X-ray spectroscopy with *XMM* :
A new powerful tool to determine fundamental parameters of early-type stars

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ABSTRACT

We briefly review the current knowledge on X-ray emission from hot massive stars based on previous X-ray missions and we highlight the potential of the instrumentation on board *XMM* to achieve considerable progress in this field. To this aim, we consider the WN7+abs star WR 25 that exhibits one of the largest X-ray emission excesses known among (apparently) single Wolf-Rayet stars. High resolution *XMM*-RGS spectra of this star will enable us to constrain the abundances of several chemical elements that play a key role in massive star evolution but for which no accurate abundance determinations are available from longer wavelength observations.

1. X-ray emission from early-type stars

Early-type stars of spectral-type O and Wolf-Rayet play a crucial role in the evolution of most of the galaxies and their study has impact beyond stellar physics (e.g. Maeder & Meynet 1995 and references therein). Their tremendous influence on the ecology of the galaxies and on the star formation processes results from their various and powerful interactions with their surroundings. In fact, these hot massive stars are the main sources of UV and ionizing radiation in the interstellar medium. Moreover, they also provide a considerable input of mechanical energy through their huge stellar winds that associate large terminal velocities, ranging from 1000 to 3000 $\mathrm{km\,s^{-1}}$, with high mass-loss rates of the order of 10^{-6} to $10^{-4}\,\mathrm{M_\odot\,yr^{-1}}$. Wolf-Rayet (WR) stars are believed to represent a late stage of the evolution of massive O stars. The winds of WR stars

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display a composition resulting from nuclear burning of hydrogen (WN subclass) and helium (WC subclass) and contribute therefore to the chemical enrichment of the interstellar medium.

Since the discovery of X-ray emission from early-type stars with the *EINSTEIN* satellite (Harnden et al. 1979, Seward et al. 1979), substantial progress has been achieved in our understanding of this phenomenon. Nowadays, it is established that the observed X-ray luminosity of single O stars roughly scales with their bolometric luminosity: $L_X/L_{bol} \approx 10^{-7}$ (Berghöfer et al. 1997). The latter relation holds also for WR stars, although with a larger dispersion (Schmutz 1991, van der Hucht 1992). The X-ray spectra of massive stars are consistent with a thermal origin and are relatively soft with little evidence for absorption suggesting that the X-ray emission is produced in shocked material distributed throughout the stellar wind.
Feldmeier et al. (1997) recently suggested that the X-ray emission of single O stars is most likely produced by mutual collisions of dense shells of gas that is compressed in shocks resulting from radiatively-induced instabilities. A crucial test for this hypothesis is the search for correlations between the X-ray variability in single stars and the changes in the state of their wind. Until now, very few X-ray observations of single early-type stars have either the statistical significance or the time-span necessary to allow for variability studies (e.g. Berghöfer et al. 1996, Gagné et al. 1997). With its high sensitivity, *XMM* will fill in this gap. In fact, *XMM* will enable us to monitor X-ray variability on different timescales with the required photon counting statistics. These observations will be of crucial importance for our understanding of the driving mechanism(s) of the stellar winds.

O + O and WR + O binary systems display systematically larger L_X/L_{bol} ratios than single stars (Chlebowski 1989, Pollock 1987). This excess X-ray emission is usually attributed to a colliding winds interaction (Williams et al. 1990, Chlebowski & Garmany 1991) and some of these binaries exhibit a phase-locked X-ray modulation (Willis et al. 1995, Corcoran 1996). Indeed, in such systems in which both components are massive O or WR stars, the collision of their hypersonic winds results in two oppositely faced shocks separated by a contact discontinuity (Stevens et al. 1992). In the shock region, the plasma is heated to a few times 10^7 K presumably generating the observed X-ray excess. In this picture, the phase-locked X-ray modulation reflects the variation, during the orbital motion, of the circumstellar opacity along the observer's sightline through the winds (e.g. Williams et al. 1990). A quantitative comparison of the EPIC lightcurves and phase-resolved spectra of a sample of colliding winds binaries with theoretical predictions will allow to constrain the properties of the stellar winds and the mass-loss rates of the stars in various evolutionary stages (Pittard & Stevens 1997). Also, given the high sensitivity of *XMM*, we will for the first time be able to investigate the short timescale variability of the X-ray flux, resulting from hydrodynamical instabilities of the shock region.

2. The chemical compositions of Wolf-Rayet winds

According to modern stellar evolution theory, massive O stars evolve into WR stars through the effect of the stellar wind that peels off the outer layers of the star. In this scenario, the 'anomalous' chemical composition of WR atmospheres reflects the exposure at the stellar surface of CNO processed material (e.g. Schaller et al. 1992).
So far, only a few chemical abundances have been determined observationally (e.g. Crowther et al. 1995). Other abundances are still a matter of debate. For instance, *ISO*-SWS observations of the WN8 star WR 147 reported by Morris et al. (1996) yield a Ne/He ratio twice the solar value, whereas theoretical models predict this ratio to increase only after the star has entered the WC stage. High resolution spectroscopy with *XMM* will help to settle this debate.
Indeed, for the first time, *XMM* will give access to reliable abundance measurements on key elements which are difficult or impossible to constrain from longer wavelengths observations, such as Fe, O, Ne and Mg (RGS), and with the EPIC also Si and S. To illustrate this purpose, we have simulated a 50 ksec *XMM*-RGS exposure of WR 25.

3. Simulated *XMM*-RGS spectra of WR 25

The WN7+abs star WR 25 (HD 93162) in the Carina OB 1 association exhibits one of the largest X-ray luminosities known among (apparently) single WR stars ($L_X = 49.4\,10^{32}$ erg s^{-1} assuming d = 2.63 kpc, Wessolowski 1996). This X-ray excess is suggestive of a colliding winds binary with a very long period (Corcoran et al. 1995) even if ground based observations have failed so far to reveal a spectroscopic signature of a companion.
Using a 'standard' model-atmosphere to fit the UV, optical and IR spectrum of WR 25, Crowther et al. (1995) derived the following abundance ratios: H/He = 1.13, N/He = 0.0085 and C/He = 0.0006 (by mass). To demonstrate the potential of X-ray line spectroscopy for assessing abundances of some other relevant chemical elements, we have used the SPEX code (Kaastra et al. 1996) to simulate *XMM*-RGS spectra of WR 25 under different assumptions on the wind composition (see Table 1). The model parameters are derived from a two-temperature model of γ^2 Vel (WC8 + O9 III) near minimum (S. Skinner, private communication). The emission measures of WR 25 were scaled to match the observed *ROSAT*-PSPC count rate of 0.194 cts s^{-1} (Wessolowski 1996) assuming a distance of 2.63 kpc.

Figure 1 shows a comparison between the synthetic spectra corresponding to models 1 and 2. The main differences between the two fake spectra concern the O VIII line at 0.65 keV, the Ne X line at 1.02 keV and the N VII line at 0.50 keV.
To illustrate the potential of actual RGS data to perform abundance studies, the simulated spectrum corresponding to non-solar abundances was rebinned to achieve a S/N $\geq$ 3 in each bin and was then fitted keeping the column densities fixed. To start, the He and C abundances were fixed at their value determined from ground-based observations. The restored parameters (Table

Table 1: Parameters used in the model calculations of a synthetic spectrum of WR 25.

Model	T (keV)	N_H (10^{21} cm^{-2})	EM (cm^{-3})	Abundances
1	0.63	1.3	$8.3\,10^{55}$	solar*
	1.23	65.0	$5.19\,10^{57}$	
2	0.63	1.3	$7.7\,10^{55}$	non-solar**
	1.23	65.0	$4.82\,10^{57}$	

*The solar abundances are taken from Anders & Grevesse (1989).

**Non-solar abundances according to the results of Crowther et al. (1995) and Morris et al. (1996): $n_{He}/n_H = 2.25$, $n_C/n_H = 0.122$, $n_N/n_H = 4.96$, $n_O/n_H = 0.65$ and $n_{Ne}/n_H = 1.82$ (by number with respect to the solar abundances). All other abundances are kept solar.

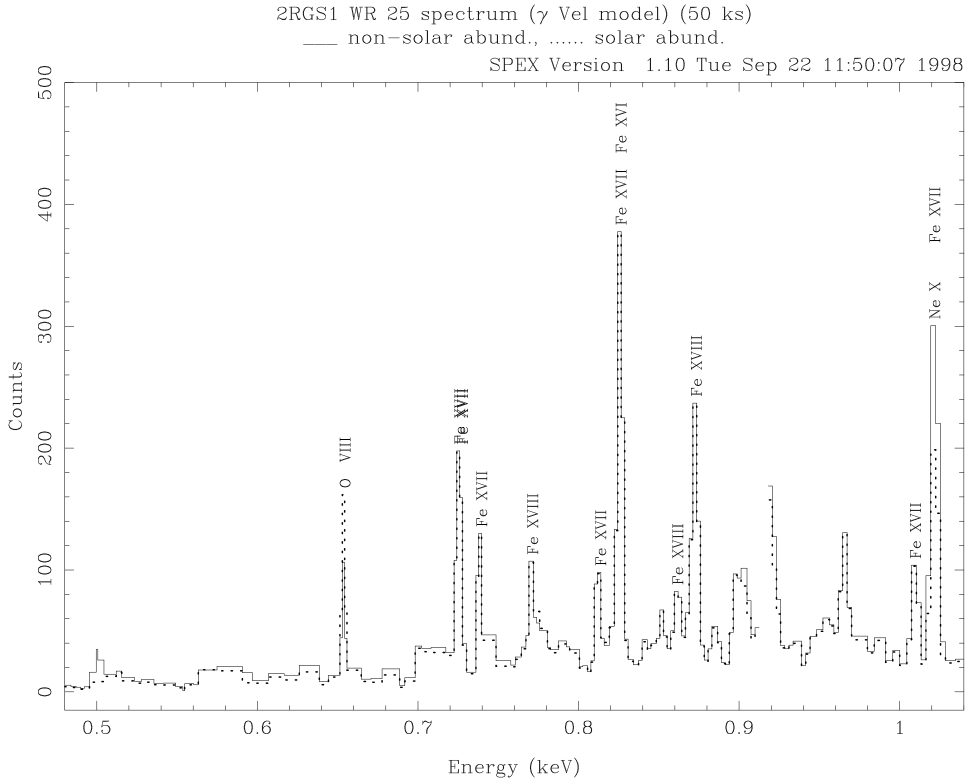

Fig. 1.— Simulated 50 ksec *XMM*-RGS spectra of WR 25 corresponding to the two temperature models with solar abundances (dotted line) and non-solar abundances (solid line).

2) indicate that we can constrain the abundances of O and Ne pretty well (to ≈ 10%) while the RGS spectrum is only weakly sensitive to the nitrogen enhancement. This latter point is not surprising since the weak N VII line at 0.50 kev is the only transition of nitrogen in the energy range considered. Fortunately, this element can be constrained through ground-based observations.

Table 2: Spectral fit to model 2.*

Parameter	Input value	Restored value
T_1 (keV)	0.630	0.626 ± 0.005
T_2 (keV)	1.23	1.13 ± 0.07
EM_1 (cm^{-3})	$7.7\,10^{55}$	$(7.6 \pm 0.18)\,10^{55}$
EM_2 (cm^{-3})	$4.82\,10^{57}$	$(5.10 \pm 0.32)\,10^{57}$
$n_{\rm N}/n_{\rm H}$	4.96	6.3 ± 1.6
$n_{\rm O}/n_{\rm H}$	0.65	0.61 ± 0.07
$n_{\rm Ne}/n_{\rm H}$	1.82	1.82 ± 0.15

*$\chi^2 = 297$ (288 d.o.f.); $n_{\rm He}/n_{\rm H} = 2.25$ and $n_{\rm C}/n_{\rm H} = 0.122$ are fixed.

To test the robustness of the method, i.e. the possibility to use it when ground-based estimates of He and C abundances either are not available or are unreliable, we performed the same analysis keeping the He and C abundances as free parameters. The results indicate that, even so, the abundances of oxygen and neon can be constrained pretty well (to about 10 - 15%). The same conclusions are reached when using a single temperature model based on the *ASCA* observations of WR 25 by Skinner et al. (1995).

EG, GR and JMV would like to thank the Fonds National de la Recherche Scientifique (Belgium) and the PRODEX XMM-OM Project for multiple supports.

REFERENCES

Anders E., Grevesse N. 1989, Geochim. Cosmochim. Acta, 53, 197

Berghöfer T.W., Baade D., Schmitt J.H.M.M., et al. 1996, A&A, 306, 899

Berghöfer T.W., Schmitt J.H.M.M., Danner R., Cassinelli J.P. 1997, A&A, 322, 167

Chlebowski T. 1989, ApJ, 342, 1091

Chlebowski T., Garmany C.D. 1991, ApJ, 368, 241

Corcoran M.F., Swank J., Rawley G., et al. 1995, Rev. Mex. Astron. Astrof. Conf. Series, 2, eds. V.P. Niemela, N. Morrell & A. Feinstein, 97

Corcoran M.F. 1996, Rev. Mex. Astron. Astrof. Conf. Series, 5, eds. V.S. Niemela & N. Morrell, 54

Crowther P.A., Hillier D.J., Smith L.J. 1995, A&A, 293, 403

Feldmeier A., Puls J., Pauldrach A.W.A 1997, A&A, 332, 245

Gagné M., Caillaut J.-P., Stauffer J.R., Linsky J.L. 1997, ApJ, 478, L87

Harnden F.R.Jr., Branduardi G., Elvis M., et al. 1979, ApJ, 234, L51

Kaastra J.S., Mewe R., Nieuwenhuijzen H. 1996, in *UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas*, eds. K. Yamashita & T. Watanabe, Tokyo: Univ. Acad. Press. Inc., 411

Maeder A., Meynet G. 1995, The Messenger, 80, 19

Morris P., van der Hucht K.A., Eenens P.R.J., Williams P.M. 1996, in *Wolf-Rayet Stars in the Framework of Stellar Evolution*, 33rd Liège Int. Astroph. Coll., eds. J.-M. Vreux, A. Detal, D. Fraipont-Caro, E. Gosset & G. Rauw, 405

Pittard J.M., Stevens I.R. 1997, MNRAS, 292, 298

Pollock A.M.T. 1987, ApJ320, 283

Schaller G., Schaerer D., Meynet G., Maeder A. 1992, A&AS, 96, 269

Schmutz W. 1991, in *Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies*, Proc. IAU Symp. 143, eds. K.A. van der Hucht & B. Hidayat, Kluwer, Dordrecht, 34

Seward F., Forman W., Giacconi R., et al. 1979, ApJ, 234, L55

Skinner S.L., Nagase F., Koyama K., Maeda Y., Tsuboi Y. 1995, in *Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution*, Proc. IAU Symp. 163, eds. K.A. van der Hucht & P.M. Williams, Kluwer, Dordrecht, 471

Stevens I.R., Blondin J.I., Pollock A.M.T. 1992, ApJ, 386, 265

van der Hucht K.A. 1992, A&A Rev., 4, 123

Wessolowski U. 1996, in *Röntgenstrahlung from the Universe*, Proc. Wurzburg Conf. MPE Special Pub. 263, eds. H.U. Zimmermann, J.E. Trümper & H. Yorke, 75

Williams P.M., van der Hucht K.A., Pollock A.M.T., et al. 1990, MNRAS, 243, 662

Willis A.J., Schild H., Stevens I.R. 1995, A&A, 298, 549

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