X-ray spectroscopy of early-type stars: the present and the future

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X-ray properties of early-type stars: the general picture before XMM-Newton and Chandra

- O-type stars are moderately bright X-ray sources with $L_X/L_{bol} \approx 10^{-7}$
- The X-ray spectra of single O stars are rather soft ($kT \approx 0.5$ keV) and display emission lines, suggesting a thermal plasma.
- WR stars do not follow a clear L_X/L_{bol} relation
- Single early-type stars usually display little variability of their X-ray flux.
- Binary systems usually display a variable excess emission compared to the above relation $\Rightarrow$ signature of wind-wind interactions.

X-ray properties of early-type stars: what are the key issues and what are the strengths of XMM-Newton to solve these questions

Stellar winds $\dot{M} \simeq 10^{-6} - 10^{-4} M_{\odot} yr^{-1}$ play key role in stellar/galactic evolution.

- BUT what are the exact values of the mass-loss rates and abundances, what are the geometry and structure of these winds?

The X-ray emission itself:

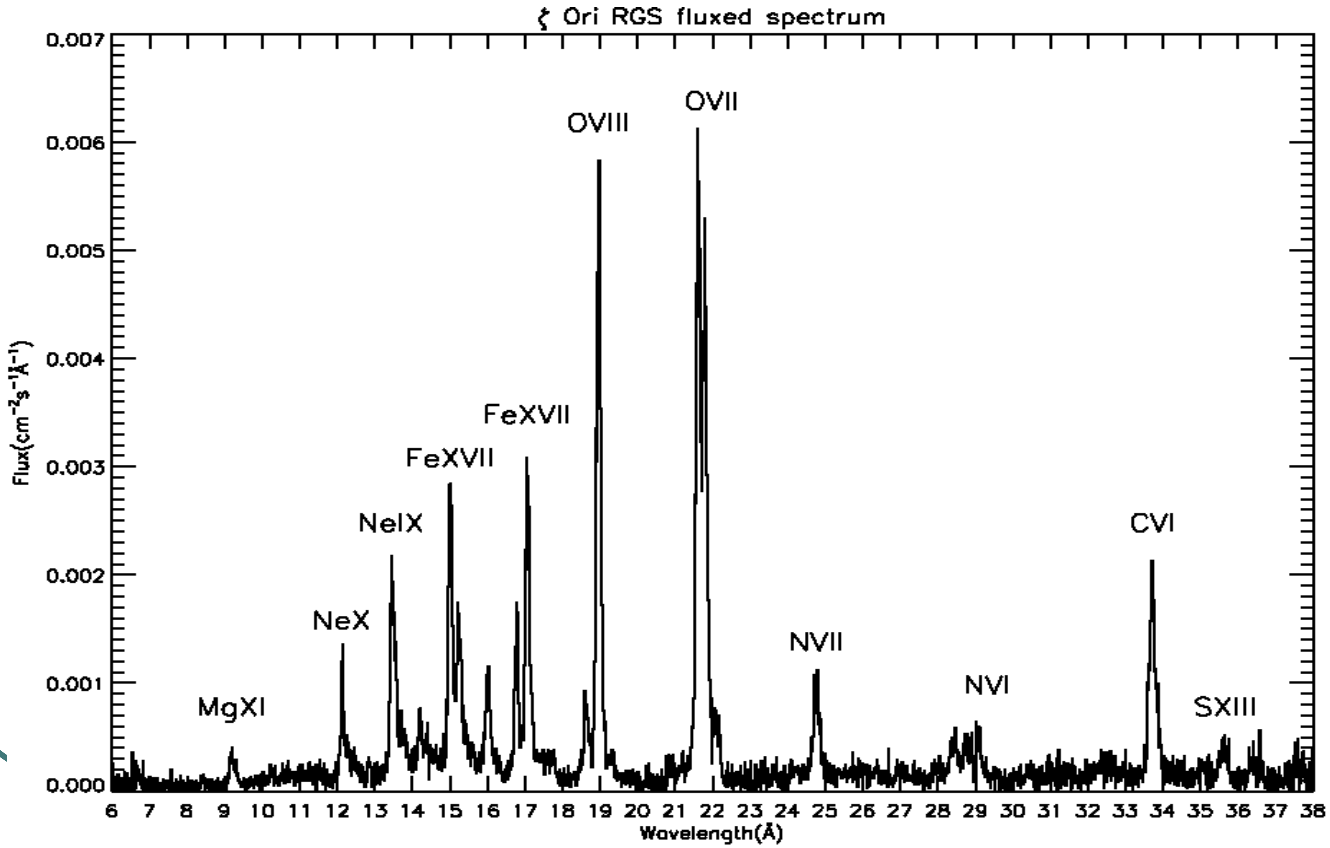
- What is the mechanism at the origin of the X-ray emission of single O-type stars?

Contributions of XMM-Newton in this domain:

- High-resolution spectroscopy.
- High sensitivity & wide field of view of the EPIC instruments.
- Capability to monitor sources.

High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

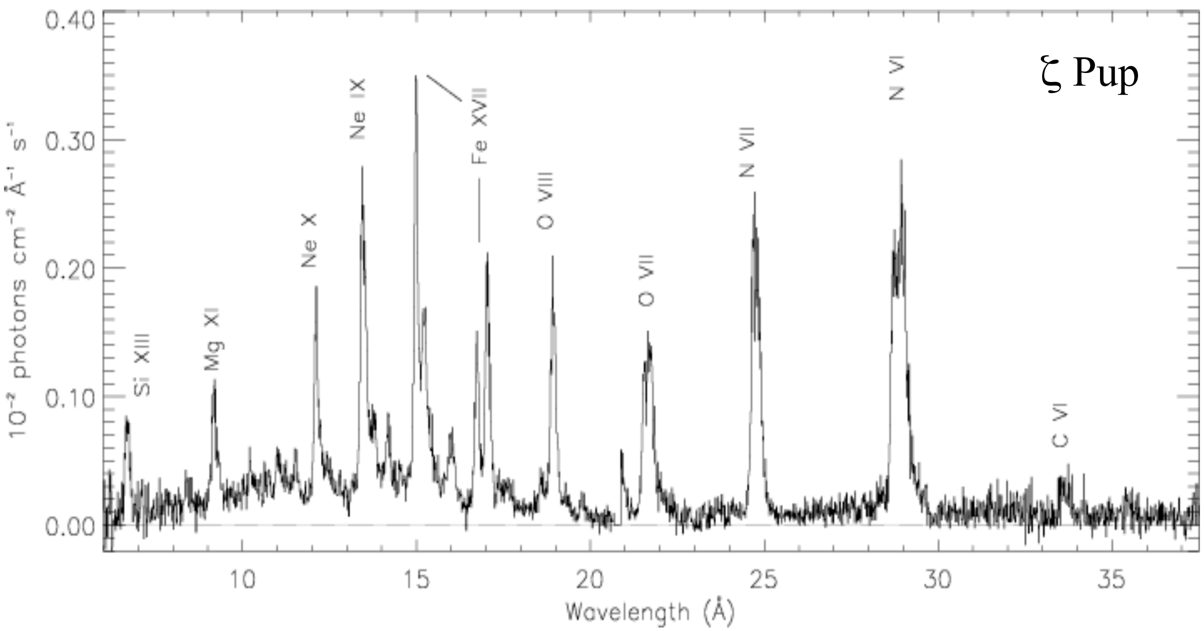
- New feature of XMM-Newton and Chandra: **high spectral resolution and great sensitivity** ⇒ first high resolution spectra of early-type stars.

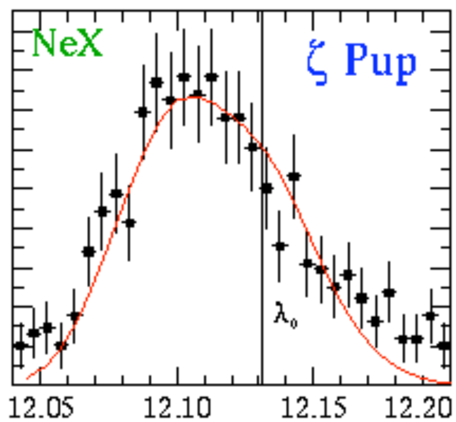


e.g. ζ Ori, Pollock 2007, (A&A 463, 1111)

High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

- Many broad emission lines (FWHM of the order 1000 – 2500 km/s).
- Diagnostics from these lines: line profile fitting

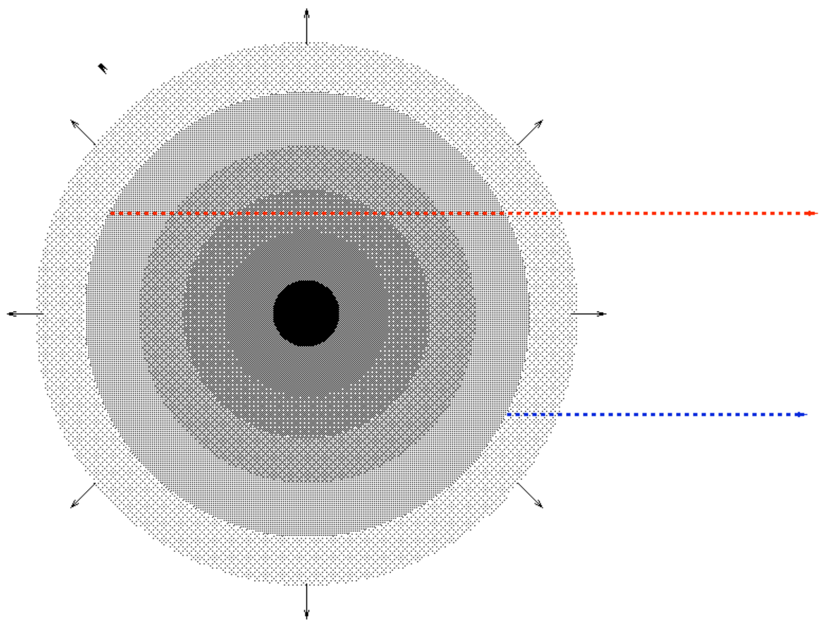


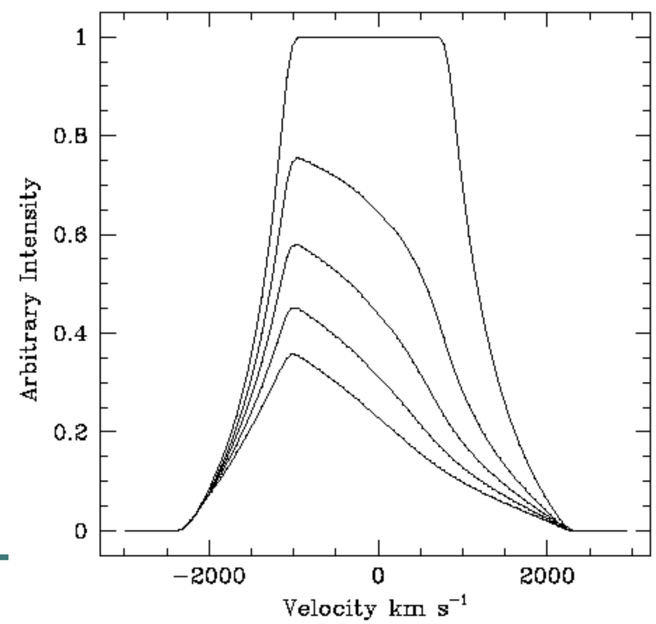


e.g. Oskinova et al. 2006, (MNRAS 372, 313)

High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

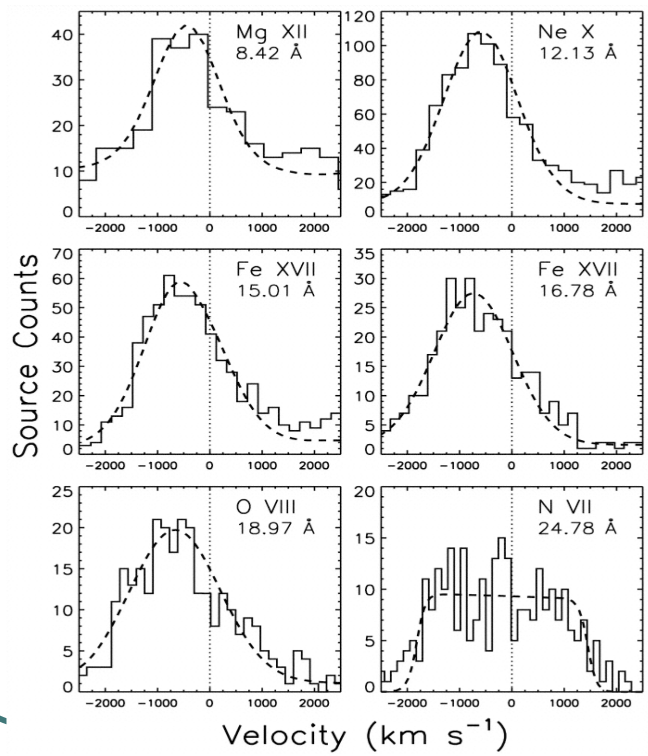
- Assuming the "standard model" of wind-embedded shocks, the line broadening is interpreted as due to the hot plasma following the motion of the wind.
- The line profile reflects the combination of the line formation radius, the wind motion and the absorption by the wind material.



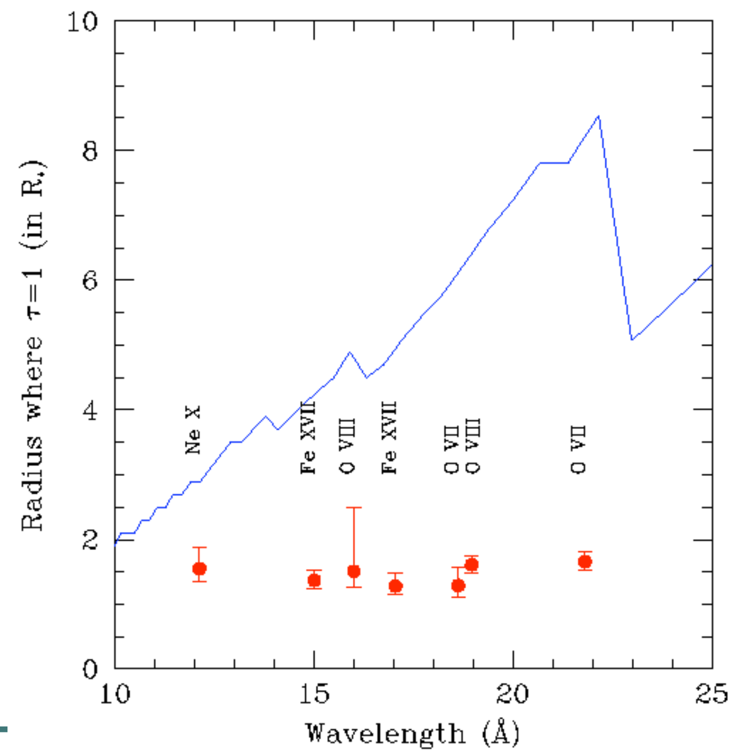


High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

- Surprising result for ζ Ori: wind optical depth significantly lower than expected from the known mass-loss rate and wavelength independent ⇒ clumpy (porous) wind



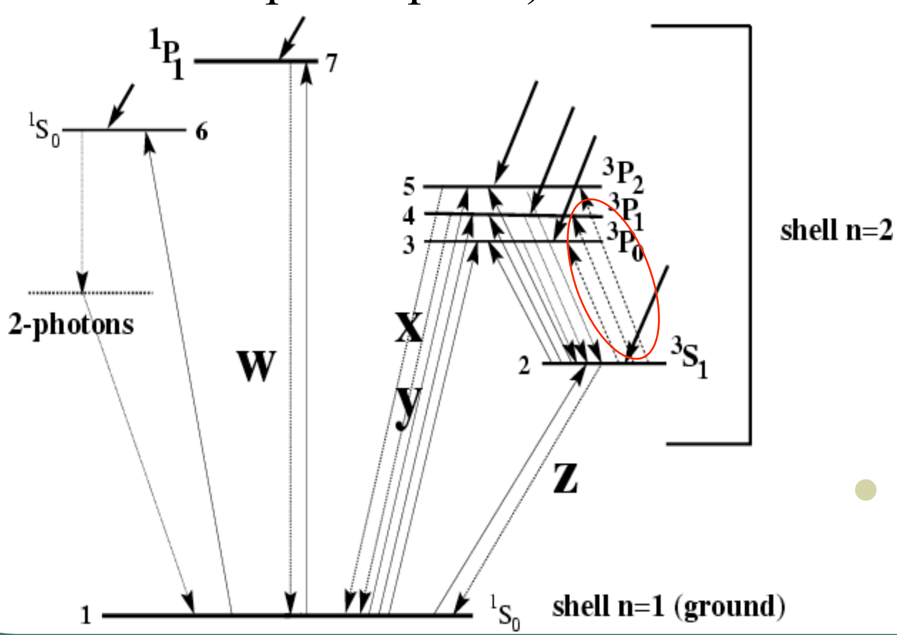
Cohen et al. 2006, (MNRAS 368, 1905)



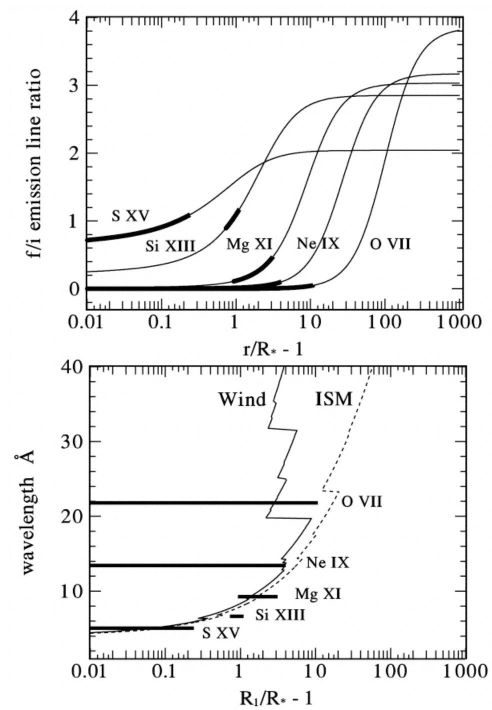
Rauw et al. 2006, (MSSL workshop proc.)

High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

- Diagnostics on line emission region from the *f i r* triplets of He-like ions: *f* /*i* ratio = sensitive diagnosis of dilution of UV radiation field (hence of the distance above the photosphere)



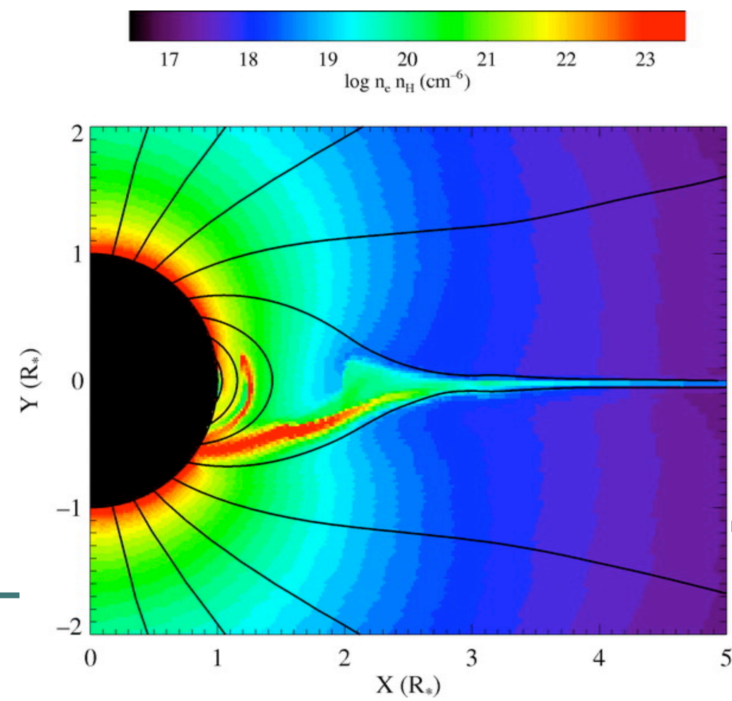
Porquet et al. 2001, (A&A 376, 1113)



- He-like triplets arise from regions between 1.25 and 1.7 R* (Leutenegger et al. 2006, ApJ 650, 1096)

High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

- The “standard model” assumes that the X-ray emission is produced by radiatively cooling hydrodynamic shocks embedded in the acceleration zone of the stellar wind and that develop from the instability of radiatively driven mass-loss.
- HiRes spectroscopy has triggered new questions about the origin of the X-ray emission:
  - A few O-type stars known to have a (rather) strong magnetic field, are likely to have their stellar wind confined into the equatorial plane of the magnetic field (e.g. θ^1 Ori C, Gagné et al. 2005, ApJ 628, 986, τ Sco, Mewe et al. 2003, A&A 398, 203). Their X-ray spectral lines are narrower and their emission is brighter and harder.



High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

- HiRes spectroscopy has triggered new questions about the origin of the X-ray emission:
- An alternative scenario has been proposed by Pollock (2007, A&A 463, 1111). In this paradigm, X-rays arise in the winds terminal velocity domain from collisionless shocks controlled by magnetic fields. The plasma should be out of equilibrium and lines would be produced through various mechanisms (collisional excitation, ionization and charge exchange) triggered by collisions with protons rather than with electrons.
  This scenario ***predicts that the lines of a given star should all have much the same shape and that the bremsstrahlung continuum should be weaker than expected from an electron excited plasma***.

High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

- To date, only about a dozen O-stars observed at high spectral resolution. BUT several targets have been observed with too short exposure times to obtain good quality HiRes spectra.
- Different stars tell different stories! ⇒ need for a larger sample + study the variability of line profiles on the relevant (dynamical) time scales of the stellar winds.
- Can we do this with XMM-Newton?
- ROSAT All Sky Survey (Berghöfer et al. 1996, A&AS 118, 481):
  - 5 O-type stars with more than 0.5 PSPC cts/s (XMM-Newton observed 3 of them, Chandra observed them all).
  - 6 O-type stars with a PSPC CR between 0.2 and 0.5 cts/s (all have been observed: 3 with XMM-Newton, 5 with Chandra).
  - 7 B0-0.5 stars with PSPC CR > 0.2 cts/s (4 observed with XMM and/or Chandra)
  - 4 B1-2 stars with a PSPC CR > 0.2 cts/s (all observed with either XMM or Chandra)

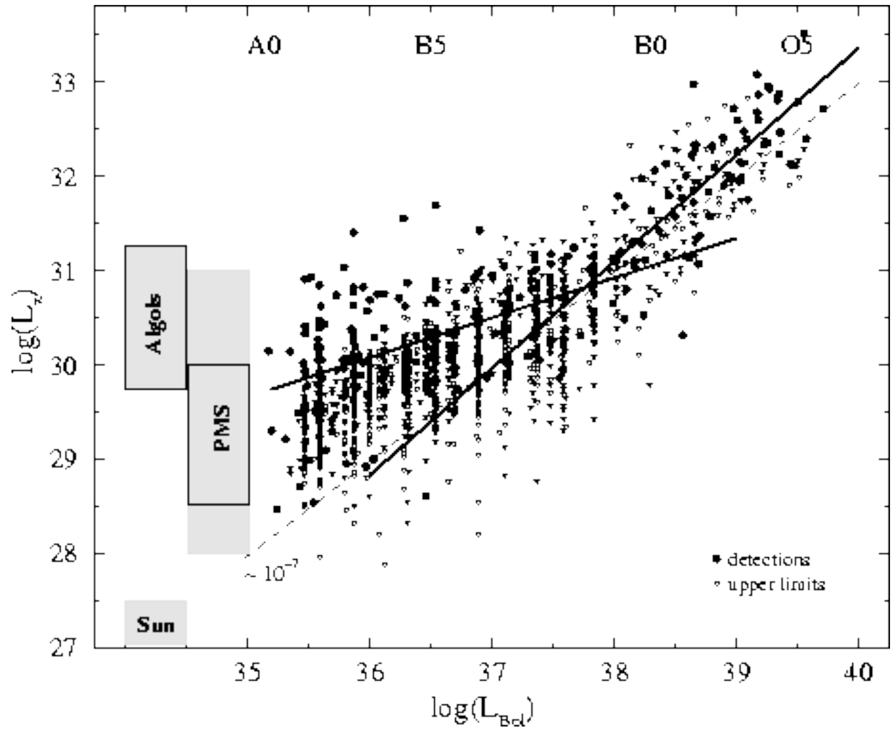
High-resolution X-ray spectroscopy of early-type stars: what we have learned from XMM-Newton and Chandra

- After (almost) 7 years of operation, XMM-Newton and Chandra have observed all the brightest O-type sources.
- A significant increase of the HiRes sample or variability studies will have to await for the next generation X-ray telescope (XEUS, Con-X). ☹
- In the meantime, we should obtain better quality spectra of those stars that are under-exposed and focus on some specific issues such as the transition between the O-star wind regime and B-star winds, the importance of magnetic fields in confining the stellar winds and test the Pollock (2007) scenario. ☺

In the near future, high-resolution X-ray spectroscopy of early-type stars should focus on obtaining high-quality spectra (~ 40 000 RGS counts) of all the sources that are within the grasp of XMM-Newton.

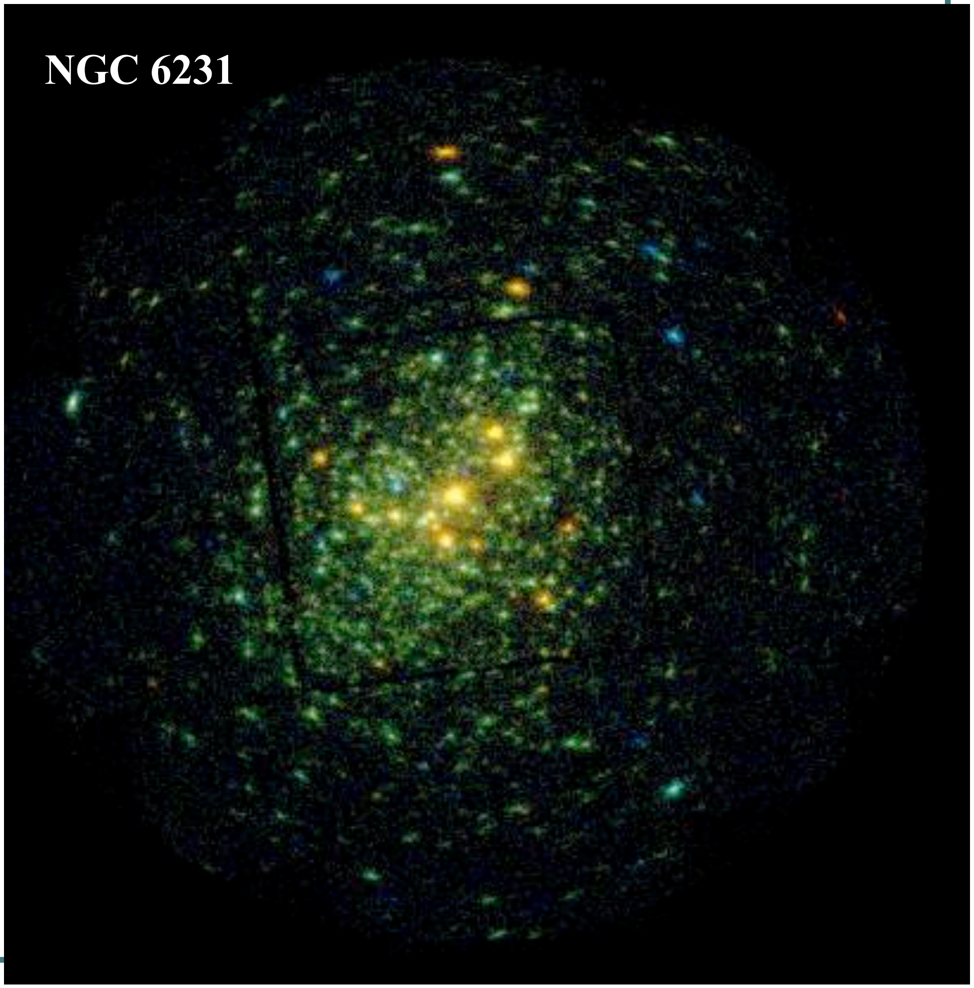
The overall X-ray properties of early-type stars as derived from large samples

- $L_X/L_{bol} \approx 10^{-7}$ scaling relation known for many years (EINSTEIN, ROSAT)
- Physical origin of this relation remains unknown (Owocki & Cohen 1999, ApJ 520, 833)
- ROSAT All Sky Survey relation (Berghöfer et al. 1997, A&A 322, 167) shows
  - large scatter
  - a break around spectral type B1-B1.5



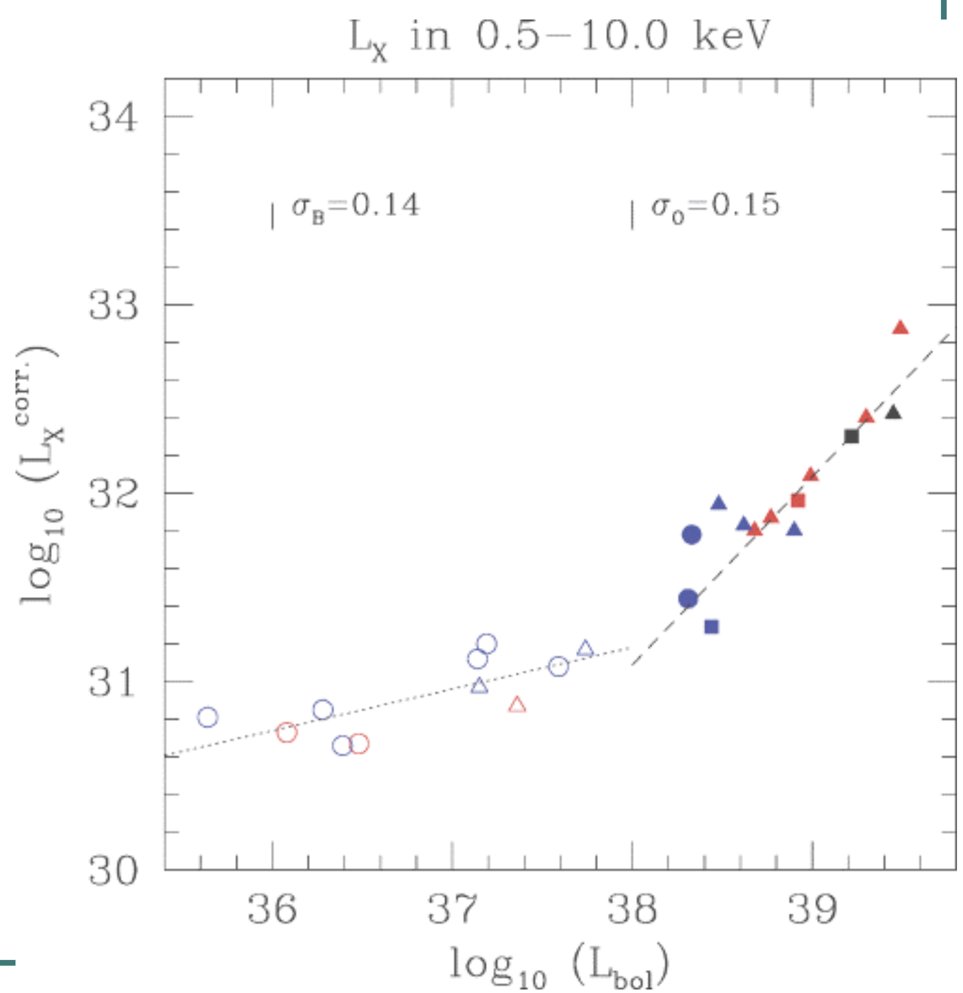
The overall X-ray properties of early-type stars as derived from large samples

- Thanks to its **wide field of view and large collecting area**, XMM-Newton is ideally suited to study the X-ray emission of very young open clusters containing a large number of O-type stars (e.g. NGC6231, Sana et al. 2006, A&A 454, 1047)
- This allows to establish a new L_X/L_{bol} relation for the OB-stars in NGC6231.



The overall X-ray properties of early-type stars as derived from large samples

- New L_X/L_{bol} relation for NGC6231 (Sana et al. 2006, MNRAS 372, 661):
  - O-star scaling relation $\log (L_X/L_{bol}) = -6.912 \pm 0.153$ in good agreement with previous results
  - BUT: dispersion (20 – 40%) much lower than for RASS relation
  - B-star scaling relation $\log (L_X) = (0.22 \pm 0.06) \log(L_{bol}) + 22.8 (\pm 2.8)$
  - Only 25% of the B0-4 stars detected.



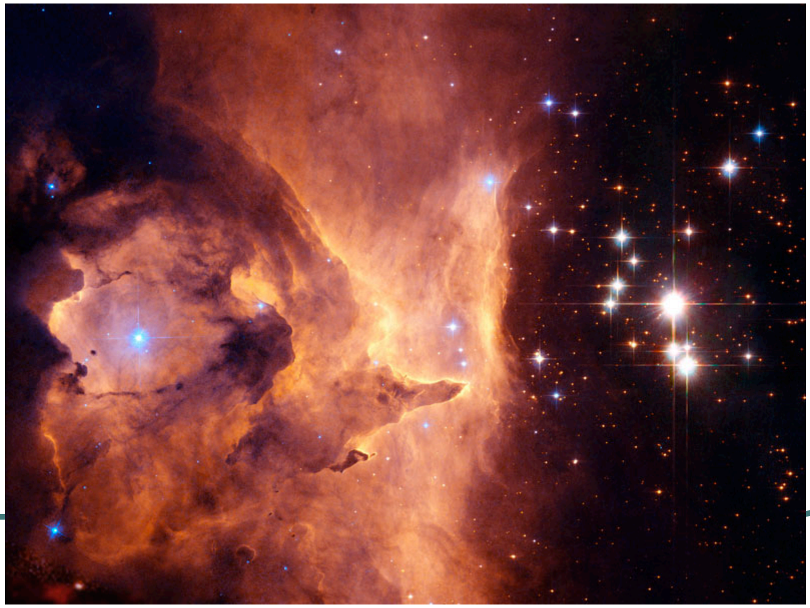
The overall X-ray properties of early-type stars as derived from large samples

- RASS relation:
  - Large sample of objects covering many spectral types.
  - Heterogeneous sample: mixture of stars from the field and inside clusters
  - L_X derived from count rate and hardness ratio conversion relations
  - Spectral types taken from Yale Bright Star Catalogue.
  - Distance and L_{bol} derived through comparison of M_V with “typical” values for each spectral type

- XMM-Newton NGC6231 relation:
  - Much smaller sample.
  - Homogeneous sample of stars at same distance, of same age and same metallicity.
  - L_X derived from a detailed fit of the EPIC spectra.
  - L_{bol} and multiplicity established through an intensive optical spectroscopic study.

The overall X-ray properties of early-type stars as derived from large samples

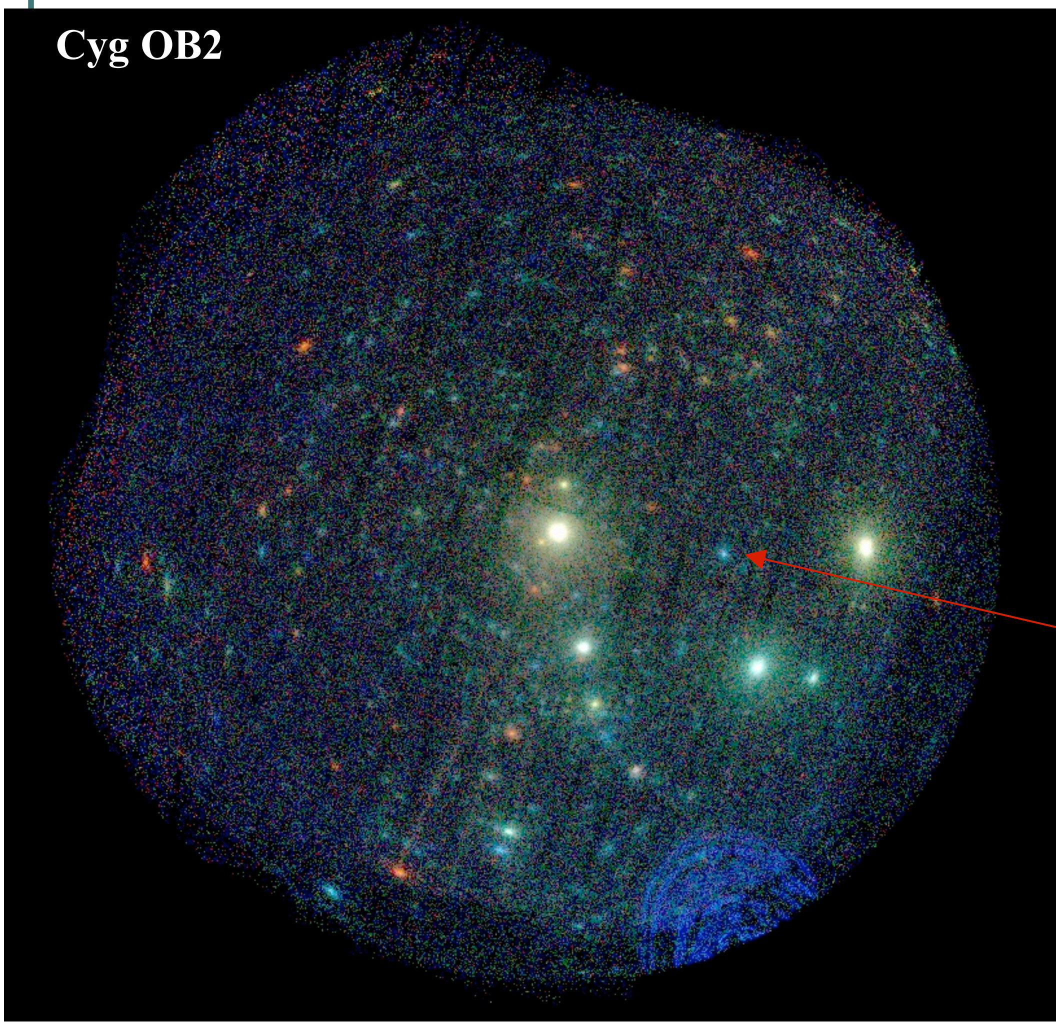
- So far 8 clusters containing at least 5 O-stars have been observed with XMM-Newton or Chandra, but not all of them are well suited for this purpose (spatial confusion, exposure times too short, lack of appropriate optical characterization of the cluster, not all spectral types represented…).
- In the WEBDA database, there are at least 8 more clusters that are rich in O-type stars and have not yet been observed with XMM-Newton or Chandra. Most of these clusters are closer than 3.0 kpc and have an angular diameter between 3' and 30'. Some of them contain stars over the full range of O spectral types from O2 to O9.



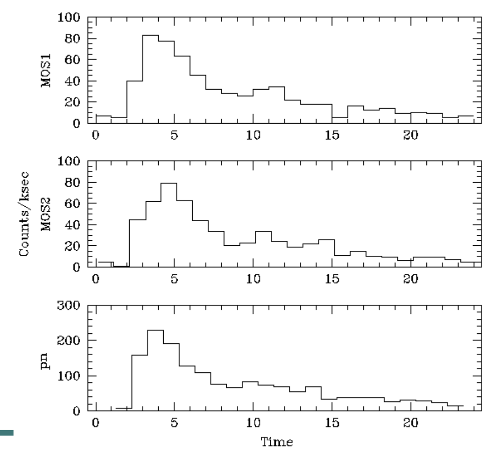
The overall X-ray properties of early-type stars as derived from large samples

- Observing spatially-resolved open clusters with the EPIC instruments onboard XMM allows to:
  - check the small scatter on the relation for the O-type population for a variety of clusters
  - investigate the impact of parameters such as cluster age, binary fraction and (to some extent) metallicity on the L_X/L_{bol} relation
  - set stringent constraints on the origin of this scaling law and hence on the theoretical models of X-ray emission from O-type stars. ☺
- A full investigation of metallicity effects (in the MCs) will have to await XEUS (angular resolution of 2’’ and sensitivity superior to XMM).
- Such studies require a large amount of optical spectroscopy and photometry support observations (establish accurate spectral types, multiplicity,…). This aspect must not be neglected!!

The feedback of early-type stars on star formation activity in open clusters (a by-product of EPIC observations of young open clusters)



- In addition to the study of the early-type star population, EPIC observations of open clusters allow to identify a wealth of secondary sources due to low-mass pre-main sequence stars (see also the other presentations in this section).



Rauw et al. 2005, JENAM proc.

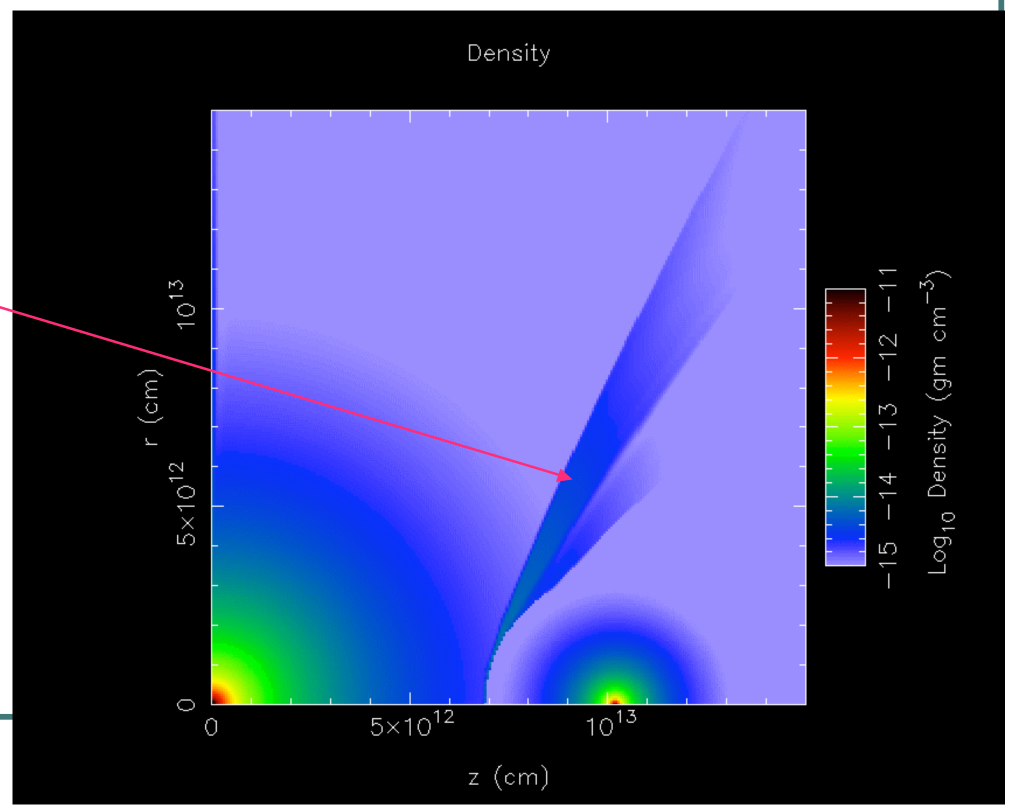
Probing the X-ray variability of early-type stars

- Colliding wind interactions in early-type binary systems. The dense, hot plasma in the wind interaction region produces observable signatures over wavelengths from the radio to the X-ray domain.

$$\rho_{s,j} = 4\,\rho_j,$$

$$v_{s,j} = v_j/4,$$

$$T_{s,j} = \frac{3\,\overline{m}_j\,v_j^2}{16\,k}$$



Stevens, Blondin & Pollock 1992, ApJ 386, 265

Probing the X-ray variability of early-type stars

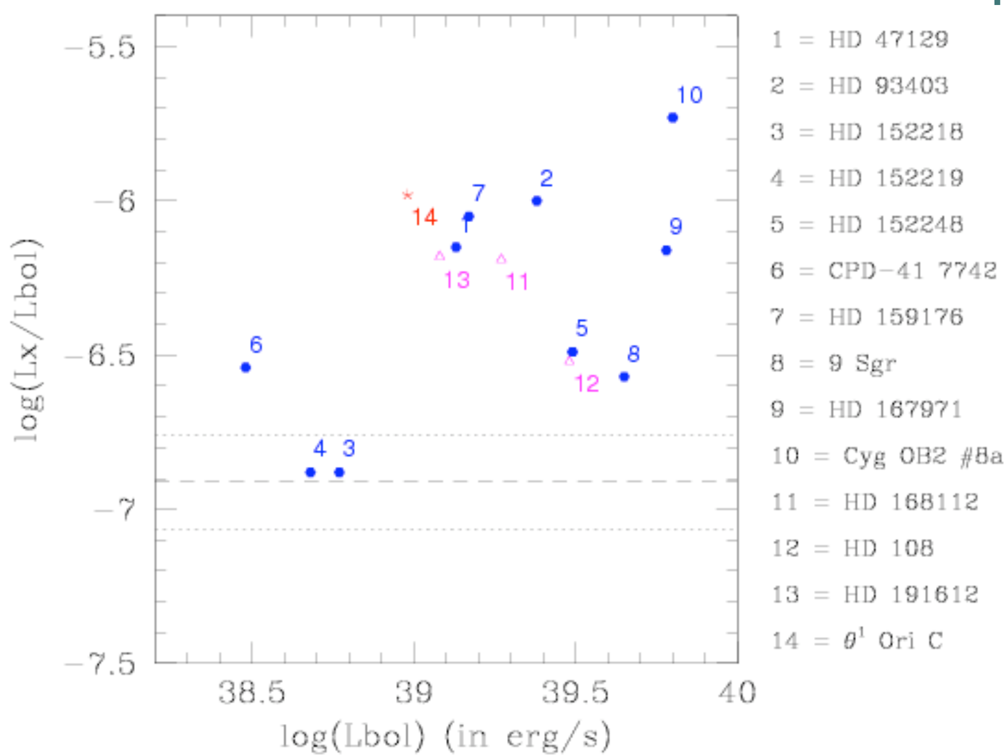
- The main X-ray features of colliding wind binaries are:
  - A higher X-ray luminosity than expected from the sum of the intrinsic contributions of the two stars.
  - A modulation of the X-ray flux due either to the changing amount of wind absorbing material along the line of sight or to a changing orbital separation.
  - A harder X-ray emission than the “usual” 0.5 keV plasma.
  - Key interacting wind systems: WR 140, η Carinae, γ Velorum, Cyg OB2 #8a, WR25…

Probing the X-ray variability of early-type stars

- A sample of Galactic O + O binaries have been monitored over a substantial part of their orbit providing phase-resolved (CCD) spectroscopy of these systems: unique set of data for comparison with theoretical models!

$$L_X \propto \frac{\dot{M}^2}{d\,v^{3.2}} \frac{(1+\mathcal{R})}{\mathcal{R}^4}$$

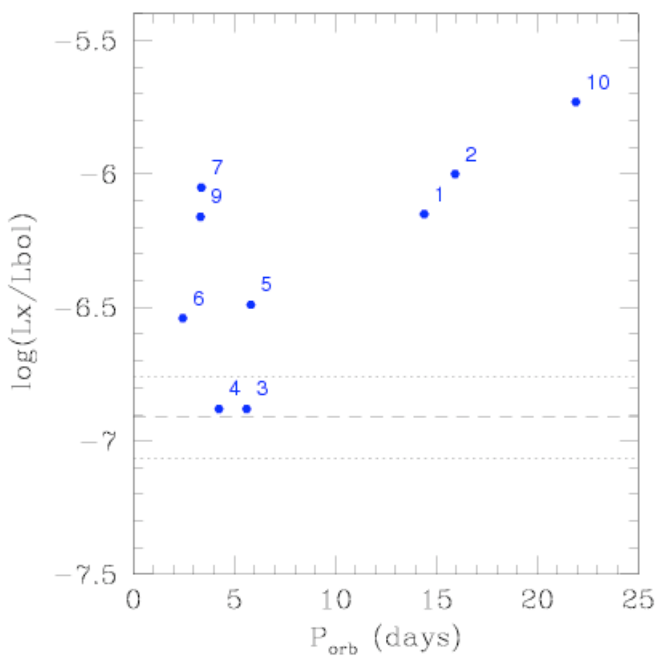
$$L_X \propto \dot{M} v^2$$



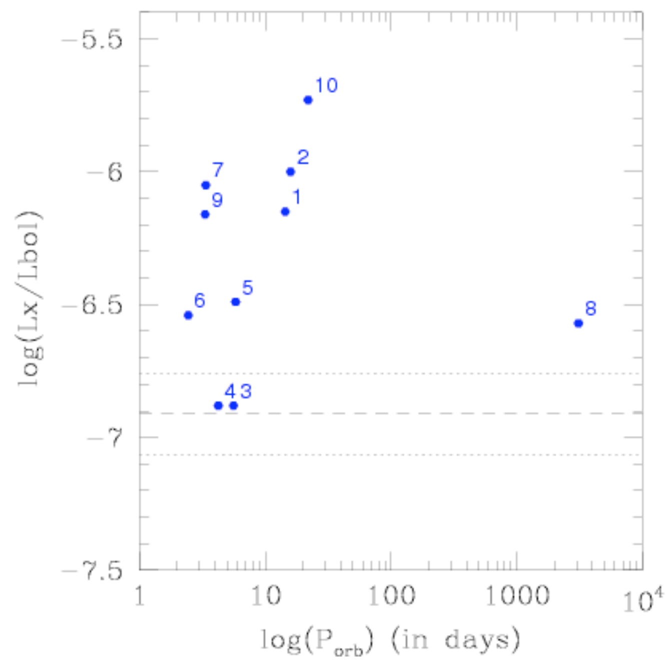
Linder et al. 2006, MNRAS 370, 1623

Probing the X-ray variability of early-type stars

- Comparison of the overall luminosities with theoretical trends allows already to gain insight into the physics of the wind interaction.



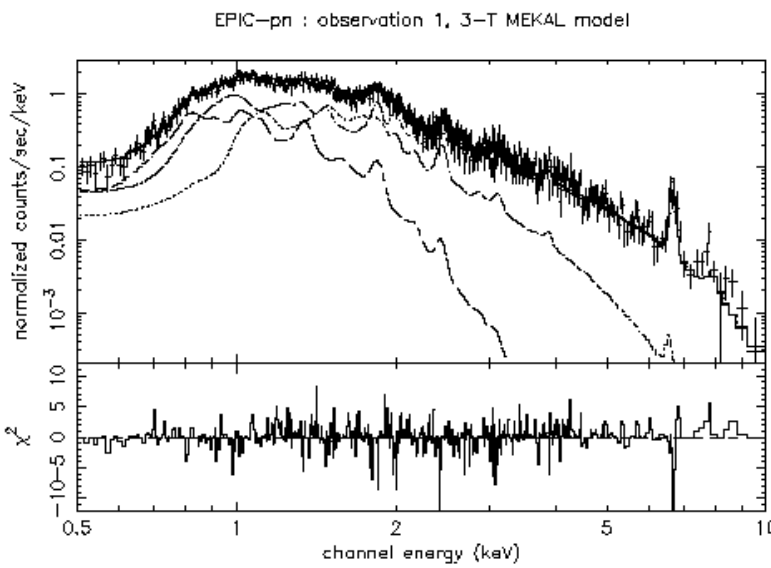
$$L_X \propto \dot{M}\, v^2$$

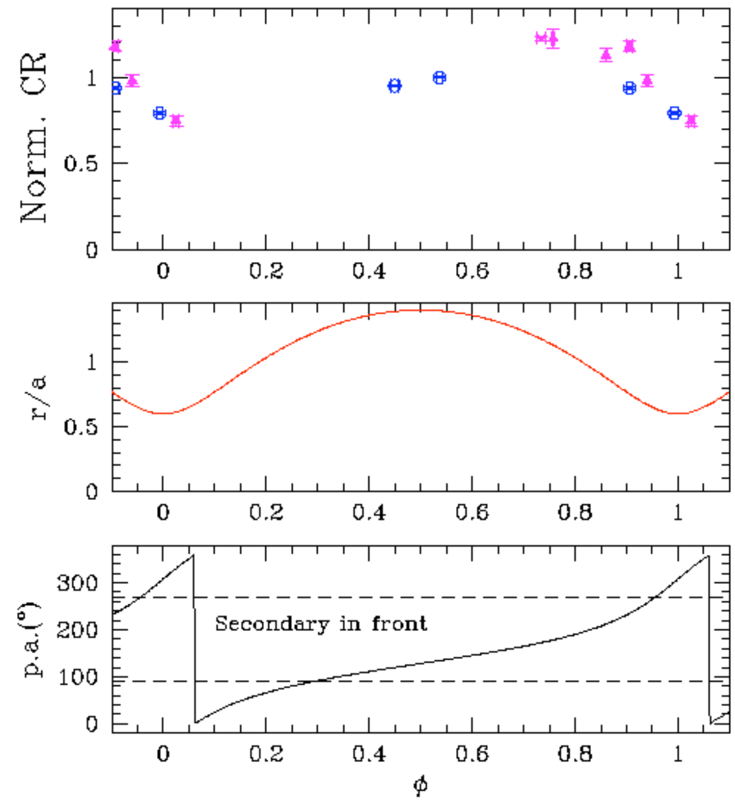


$$L_X \propto \frac{\dot{M}^2}{d\, v^{3.2}} \frac{(1+\mathcal{R})}{\mathcal{R}^4}$$

Probing the X-ray variability of early-type stars

- Example of the light curve of an interacting wind system: Cyg OB2 #8a (O6f + O5.5(f), P = 21.9 days, e=0.24, De Becker et al. 2006, MNRAS 371, 1280).

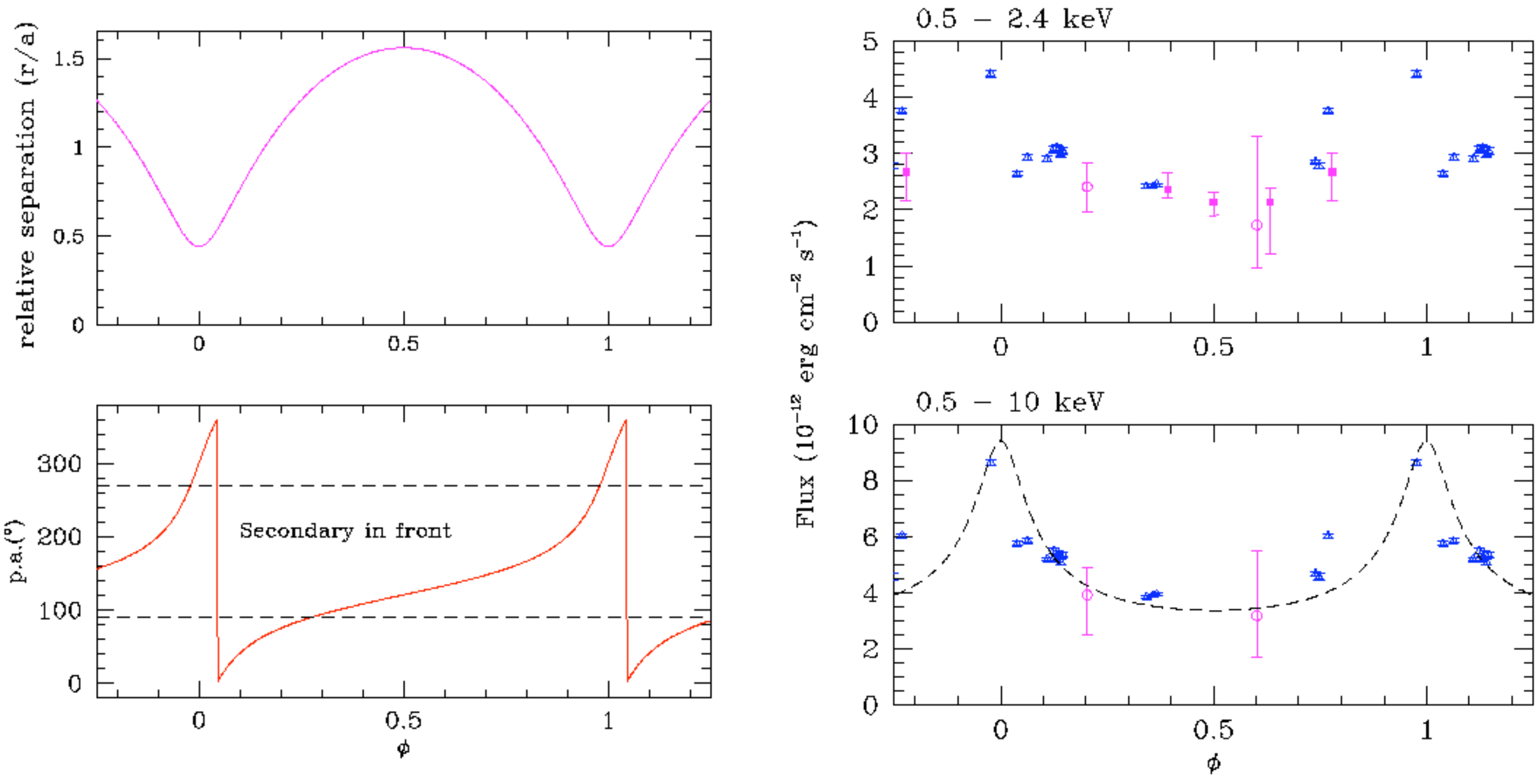




Hot X-ray plasma (1.7 keV) + modulation mainly due to changing optical depth along the line of sight.

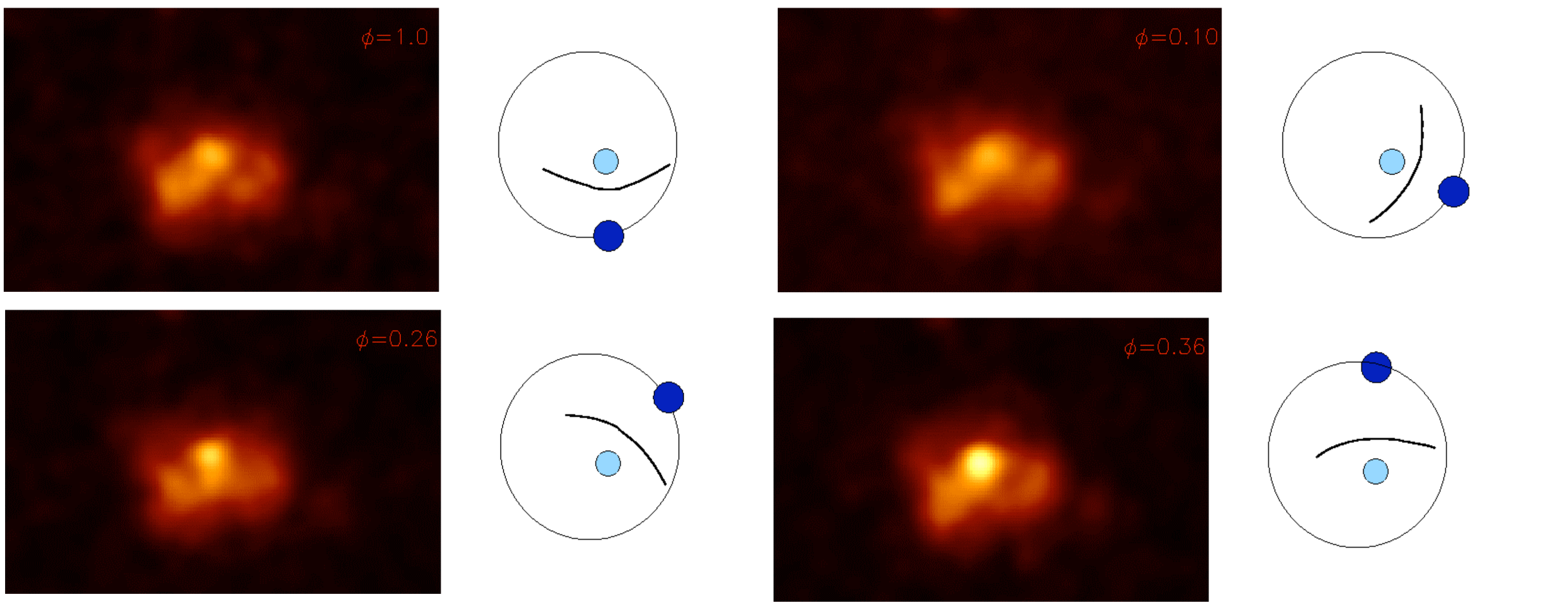
Probing the X-ray variability of early-type stars

- Light curve of the colliding wind system: WR25 (WN6ha + O, P = 208 days, e=0.56). X-ray variability by factor 2 (Pollock & Corcoran 2006, A&A 445, 1093).



Probing the X-ray variability of early-type stars

XMM can do this out to the distance of the Magellanic Clouds! A challenging case: the modulation of the X-ray flux of the eccentric colliding wind binary HD5980 in the SMC (Nazé et al. 2007, ApJ 658, L25)



Probing the X-ray variability of early-type stars

- Time variability studies of early-type stars have the potential to provide important scientific results! ☺
- XMM-Newton is clearly the leader in this field! ☺ ☺

Conclusions:

- The main strengths/capabilities of XMM-Newton in the field of early-type stars over the next decade concern:
  - Obtaining higher quality HiRes spectra (to C VI) of a limited sample of X-ray bright early-type stars.
  - Investigations of the overall X-ray properties of large samples of stars through observations of spatially resolved open clusters.
  - Investigations of the time variability of early-type stars and more specifically of early-type binaries.
- XMM-Newton clearly has the potential to make major contributions to this field!