et al. 2017, MNRAS 465, L119).

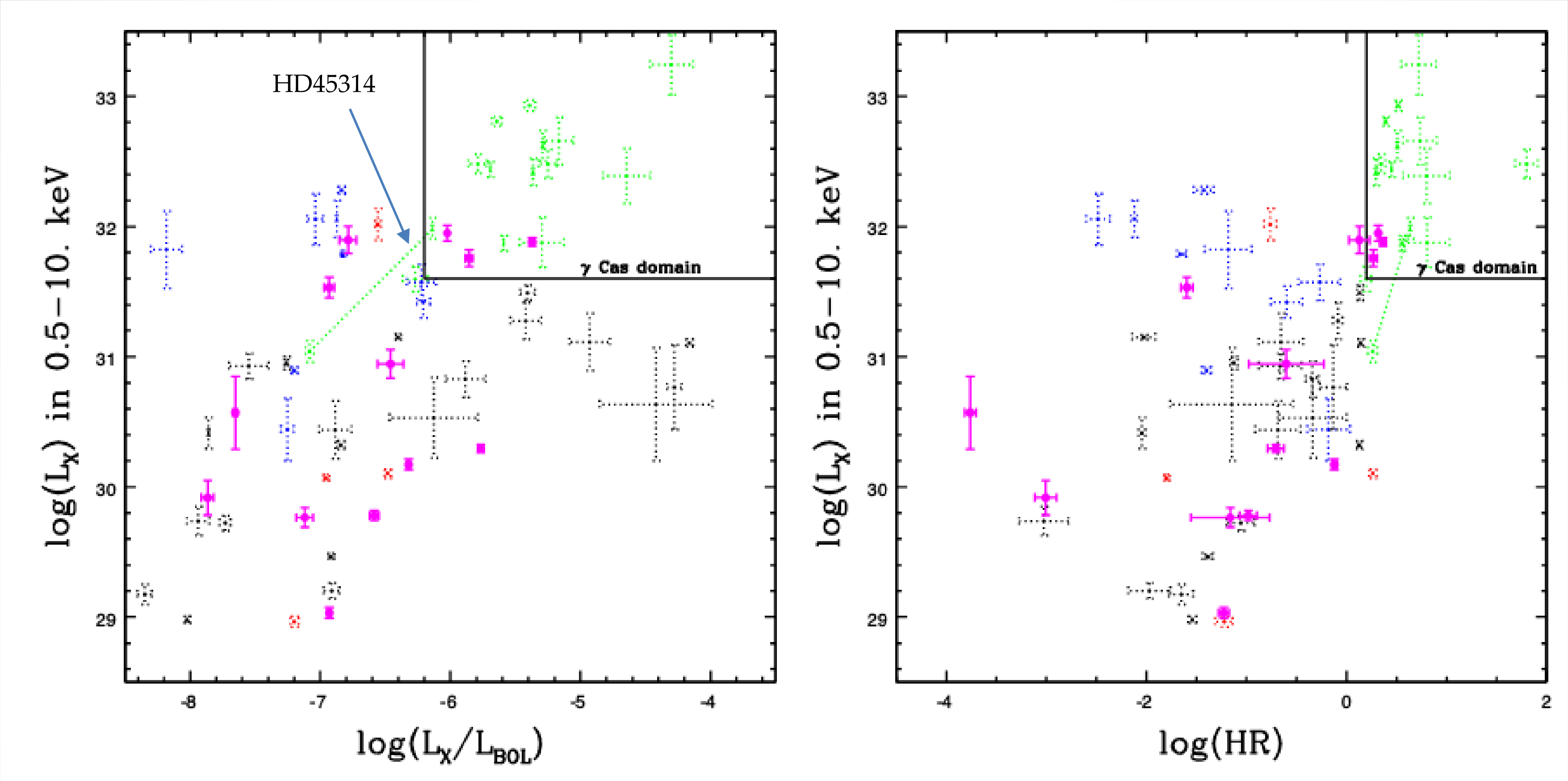


Star-disk interactions via (localized) magnetic fields (Smith et al. 1998, ApJ 503, 877; Motch et al. 2015, ApJ 806, 177).



In all scenarios the level of X-ray emission somehow depends on the disk properties:

- Disk dissipation of HD45314 associated with considerable weakening of γ Cas-like emission (Rauw et al. 2018, A&A 615, A44)
- No such effect seen in π Aqr (Nazé et al. 2019, A&A 632, A23)…



Nazé et al. 2020, MNRAS 493, 2511

Increasing number of γ Cas stars (and intermediate cases, Nazé et al. 2020, MNRAS 493, 2511): relevant information about the evolution of massive stars and the origin of Be stars (Shao & Li 2021, ApJ 908, 67)?

Future high-res spectroscopy will unveil morphology of fluorescent Fe K line, hence provide clues on the location of the hard X-ray source.

Conclusions/open questions

- LDI predicts the strongest shocks in the outer winds, but observations indicate onset of X-ray emission at about 1.5 R_*.
- Recurrent modulations of X-ray flux: what is their origin? Role of co-rotating interaction regions and pulsations in generating or absorbing X-rays?
- LDI also in single WR stars? Need more high-resolution spectra to confirm Gayley (2016) scenario.
- Only a fraction of massive binaries display clear X-ray emission from colliding winds. Action of thin shell instability?
- What is the origin of the unusual X-ray emission of γ Cas stars? Is there a continuum of behaviours between normal Be stars and γ Cas stars?