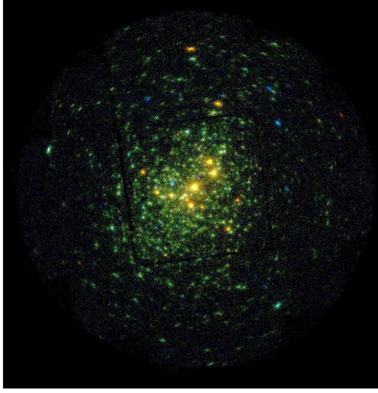
X-ray emission from hot stars



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Outline of the talk

1. Introduction
2. Global properties
3. Origin of the X-ray emission:
   insights from high-resolution spectroscopy
4. Peculiar objects
5. Conclusions

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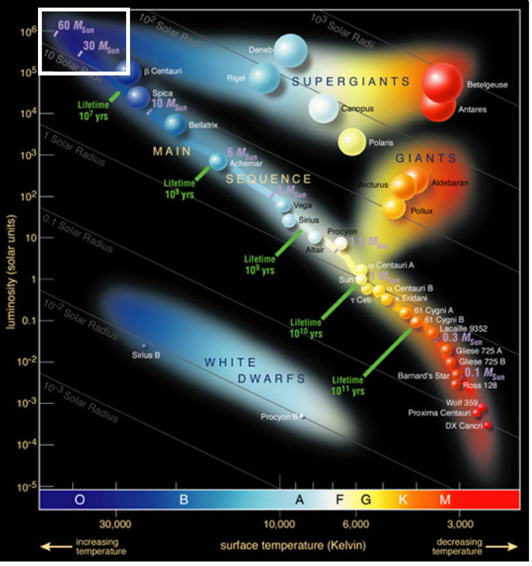
1. Introduction

Hot, massive stars?

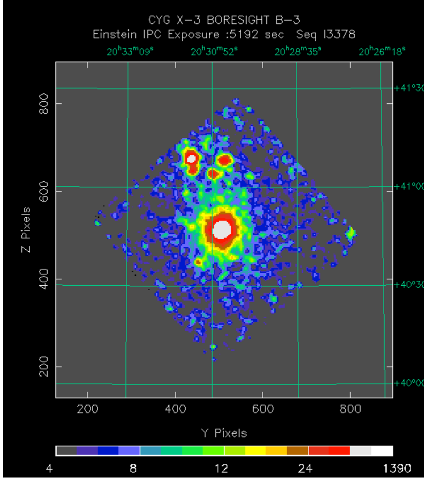
- the top of the MS (**O**BAFGKM)
- T > 30kK, M > 20 M_{sol}
  - Blue ⇒ lot of UV
  - Luminous (10^6 L_{sol})
  - Short-lived (< 10 Myr)
  - Precusors of SN, NS, BH (+GRB?)
- Rare objects but major contributor to mech. input & chem. enrichment
- Strong stellar winds !

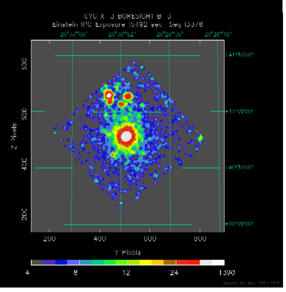


1. Introduction

The 30^{th} anniversary !

X-ray emission serendipitously discovered in Dec. 1978 by Einstein

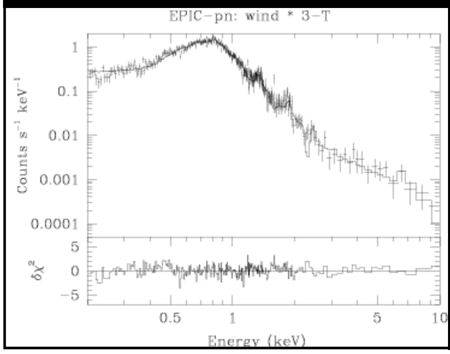




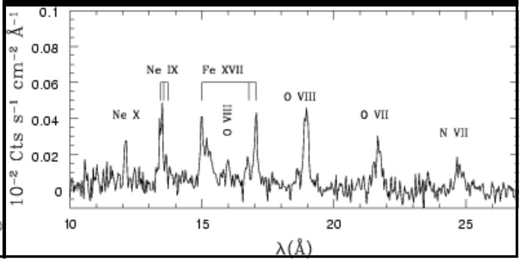
2. Global properties

Nature of the spectrum :

- lines & bremsstrahlung ⇒ Thermal !
- moderate NT emission ?
  possibly in some cases, not yet convincingly detected *(De Becker 2007)*



X-ray spectra at medium (left) and high (bottom) resolution – *Rauw et al. 2002*

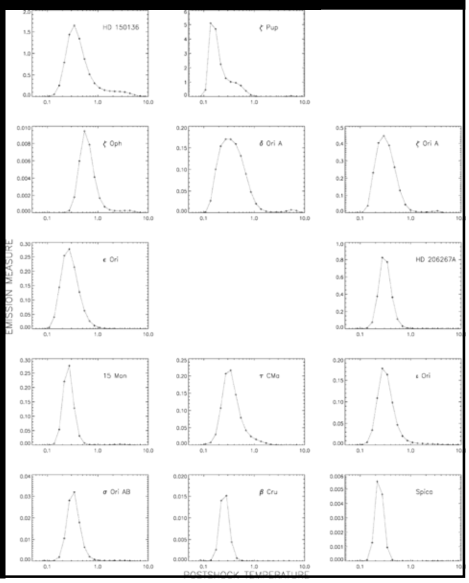


2. Global properties

Temperature :

- Soft spectra
- 2T *mekal* fits of medium-res spectra : kT_1~0.3keV, kT_2~0.7 keV
  (e.g. Sana et al. 2006)
- DEM analysis of high-res spectra : broad peak at kT~0.1-0.4 keV
  + weak hard tail ?
  (Zhekov & Palla 2007)

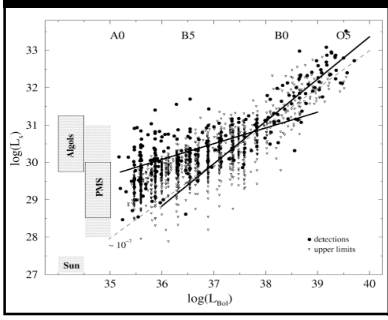
Zhekov & Palla 2007



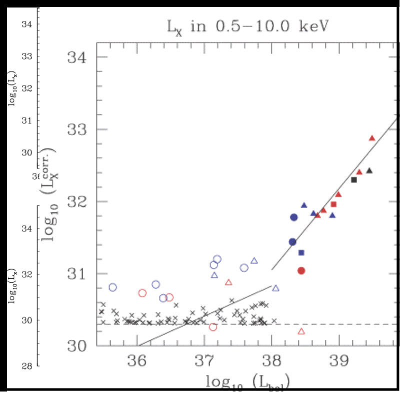
2. Global properties

Luminosity :

- Very soon, it was found that for O stars, $L_x \propto 10^{-7} L_{bol}$
- ROSAT-all sky survey *(Berghöfer et al. 1997)* : lot of dispersion !
- XMM/Chandra observations of clusters :
  - tighter relation *(e.g. Sana et al. 2006, Antokhin et al. 2008)*
  - in soft & medium bands only
  - same for other clusters, O I&III, B stars?



ROSAT (left, based on CRs & HRs) vs XMM (right, based on spectroscopy)



3. Origin of the emission

Where do the X-rays come from ?

- Corona but absorption in HMXBs and not enough in hot stars, no coronal line at 530nm, UV superionization profiles not well fitted…
- Shocks between shells in stellar wind but fragmentation needed !

Predictions of the wind-shock model

- Location of the X-rays :
  not at photosphere, a few stellar radii above
- Line profiles :
  broad (wind accelerated!) + either flat-topped or blueshifted

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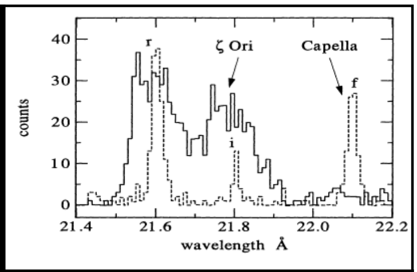
3. Locating the X-ray emitting region

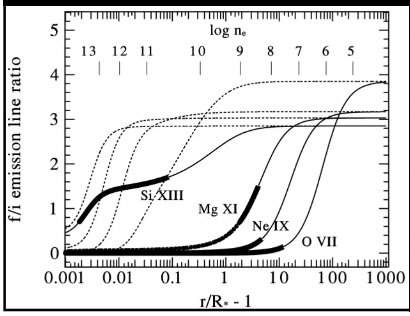
He-like triplets : f/i ratio !

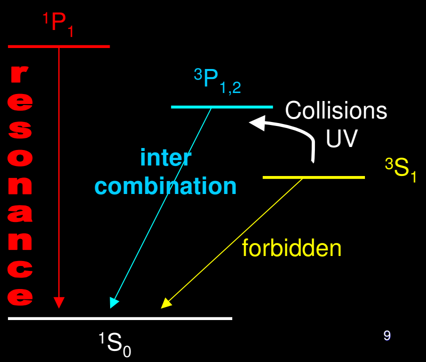
(Porquet et al. 2001, Leutenegger et al. 2006)



Waldron ASPC 2002

Waldron & Cassinelli 2001





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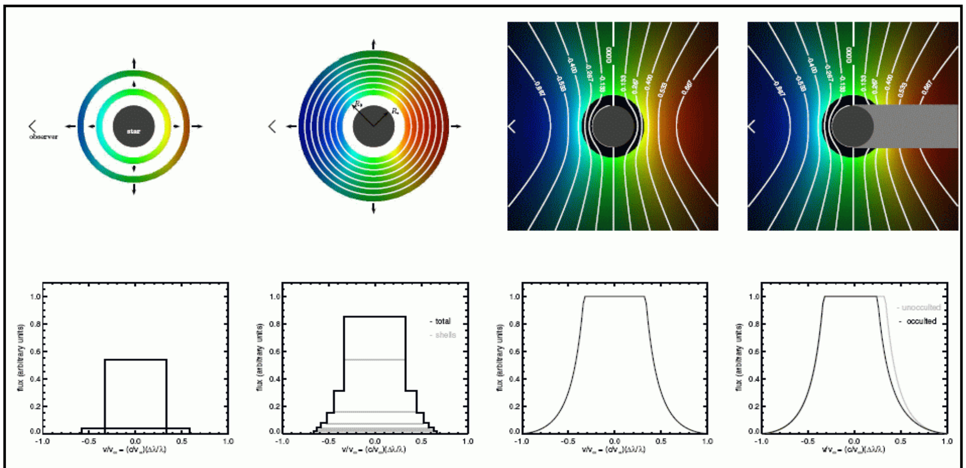
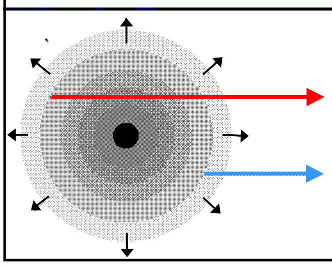
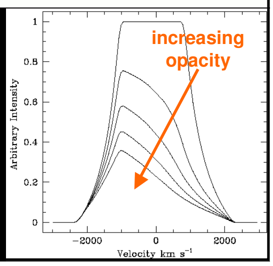




Expected X-ray line profiles :

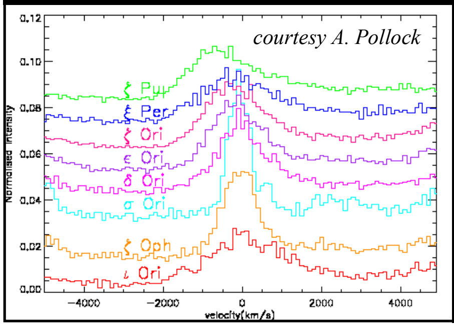
- broad +
- either symmetric & flat-topped or blueshifted & skewed

Cohen et al. 2002
& courtesy G. Rauw



3. Results from high-resolution spectroscopy

1. Only a small fraction of the wind emits
2. X-ray lines are broad, though not as broad as expected
3. Profiles are more symmetric, without evidence for flat-topped shapes
4. Blueshifts are small or non-existent (except ζ Pup)
5. Line profiles similar whatever the wavelength
6. R (fir) close to photosphere ($< 2R_*$) & ~ R(τ=1)
7. Opacity lower than expected & independent of λ



Waldron & Cassinelli 2001,2007; Kahn et al. 2001; Miller et al. 2002 ; Leutenegger et al. 2006 ; Cohen et al. 2006 ; Oskinova et al. 2006 ; ...

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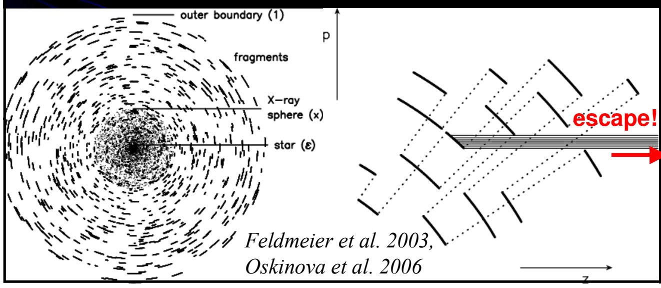
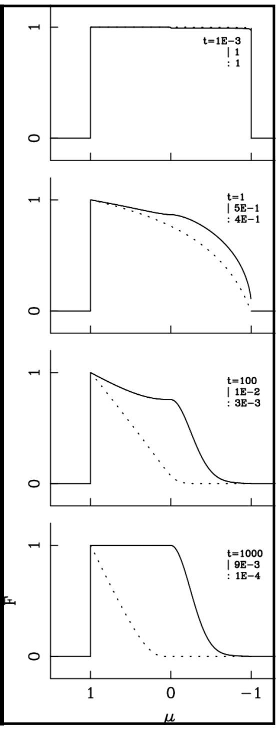
3. A change of mind…

Solutions ? Decrease opacity !

- A drastic decrease in mass-loss rates *(e.g. Cohen et al. 2006)*
  but HMXBs ?
- Porosity *(e.g. Feldmeier et al. 2003, Oskinova et al. 2006)*
  but not linked to line-driving instabilities ?





3. A change of mind…

Solutions ?

- A corona-like contribution in addition to wind-shocks *(e.g. Waldron & Cassinelli 2007)*
  - R(fir)~R(τ=1) only if mass-loss rate not too small
  - Lines from high-mass ions formed closer to photosphere, too close for wind-shock model

  but controversy about the observational bases ?

- A radical shift of thought *(e.g. Pollock 2007)*
  - Forget Coulomb interactions ⇒ Collisionless shocks
  - Plasma NOT at equilibrium
  - Ion-ion interactions : ionization, charge exchange

  but need to develop a full, quantitative model ?

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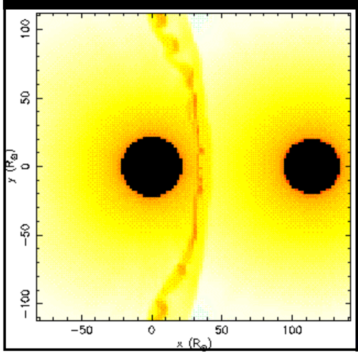
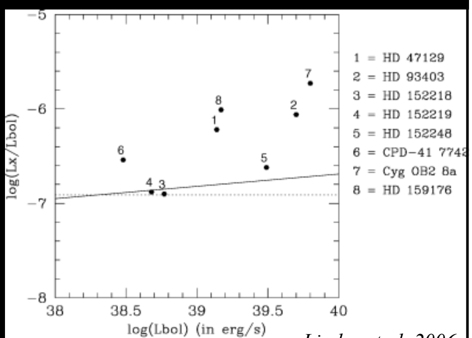
4. Peculiar objects

Interacting winds in binaries

- Strong stellar winds for O-type stars:
  $dM/dt \sim 10^{-6}\ M_{sol}/yr$ and $v \sim 2000$ km/s
- Gas heated to high temperatures :
  $kT=3mv^2/16$ ⇒ additional source of hard X-rays !





Linder et al. 2006

4. Peculiar objects

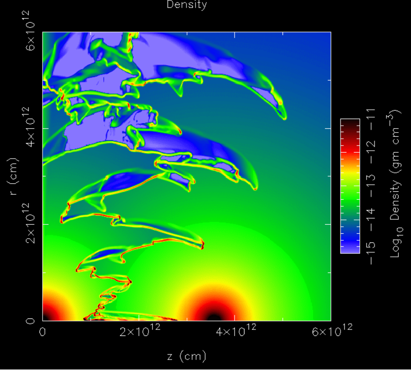
Interacting winds in binaries

- When does the gas cool ?

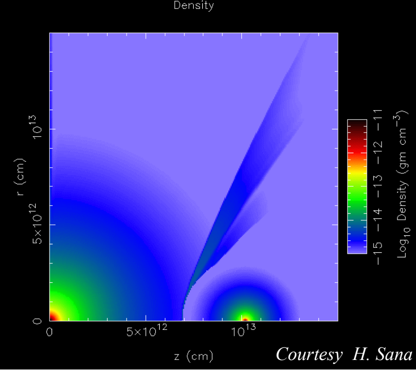
$$\chi = \frac{t_{\rm cool}}{t_{\rm esc}} \simeq \frac{v_8^4\, x_{12}^{\rm stag}}{\dot{M}_{-7}}$$

Stevens et al. (1992)

If cooling time < escape time : radiative case (short-P binaries)



If cooling time > escape time : adiabatic case (long-P binaries)



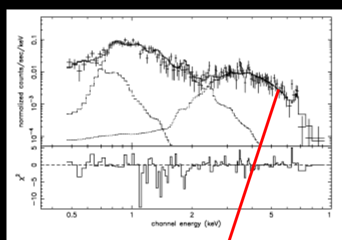
Courtesy H. Sana

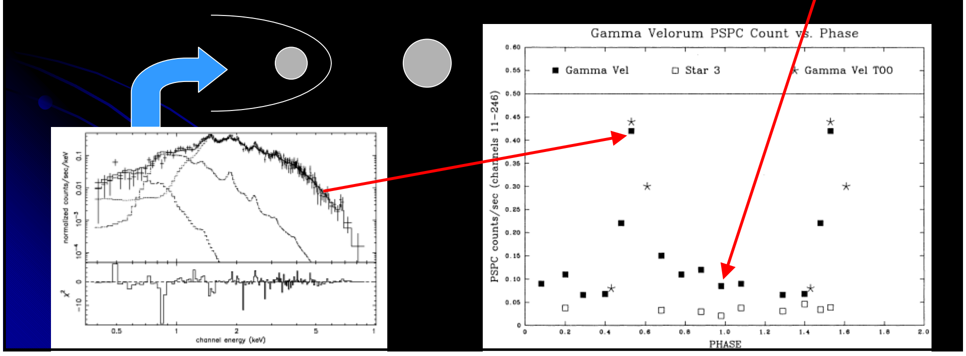
4. Peculiar objects

Interacting winds in binaries

Phase-locked variations

- Absorption effects
  (winds not identical, e.g. with WRs :
  γ^2 Vel *Willis et al. 1995, Rauw et al. 2000* ; WR22 *Gosset et al. 2008* ; HD5980? *Nazé et al. 2007*)





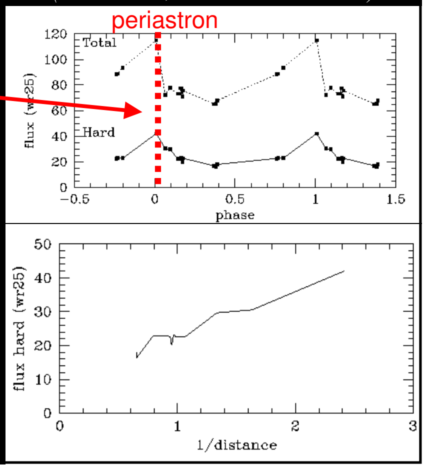
4. Peculiar objects

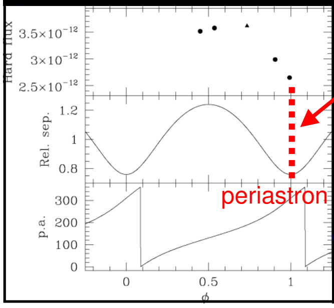
Interacting winds in binaries

Phase-locked variations

- Changing separation effects (for eccentric binaries)
  - If adiabatic : $L_x \propto (dM/dt)^2\ v^{-3/2}\ D^{-1} \propto 1/D$ (winds have reached their terminal velocity : **MAX** @ periastron)
  - If radiative : $L_x \propto (dM/dt)\ \ v^2 \propto D$ (winds still in the acceleration zone, **MIN** @ periastron)

The long-period WR25
(Gosset 2007, see also Pollock's talk)





Cyg OB2 #8A
(De Becker et al. 2006, see also Rauw's poster)

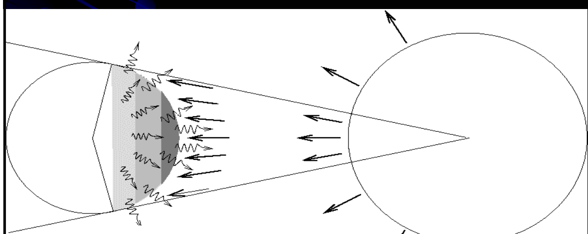
4. Peculiar objects

Interacting winds in binaries

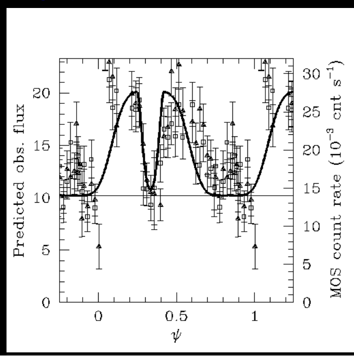
Phase-locked variations

- Crash on photosphere :
  broad occultation when the secondary is in front
  + narrow eclipse when the primary is in front

(Sana et al. 2005)



CPD-41°7742 : O+B

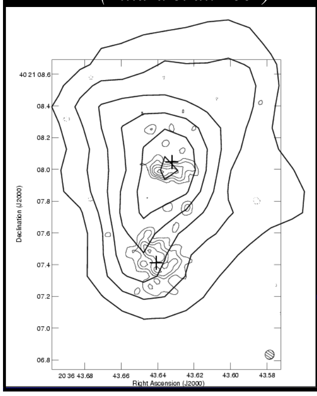


4. Peculiar objects

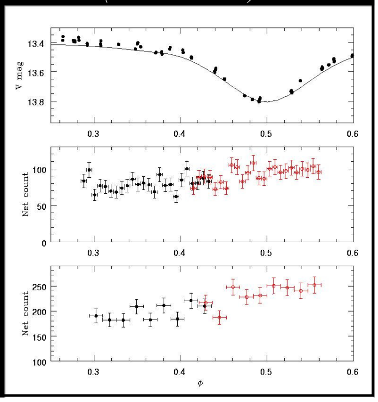
Interacting winds in binaries

- X-ray emission from the interaction region
  ⇒ should be spatially extended !

X-ray & radio contours of WR147 *(Pittard et al. 2002)*



Visible and X-ray lightcurves of WR20a *(Nazé et al. 2008)*



4. Peculiar objects

Wolf-Rayet stars

- Evolved descendants of O-type stars with very dense winds
- First surveys: no obvious L_x - L_{bol} relation, detection of WR binaries mainly
  (Pollock et al. 1995 : 20 detections associated with WRs
  – 10 binaries, 4 cand. bin. & 6 single ; 5/3/4 for WN and 5/1/1 for WC)
- New investigations with increased sensibility :
  - WC : no detection of single WR so far ⇒ $\log(L_x/L_{bol}) < -7.5..-9$
    (Oskinova et al. 2003, Skinner et al. 2006)
    ⇒ due to high absorption of these highly enriched winds?
  - WN : conflicting situation !
    WR6, WR46, WR110, WR20b : high kT, hard, variab. ⇒ binaries ?
    (Skinner et al. 2002, Gosset et al. 2008, Nazé et al. 2008)
    WR1 : no emission above 4keV *(Ignace et al. 2003)* ⇒ single ?
    WR40 : undetected *(Gosset et al. 2005)*
    ⇒ can be explained by hidden binaries or porous winds ?

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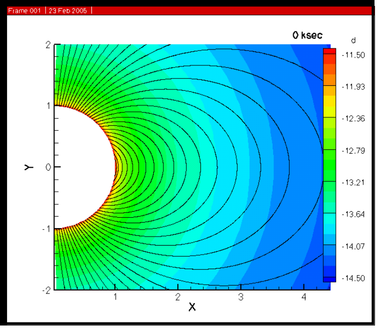
4. Peculiar objects

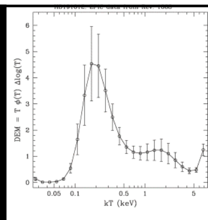
Magnetic objects

- Polarimetric measurements are now unveiling magnetic fields in some hot stars
- If the field is strong enough ($\eta = B^2R^2/[v\ dM/dt] > 1$), it can channel the stellar wind towards the equator
  - collision at high speed
    $\Rightarrow$ high kT, hard X-ray emission
  - close to the surface
    $\Rightarrow$ narrow, unshifted X-ray lines
  - modulation expected if the rotation and magnetic axes differ

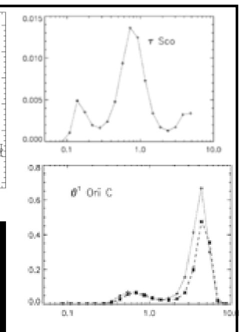


Gagné et al. (2005)

4. Peculiar objects



Nazé et al. (2007)



Zhekov & Palla (2007)

Magnetic objects

Observations : mitigated results

- θ^1Ori C and τ Sco
  (Gagné et al. 2005, Mewe et al. 2003, Cohen et al. 2003)
  - narrow lines (σ~350km/s), line shifts ~ 0 km/s, hard emission, $\log(L_x/L_{bol})$ ~ -6..-6.5
  - for θ^1Ori C : X-ray and optical emissions simultaneously MAX
- Of?p stars *(Nazé et al. 2004, 2007, 2008)*
  - broad unshifted lines, soft emission BUT $\log(L_x/L_{bol})$ ~ -6, kT_2 ~ 1keV
  - for HD191612 : X-ray and optical emissions simultaneously MAX (?)
- Others *(Rauw et al. 2002, Stelzer et al. 2005, Cassinelli et al. 1994, Nazé et al. 2008)*
  - 9 Sgr : broad blueshifted lines, X-ray formation region far in the wind
  - COUP : ν Ori (B0.5V) has $\log(L_x/L_{bol})$ ~ -6.7 while Par 1772 (B2V) has -7.9
  - ξ^1CMA : strong X-ray source, soft emission ;
    θ Car, β Cru : narrow, unshifted lines but very soft emission & B uncertain !

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5. Conclusions

What have we learned on hot stars from the current generation of X-ray telescopes ?

- High sensitivity and/or high-resolution spectroscopy offer the possibility to confront observations & models in detail (for both “normal” or peculiar objects)
- X-ray emission is not as we thought !

$\Rightarrow$ need to revise models

What to do next ?

- Study line-profile variations !
- Go to other metallicities !

$\Rightarrow$ need of a high spectral & spatial resolution, high-sensitivity facility !