Hot gas distribution in the wind of ζ Pup and ζ Ori

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Abstract : We have developped a new X-ray modelling code based on embedded shocks which computes synthetic spectra as a function of plasma temperature, abundances and localization of the X-ray emitting shell in the wind. We have also included a proper treatment of the radial dependence of the X-ray opacity of the cool matter as well as a treatment for the Forbiden Inter combination Resonance (*FIR*) lines of He-like ions. Our code combines several synthetic spectra in order to fit all the lines of an X-ray spectrum simultaneously and coherently.

Our results on two O-type stars ζ Pup and ζ Ori reveal non-porous winds with a mass loss rate consistent with studies in the optical domain as well as non-solar abundances for the CNO elements as expected for evolved stars. More important, the X-ray plasma starts emitting close to the stellar surface. An improved version of our code allowing an analysis of the radial dependence of the hot gas filling factor reveals for ζ Ori a non continuity of the X-ray emission regions associated to high values of the hot gas filling factor.

Introduction :

XMM and ***Chandra*** have pioneered high-resolution X-ray spectroscopy, allowing among other things, the detailed analyses of massives star' winds.

We are developping **new modelling tools** to **determine** the **mass loss rate, abundances** as well as the **distribution** of the temperature of the **X-ray emitting plasma** in the wind and the associated hot gas filling factor.

We present the basics of our modelling tools and the results obtained with the first version of our code on the well observed star ζ Pup (Naze et al 2012,2013, Hervé et al 2013). The analysis with our improved code of the spectrum of the second most observed massive star, ζ Ori, reveals very interesting results about the location of the X-ray emission plasma (Hervé et al, in prep).

Modelling tools :

1/ synthethic spectra generator (Hervé et al, 2012, 2013):

- Wind embedded shock scenario.
- Emissivity from AtomdB as a function of plasma temperature and abundances.
- Mass absorption coefficients (κ) calculated with *CMFGEN* (Hillier & Miller, 1998).
- Wavelength and **radial dependence of *κ*** included in the code with an analytic solution of the modified Owocki & Cohen (2006) calculation of the wind optical depth in conventional (p,z) coordinates :

$$\tau(\lambda, r) = \int_{z_0}^{\infty} \kappa(r)\rho(r)\mathrm{d}z = \int_{z_0}^{\infty} \frac{\alpha\kappa(r)R_*}{r(r-R_*) + \alpha\kappa(r)hR_*r}\,\mathrm{d}z$$

Where κ(r) is described as a spline function and h is the porosity length

- **Modification** of the **FIR line emission** due to the stellar UV radiation field (Leutenegger et al, 2006).

2/observation fitting procedure :

- Bound Variables Least Square algorithm (**BVLS**) used to determine the hot gas filling factor of sub-shells :

$$S_i = \sum_{j=1}^{n} \sum_{r=R_{in}}^{R_{out}} f_{hotgas,j,r} M_{j,r,i} + \epsilon.$$

Where S_i is the observed flux at the wavelength i, $f_{hotgas,j,r}$ is the classical volume filling factor of the hot gas component j at the position r in the wind, $M_{j,r,i}$ is the synthetic flux of each X-ray emitting plasma component at the wavelength i at the position r in the wind, and ε is the error of regression.

Results :

Fig 1 : Our best model (in red) compared to the RGS spectrum of ζ Puppis (in black)

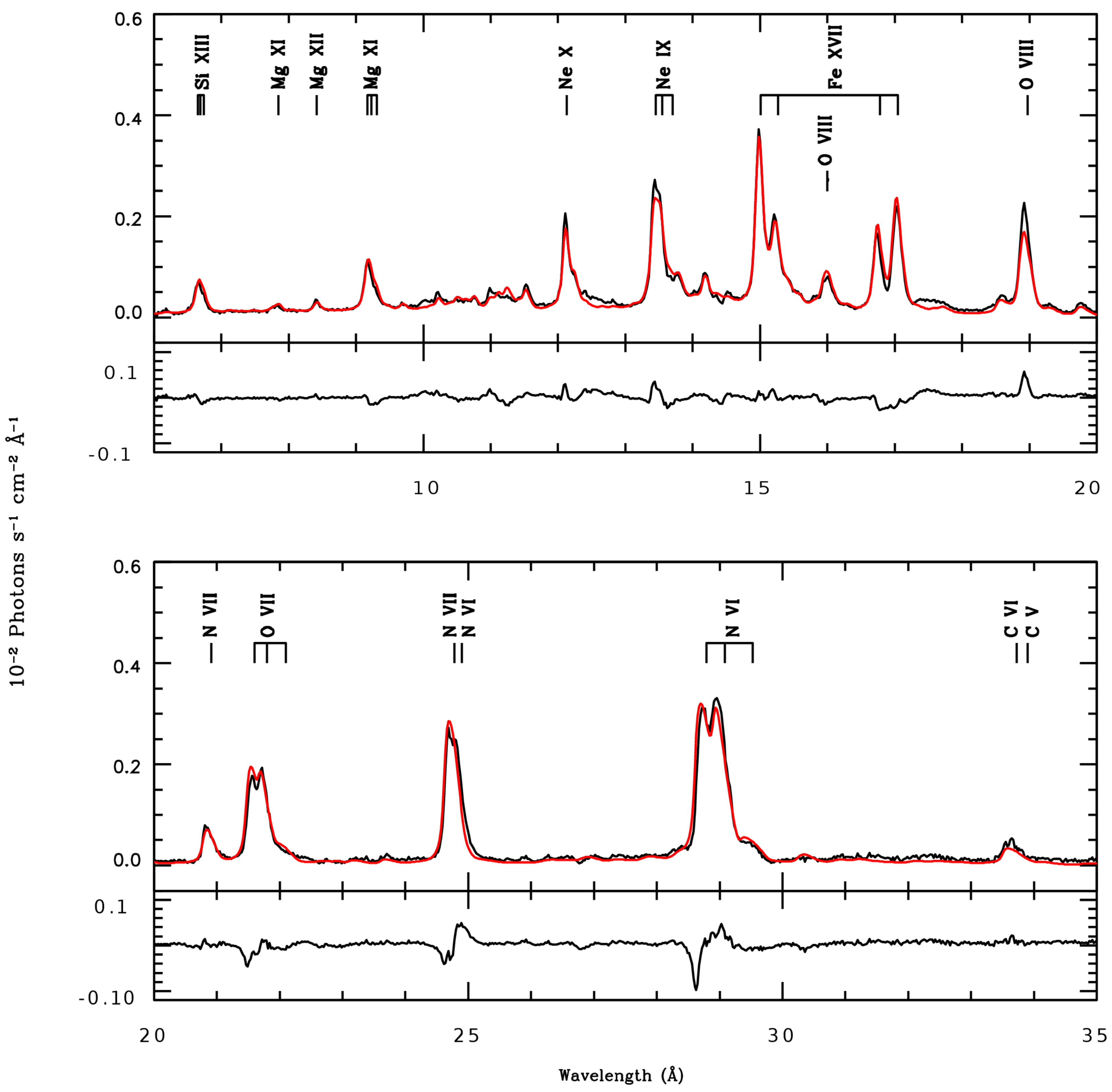
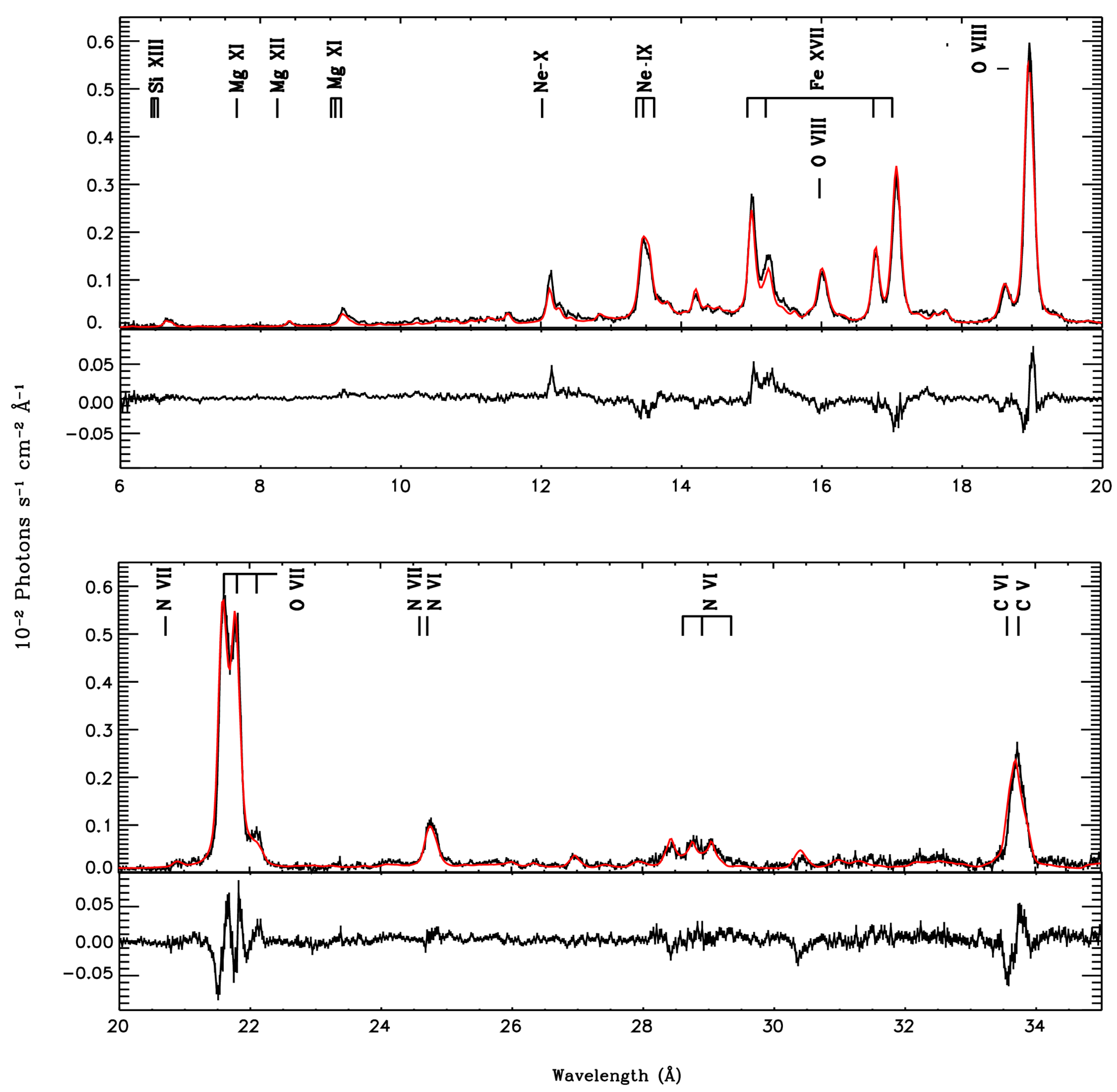


Fig 2 : Our best model (in red) compared to the RGS spectrum of ζ Ori (in black)



Tab 1 : Temperature distribution of the X-ray emitting plasma and gas filling factor in the wind of ζ Pup with the first version of the code

	model$_1$	h'=0.0	$\chi^2_\nu = 15.16$
kT keV	f_{hotgas}	R_{in} R_*	R_{out} R_*
0.10	0.012	7.5	85.
0.20	0.012	1.5	38.
0.40	0.020	2.7	4.0
0.69	0.007	3.1	4.1

Tab 2 : Stellar wind parameters of ζ Pup determined from the best fit model.

$\dot{M}$ $10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$	X(C)	X(N)	X(O)
3.5	6.00×10^{-4}	7.7×10^{-3}	3.05×10^{-3}

Tab 3 : Stellar wind parameters of ζ Ori determined from the best fit model.

$\dot{M}$ $10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$	X(C)	X(N)	X(O)	h
1.	2.45×10^{-4}	4.5×10^{-5}	3.4×10^{-4}	0.0

Our model yields the distribution of the X-ray emitting shells in the wind. However, there exists a degeneracy between the size of a plasma shell and its filling factor. We are currently investigating how this degeneracy can be lifted

Conclusions :

- Development of a ***new X-ray spectra modelling code.***
- ***First fitting*** of the full *RGS* spectra of massive stars, ζ Pup (Hervé et al 2013) and ζ Ori (Hervé et al, in prep).
- Agreement between our results (mass loss rate and abundances) and optical studies. Small differences due to atomic data uncertainties and modelling code approximations.
  - **No porosity** needed.
- Determination of the X-ray temperature plasma distribution.

1/ *ζ Pup* : - **Small shell** of very **hot plasma** (0,69 keV) at 3 R* included in shell (2,7R*-4.R*) of a slightly lower temperature (kT=0,4keV).
- **Extended shells** (> 35R*) of **low temperature** X-ray plasma (kT = 0,1keV and kT=0,2keV) one located far in the wind (7,5R* for kT=0,100 keV) the other close to the stellar surface (1,5R*).

BUT Too much flux in the blue part of emission lines at longer wavelengths → Models are too heavily absorbed in the inner part of the wind and/or for the X-ray photons produced on the rear side of the star. → Modification of our code for the study of ζ Ori.

2/ *ζ Ori* : - First shocks/**X-ray emission very close to the star surface** (1,3 R*) associated to low X-ray temperature plasma.
- temperature plasma between 0,08 kev and 0,69 keV
'- degeneracy between the size of a plasma shell and its filling factor
- research of physical constraints to break the degeneracy on the size of shells and the associated hot gas filling factor in progress.

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