X-RAY EMISSION FROM EARLY-TYPE STARS: NEW RESULTS AND NEW CHALLENGES

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ABSTRACT

Early-type stars of spectral types O and Wolf-Rayet are moderately bright X-ray sources. The X-ray emission is usually attributed to a shock-heated plasma. In single stars the shocks could arise from the intrinsic instability of the stellar winds, whilst in binary systems, the collision of the two stellar winds can provide an additional emission. *XMM-Newton* and *Chandra* have observed a number of these stars, obtaining spectra of unprecedented quality. These observations provide new insight into the properties of the hot plasma in early-type stars winds, but raise also new questions that challenge our 'standard' model for the X-ray emission of hot stars. In this review, I highlight some of the most important results obtained over the last six years.

Key words: binaries: general – Stars: early-type – Stars: Wolf-Rayet – Stars: winds, outflow – X-rays: stars.

1. WHAT WE (THOUGHT WE) KNEW

O stars are massive ($\geq 20\,\mathrm{M}_\odot$), hot ($\mathrm{T}_\mathrm{eff} \simeq 30\,000 - 90\,000\,\mathrm{K}$) and luminous ($\mathrm{L}/\mathrm{L}_\odot \simeq 3\times10^4 - 3\times10^6$) objects that play a key role in many astrophysical contexts. Among the most remarkable features of these early-type stars are their tremendous stellar winds that associate large terminal velocities ($v_\infty \sim 1000$ – $3000\,\mathrm{km\,s}^{-1}$) along with high mass loss rates (of the order of $\dot{\mathrm{M}} \simeq 10^{-6} - 10^{-4}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$). Wolf-Rayet (WR) stars are believed to represent a late stage of the evolution of massive O stars and the winds of WR stars display a composition resulting from nuclear burning of hydrogen (WN subclass) or helium (WC subclass).

X-ray emission from early-type stars was first discovered serendipitously with *EINSTEIN* (Harnden et al. (1979), Seward et al. (1979)). Subsequent studies with *EINSTEIN* and *ROSAT* indicated that the observed X-ray luminosity of O-type stars roughly scales with their bolometric luminosity as $\mathrm{L_X}/\mathrm{L_{bol}} \approx 10^{-7}$ (e.g. Berghöfer et al. (1997) and references therein).
Various attempts have been made to explain the X-ray emission from single O and WR stars. By analogy with late-type stars, early models involved a corona at the base of the wind (e.g. Cassinelli & Olson 1979). However, from observations of high-mass X-ray binaries harbouring a neutron star orbiting near the surface of an O-type star (e.g. HD 153919), it is known that the stellar winds of O-type stars are optically thick to soft X-rays. Therefore, any X-ray emission from a base corona of an early-type star should exhibit a dramatic absorption by the cool stellar wind below 1 keV (see the discussion in Pollock & Oskinova 2002). Low and medium dispersion X-ray spectroscopy of massive stars with *ROSAT* and *ASCA* revealed instead relatively soft thermal spectra with little evidence for strong circumstellar absorption. Furthermore, the lack of an outer convective zone in hot stars and the lack of a correlation between the X-ray luminosity and the stellar rotation rate suggest that X-rays of early-type stars are not produced by magnetic activity associated with a solar-type dynamo.
Alternatively, in what has become now the 'standard' model for X-ray emission from single early-type stars, the X-rays are thought to arise from a shock-heated plasma distributed throughout the stellar wind (e.g. Lucy (1982)). In fact, the winds of O-type stars are driven by the radiation pressure of the numerous UV spectral lines, and this mechanism is intrinsically unstable. These instabilities lead to hydrodynamic shocks that could heat the post-shock material to temperatures consistent with the $\sim 0.5\,\mathrm{keV}$ emission observed for most presumably single early-type stars. The most recent models of this kind yield predicted X-ray luminosities that are in rough agreement with the observed values (see Feldmeier et al. (1997) and references therein).
One difficulty of these wind shock models is that they predict a strong X-ray variability on rather short timescales which has so far not been observed for single O-stars (Berghöfer & Schmitt, 1994). Another shortcoming of this model is that simple theoretical considerations indicate that the most natural scaling of the X-ray luminosity should be with the wind density parameter $\dot{\mathrm{M}}/v_\infty$ rather than with $\mathrm{L_{bol}}$ (Owocki & Cohen, 1999). Owocki & Cohen (1999) indeed found that a rather subtle balance of X-ray absorption and emission is required to account for the empirically inferred $\mathrm{L_X}/\mathrm{L_{bol}}$ scaling.

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Interestingly, Wolf-Rayet stars do not show a clear empirical correlation between $\mathrm{L_X}$ and either $\mathrm{L_{bol}}$ or $\dot{\mathrm{M}}\,v_\infty$ (Wessolowski, 1996). Ignace & Oskinova (1999) interpreted the lack of a clear scaling relation as a result of the larger optical depth in the stellar winds of WR stars compared to O-star winds. On average, presumably single WN stars tend to be slightly more X-ray luminous than presumably single WC stars. In addition, WR binaries are found to be X-ray brighter than single WR stars (Pollock, 1987).

In a similar way, the first extensive surveys of early-type stars with *EINSTEIN* revealed that O + O binary systems display systematically larger $\mathrm{L_X}/\mathrm{L_{bol}}$ ratios than single O stars (Chlebowski & Garmany, 1991). This X-ray 'overluminosity' of massive binaries is usually attributed to the emission from a plasma heated by the collision of the stellar winds of the two stars (e.g. Stevens et al. (1992) and references therein). In some cases, massive binaries exhibit a phase-locked modulation of their X-ray flux (e.g. Willis et al. (1995), Corcoran (1996)) that reflects either the variation, during the orbital motion, of the circumstellar opacity along the observer's sightline through the winds or the variation of the separation between the stars in eccentric systems.

2. WHAT WE HAVE LEARNED

2.1. Line diagnostics

Previous X-ray observatories lacked the high-resolution facilities and the sensitivity to study the spectra of early-type stars in great detail. With the launches of *Chandra* and *XMM-Newton*, both equipped with grating spectrometers, it became possible for the first time to study individual lines in the X-ray spectra of these stars. Two types of line diagnostics are commonly used to derive constraints on the properties of the X-ray emitting plasma: the ratio of line intensities in helium-like ions and the detailed morphology of individual lines.

In helium-like ions, the transitions from the $n = 2$ levels to the ground level give rise to a triplet consisting of a *resonance* ($1s2p\,{}^1P_1 \rightarrow 1s^2\,{}^1S_0$), an *intercombination* ($1s2p\,{}^3P_1 \rightarrow 1s^2\,{}^1S_0$) and a *forbidden* ($1s2s\,{}^3S_1 \rightarrow 1s^2\,{}^1S_0$) line. In the coronae of late-type stars, the ratio $\mathcal{R} = f/i$ of the intensities of the forbidden and intercombination lines is essentially sensitive to the electron density. However, in a hot plasma surrounding an early-type star, the stellar UV radiation field introduces a radiative coupling between the upper level of the forbidden line and the upper level of the intercombination lines. In this way, $\mathcal{R}$ is determined by the UV radiation field and provides a sensitive diagnosis of the dilution factor $w(r) = \frac{1}{2}\left(1 - \sqrt{1 - \left(\frac{R_*}{r}\right)^2}\right)$ of the UV radiation field, and hence of the distance r from the centre of the star where the X-rays are emitted (e.g. Blumenthal et al. (1972), Porquet et al. (2001)). High-quality grating spectra therefore yield strong constraints on the location of the X-ray emitting plasma in a stellar wind. In fact, X-ray line emission is proportional to the density squared: in a stellar wind with outwardly decreasing density, it thus occurs as near to the stellar surface as possible. Therefore, if the X-ray emitting material is distributed throughout the wind, the X-ray lines should form near the radius of monochromatic optical depth unity $r(\tau_\lambda = 1)$.

Crucial information about the origin of the X-ray emission can also be obtained from the shape of the strongest emission lines. Various predictions have been made in the context of the 'standard' wind-shock model. For instance, X-ray emission lines formed in an optically thin plasma[1] (assuming a uniform distribution of X-ray emitters and a constant wind speed) without photoelectric absorption by the cool wind, are expected to show a flat-topped profile (e.g. Feldmeier et al. (2003)). When the photoelectric absorption by the wind is included in the profile calculation, it mostly affects the emission from the material that moves away from us (Owocki & Cohen, 2001), thus leading to blue-shifted line profiles. Ignace & Gayley (2002) investigated the effect of line opacity on the line profiles. For strong lines of abundant metals, newly created photons may undergo resonance scattering in the same line. This leads to broad emission profiles that have blue-shifted centroids, but are considerably less asymmetric than in the optically thin case. Feldmeier et al. (2003) investigated the effects of absorption in a fragmented wind. In fact, as a result of the same instabilities that are thought to produce the X-ray emission, the stellar wind is expected to be rather clumpy, instead of being smooth and homogeneous. Once more, it was found that the red-shifted part of the profile should be heavily absorbed while the blue-shifted part remains flat-topped. Interestingly, if the X-rays were emitted at the reverse shock on the starward side of the fragments, one would expect absorption by the natal fragment, leading to a zero flux at the line centre. This should then produce a double-peaked profile, which, however, has never been observed so far.

The high-resolution X-ray spectra of O-type stars that have been obtained so far show a variety of situations. The two most extreme cases are probably ζ Pup and θ^1 Ori C.

The spectrum of ζ Pup (O4Ief) displays strongly broadened (1000 – 1500 $\mathrm{km\,s^{-1}}$), asymmetric and blue-shifted (e.g. $400 \pm 80\,\mathrm{km\,s^{-1}}$ for O VIII Lyα) lines (Kahn et al. (2001), Cassinelli et al. (2001)). No photoelectric absorption edges with $\tau_0 \geq 0.5$ were detected in the RGS spectrum, indicating that the X-rays cannot be concentrated at the base of the wind. The $\mathcal{R} = f/i$ ratio of the S XV, Si XIII, Mg XI, Ne IX and O VII helium-like triplets suggest formation radii that are consistent with their associated radius of optical depth unity (Cassinelli et al. (2001), Kahn et al. (2001)). All these results are in rather good agreement with the expectations for the 'standard' wind-shock model (Kramer et al., 2003), thereby making ζ Pup the prototype of an O-star for which the X-rays probably arise from shocks distributed throughout the wind.

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[1] Here it is important to distinguish the optical depth of the hot X-ray emitting plasma from that of the overlying cool wind. The latter is mainly due to photoelectric absorption.

Kramer et al. (2003) presented fits of individual X-ray lines, finding that there is less attenuation of the red wings than expected for a smooth overlying cool wind. This is tentatively attributed to the clumping of the stellar wind.

An alternative to the wind-shock scenario comes from the magnetically channeled wind shock model, originally designed for the special case of θ^1 Ori C (Babel & Montmerle (1997), ud-Doula & Owocki (2002)). In fact, a large-scale magnetic field may confine the stellar wind into the equatorial region. The wind confinement is measured by the so-called confinement parameter $\eta = (B_0^2\, R_*^2)/(\dot{M}\, v_\infty)$ where B_0 is the equatorial field strength, all other parameters having their usual meaning. For $\eta \ll 1$, the field is stretched out by the wind, whereas for $\eta \gg 1$, the wind is confined by the magnetic field. In the latter case, high velocity flows from the two hemispheres meet near the magnetic equator producing a head-on collision that heats the plasma to temperatures much higher than typically expected for single stars in the 'standard' model. Gagné et al. (2005) discuss four *Chandra* grating observations of the oblique magnetic rotator θ^1 Ori C (O4-6 Vp), that sample its rotational cycle. In this star, the strong dipole magnetic field ($B_0 = 530$ G implying $\eta = 7.5$, Donati et al. (2002), Gagné et al. (2005)) is inclined by $\sim 45°$ with respect to the rotation axis. As the star rotates, our viewing angle towards the confined wind changes, resulting in a modulation of the observable X-ray flux (Gagné et al., 2005). The four high-resolution spectra of θ^1 Ori C reveal rather narrow spectral lines with almost constant line widths, whilst the f/i ratios of the He-like ions indicate that the hot plasma must be located quite close to the stellar photosphere. All these features as well as the temperature and total luminosity of the X-ray plasma are extremely well reproduced by the magnetically channeled wind model (Gagné et al., 2005).

Intermediate situations between ζ Pup and θ^1 Ori C were found for several other O-type stars.

For instance, the RGS spectrum of the O4 V((f$^+$)) star 9 Sgr is quite similar to that of ζ Pup, showing broad blue-shifted Lyα lines of Ne X, O VIII and to some extent N VII (Rauw et al. (2002b), see Fig. 1). While it is now established that 9 Sgr is indeed a long-period binary system (Rauw et al., 2005a), at least the bulk of its soft X-ray emission likely arises in the wind of the primary component of the system. Indeed, the X-ray spectrum is dominated by a rather soft thermal emission ($kT_1 \sim 0.26$ and $kT_2 \sim 0.70$ keV). The EPIC spectrum exhibits also a hard tail which could be either thermal ($kT_3 \geq 1.5$ keV) or non-thermal emission ($\Gamma \geq 2.9$) and arises most probably in the wind interaction zone (Rauw et al., 2002b).

ζ Ori (O9.7 Ib) was observed with the gratings onboard *Chandra* (Waldron & Cassinelli, 2001). The spectral lines are broadened to $900 \pm 200\,\mathrm{km\,s^{-1}}$, but unlike the situation in ζ Pup, they are symmetric and show no blueshift. The He-like triplets of O VII, Ne IX and Mg XI indicate that these lines are produced high in the wind. On the other hand, the Si XIII f/i ratio indicates that the latter triplet forms very close to the stellar surface. This is surprising since the wind velocity should be too small to produce a shock jump so close to the star. Again, it is found that the X-ray emission lines originate primarily from just above $r(\tau_\lambda = 1)$. However, the shape of the lines is not that expected for a shock-heated plasma distributed throughout the wind. Waldron & Cassinelli (2001) therefore propose a composite model involving wind shocks as well as some magnetic confinement of turbulent hot plasma in a non-symmetric wind.

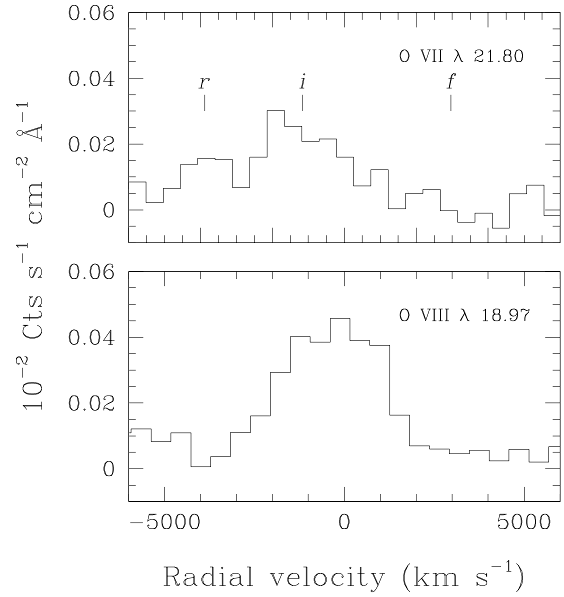

Figure 1. O VII and O VIII lines in the RGS spectrum of 9 Sgr. Note the broadening of the O VIII Ly α line and the absence of the f component in the He-like triplet (Rauw et al. 2002b).

In the spectrum of δ Ori (O9.5 II + B0.5 III + ...), the lines are broadened to only $430 \pm 60\,\mathrm{km\,s^{-1}}$ (HWHM), which is much less than $v_\infty \simeq 2000\,\mathrm{km\,s^{-1}}$ (Miller et al., 2002a). The characteristic wind optical depth of the O9.5 II stellar wind is intermediate between those of ζ Ori and ζ Pup and one would thus expect to observe line profiles intermediate between these two stars. However, the lines are narrow, essentially unshifted and symmetric. Either the wind is porous or the mass loss rate has been overestimated. An alternative explanation could be that the X-ray emission is dominated by the colliding wind region in this multiple system. The shocked material would be roughly at rest with respect to the observer, thus explaining the narrow lines. Furthermore, most of the X-ray emission would suffer similar wind absorption (leading to symmetric lines). However, in such a configuration, one would expect to see eclipses in the X-ray light curve, which is not the case (Miller et al., 2002b).

2.2. Colliding wind binaries

As pointed out in the introduction, early-type binaries are often more X-ray luminous than what is expected from their bolometric luminosity (see also Fig. 2). If the winds reach rather high pre-shock velocities, the X-ray emission produced in a wind interaction is a priori expected to be quite hard. In addition, the changing optical depth along the line of sight and/or the changing separation between the two stars can lead to a substantial phase-locked variability of the flux level. A key parameter of a colliding wind interaction is the efficiency of radiative cooling. In close binary systems where the densities in the wind interaction zone are high, the shock-heated plasma cools down rapidely via radiative recombination. In wide binary systems or binaries with low density winds, radiative cooling is much less efficient: the plasma cools only through adiabatic expansion and the resulting X-ray emission is expected to scale roughly as $1/d$, where d is the orbital separation between the two components (Stevens et al., 1992).

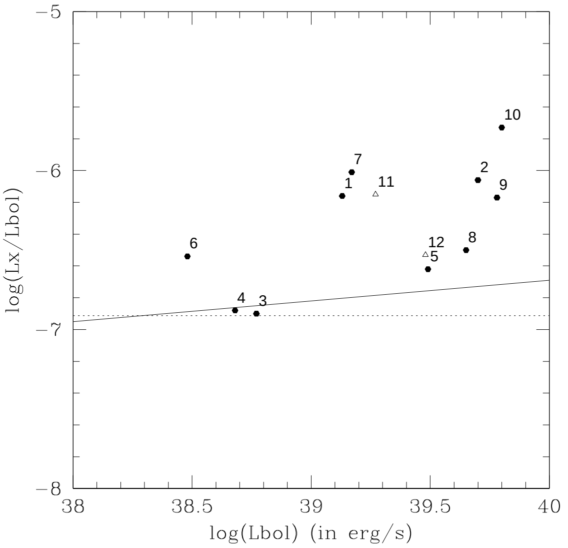

Figure 2. $\log(\mathrm{L_X/L_{bol}})$ *(in the 0.5 – 10 keV energy range) for a number of O-type binaries as a function of* $\log \mathrm{L_{bol}}$. *All data were obtained with XMM-Newton. The filled dots stand for binary stars: 1 = HD 47129 (Linder & Rauw 2005), 2 = HD 93403 (Rauw et al. 2002a), 3 = HD 152218 and 4 = HD 152219 (Sana et al. 2005b), 5 = HD 152248 (Sana et al. 2004), 6 = CPD-41° 7742 (Sana et al. 2005a), 7 = HD 159176 (De Becker et al. 2004a), 8 = 9 Sgr (Rauw et al. 2002b), 9 = HD 167971 (De Becker et al. 2005), 10 = Cyg OB2 #8a (De Becker & Rauw 2005). Open triangles indicate two suspected binaries: 11 = HD 108 (Nazé et al. 2004a) and 12 = HD 168112 (De Becker et al. 2004b). The solid and dashed lines yield the empirical scaling relations of Berghöfer et al. (1997) and Sana et al. (2005b) respectively.*

XMM-Newton has gathered phase-resolved X-ray spectroscopy of several O star binaries spanning a wide range of stellar wind parameters as well as orbital periods, thereby providing a more detailed description of the colliding wind phenomenon.

The early-type binary with the shortest orbital period that has been (almost) completely covered by *XMM-Newton* is the eclipsing system CPD-41° 7742 (O9 V + B1-1.5 V, $\mathrm{P_{orb}} = 2.44$ days, Sana et al. (2005a)). The light curve shows a broad occultation as well as a narrow eclipse respectively when the secondary or the primary star is in front. Sana et al. (2005a) interpreted the main features of this light curve with a simple geometrical model where the primary wind crashes into the photosphere of the secondary.

Six phase-resolved *XMM* observations of HD 152248 (O7.5 III(f) + O7 III(f), $\mathrm{P_{orb}} = 5.8$ days, $e = 0.13$) were analysed by Sana et al. (2004). The EPIC spectra are surprisingly soft ($kT \leq 0.71$ keV), most probably because the winds collide well before they have reached their terminal velocities. The flux of this system displays an asymmetric modulation with phase, which is clearly a phase-locked phenomenon as confirmed by archive *ROSAT* data. This variation is most probably due to the changing optical depth along our line of sight towards the wind interaction zone (Sana et al., 2004).

With an orbital period of 15 days, the eccentric ($e = 0.23$) system HD 93403 (O5.5 I + O7 V) provides an interesting illustration of both the effects of the changing optical depth and the changing orbital separation. Indeed, using four *XMM* pointings, Rauw et al. (2002a) found that the soft X-ray emission is essentially modulated by the opacity of the primary star, while the flux at higher energies varies roughly as $1/d$, pretty much as expected for a shock producing a roughly adiabatic post-shock plasma.

De Becker et al. (2004a) investigated an X-ray spectrum of the short period binary HD 159176 (O7 V + O7 V, $\mathrm{P_{orb}} = 3.37$ days). The EPIC spectrum could be fitted by a model consisting of two rather soft thermal components (0.2 and 0.58 keV) along with a non-thermal power-law component with a photon index of $\Gamma \sim 2.5$. The latter component could be produced through inverse Compton scattering by a population of relativistic electrons accelerated in the shock region. Since the wind interaction zone is expected to be in the radiative regime, all the kinetic power of the wind affected by the collision should be radiated away almost instantaneously. Interestingly, a steady-state colliding wind model based on the latter assumption, while reproducing the overall shape of the thermal spectrum, overestimates the observed X-ray luminosity by at least a factor 4. The origin of this discrepancy is at present still unkwnon. Part of the kinetic power could actually be used to accelerate relativistic electrons in the shock region.

In the latter context, Cyg OB2 #8a (O6f + O5.5(f), $\mathrm{P_{orb}} = 21.9$ days, $e = 0.24$) provides an extremely interesting test case. Indeed, this binary is a known non-thermal radio source where a phase-modulated synchrotron radio emission is produced by relativistic electrons accelerated in the wind interaction zone (Blomme, 2005). The radio flux is maximum near periastron (i.e. at $\phi \sim 0$) and reaches a minimum shortly after $\phi \sim 0.6$. On the other hand, *XMM-Newton*, *ROSAT* and *ASCA* data reveal a phase-locked variation of the X-ray flux by about a factor 1.5, with a minimum shortly after $\phi = 0.0$ and a maximum near $\phi \sim 0.75$ (De Becker & Rauw, 2005). Therefore, the X-ray emission varies essentially in the opposite sense of the radio flux. The EPIC spectra can be represented by a thermal model with three temperatures of

0.26, 0.78 and 1.7 keV and reveal a strong overluminosity (about a factor 10). This hard and bright X-ray emission is a clear indication of a colliding wind interaction. Given these properties, a full phase-coverage of the orbital cycle of Cyg OB2 #8a with *XMM-Newton* could provide unprecedented insight into the connection between colliding winds, particle acceleration and non-thermal radio emission.

Because of its rather hard and strong X-ray emission, WR 25 (WN6ha), one of the X-ray brightest WR stars, was often suspected to be a colliding wind binary system. An analysis with a differential emission measure thermal plasma model of *XMM-Newton* spectra by Raassen et al. (2003) revealed two dominant components at 0.6 and 2.8 keV and a rather extreme $\log \mathrm{L}_X/\mathrm{L}_{\mathrm{bol}} = -5.62$. Quite recently a radial velocity study (Gamen (2005), Gosset et al. (2006)) showed that WR 25 is indeed a rather long period spectroscopic binary. A preliminary analysis of all the available EPIC data (Gosset et al., 2006) reveals a rather strong variation of the X-ray flux (by about a factor two), roughly consistent with a $1/d$ modulation.

A textbook example of a WR + O colliding wind binary is γ^2 Vel (WC8 + O7.5 III, $\mathrm{P}_{\mathrm{orb}} = 78.5$ days). At most orbital phases, the X-ray emission of γ^2 Vel is highly absorbed by the dense and opaque WC8 wind. However, shortly after conjunction when the O-star is in front (i.e. when the collision zone can be seen through a rarefied cavity around the O-star), the flux is significantly enhanced (see Willis et al. (1995)). The system was observed with *XMM-Newton* at two phases (0.1, i.e. high state and 0.4, i.e. low state). The spectrum consists of a high energy emission that is absorbed by a variable column density and a presumably constant emission line spectrum at low energies. The low energy emission displays a radiative recombination continuum of C VI and C V at 25.3 Å. Schild et al. (2004) constrained the temperature of the recombining electrons to be in the range 20 000 to 60 000 K which could indicate that the feature arises from WR material in the outer wind photoionized by the X-rays from the wind-wind collision. Skinner et al. (2001) analysed a *Chandra* HETG observation of γ^2 Vel at phase $\phi = 0.08$, i.e. when the O-star component is almost in front of the WC8 star. They found no evidence for Doppler shifts of the line centroids of the strongest lines, as well as no detectable photo-excitation effect in the He-like triplets of Si XIII, Mg XI and Ne IX. This indicates that these emission lines are probably formed at several tens of stellar radii above the surface of the O-star and not at $\sim 2\,\mathrm{R}_*$ as expected from the location of the colliding wind shock (Skinner et al. (2001), Schild et al. (2004)). This result suggests that these lines actually represent the intrinsic X-ray emission from the O-star itself, rather than the emission from the wind-wind interaction zone.

Finally, the long-period (7.9 yrs), highly eccentric ($e = 0.88$) WC7 + O4-5 binary WR 140 was observed with the HETG at two phases around periastron passage (Pollock et al., 2005). Pollock et al. argue that the lower line widths of cool ions indicate that the plasma in the wind interaction zone is not in equilibrium. They suggest that this is due to the collisionless nature of the shock and the slow character of the energy exchange between electrons and ions in the postshock plasma. This would imply that a quantitative interpretation of the X-ray emission from colliding wind binaries actually requires the use of non-equilibrium plasma models.

2.3. Presumably single Wolf-Rayet stars

As stated in the introduction, no clear relationship between L_{X} and $\mathrm{L}_{\mathrm{bol}}$ was found for WR stars. One of the intriguing questions that came up over the last couple of years is whether single WR stars actually do emit X-rays.

Oskinova et al. (2003) reported on an *XMM-Newton* exposure on the presumably single WC5 star WR 114. Despite the sensitivity of the EPIC cameras and a 15.9 ksec exposure time, the star was not detected. Assuming a plasma temperature of 1 keV yields an upper limit of 2.5×10^{30} erg s^{-1} on the X-ray luminosity of WR 114 (corresponding to $\mathrm{L}_{\mathrm{X}}/\mathrm{L}_{\mathrm{bol}} \leq 4 \times 10^{-9}$). This non-detection prompted Oskinova et al. (2003) to investigate the X-ray emission of single WC stars in general. The result was that no single WC star has so far been convincingly detected in X-rays. All WC stars that are known to emit X-rays are binaries and even here, only about 20% of the WC binaries are detected. Either X-rays are not produced in WC winds, or they are totally absorbed by the opaque stellar winds. The latter possibility seems quite plausible since the winds of WC stars are dense and metal-rich, making them optically thick out to several hundred stellar radii.

Gosset et al. (2005) analysed a 20 ksec *XMM-Newton* observation of the WN8 star WR 40. The star was not detected and Gosset et al. derived a very conservative upper limit on the X-ray luminosity of 4×10^{31} erg s^{-1} leading to $\mathrm{L}_{\mathrm{X}}/\mathrm{L}_{\mathrm{bol}} \leq 2.6 \times 10^{-8}$. At first sight, this result is quite surprising given the considerable optical variability (both photometric and spectroscopic) of WR 40 that suggests the existence of numerous structures and instabilities in its wind which could trigger a substantial X-ray emission. However, Gosset et al. (2005) showed that the wind opacity of WR 40 is very large and is probably sufficient to block out all the flux below 2.5 keV that would be emitted within 20 R_* from the stellar surface.

On the other hand, Ignace et al. (2003) presented a 9 ksec *XMM-Newton* observation of WR 1 (WN4). The star was detected at energies up to 4 keV. The lack of a hard emission component suggests that there is no contribution of a colliding wind emission in this case. Modelling with thermal models failed to reproduce the spectrum around 0.6 and 2.6 keV (i.e. at energies coincident with the K-shell photo-ionization edges of N VI and S IV – VI respectively). For the sulphur feature, Ignace et al. derive an associated optical depth $\tau_\lambda \sim 6$. Therefore, at least some of the X-ray emitting gas in WR 1 must reside below the radius of optical depth unity.

Finally, Skinner et al. (2002) reported on a 25 ksec *XMM-Newton* observation of the WN5-6 star WR 110. While WR 110 is not a known binary system, the X-ray spectrum of the star exhibits a soft ($kT_1 \sim 0.5$ keV) component along with a hard one that could either be thermal ($kT_2 \geq 3\,\mathrm{keV}$) or non-thermal ($\Gamma = 2.2$) emission. Skinner et al. slightly favour the interpretation of the hard component as being thermal emission originating in a wind interaction between the WR star and a yet undetected companion.

In summary, existing observations suggest that single Wolf-Rayet stars do indeed produce X-rays, but the level of observable emission strongly depends on the actual wind opacity. Denser or more metal rich winds probably absorb the entire X-ray emission that is produced in the inner regions of the wind.

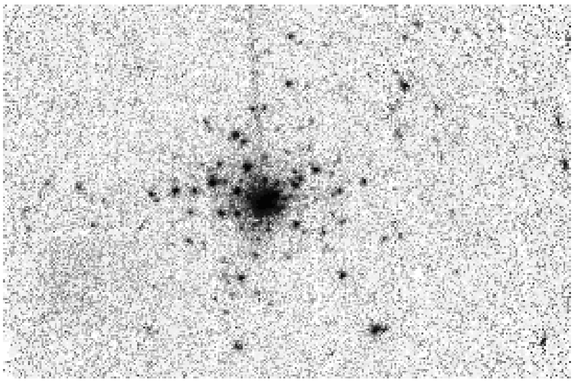

Figure 3. Grey scale image of the NGC6383 cluster as observed with XMM-Newton (Rauw et al. 2003). The EPIC images were exposure corrected before they were combined. The central source is the O-type binary HD 159176 (i.e. the sole O-type object in this cluster). Note the number of faint X-ray sources near HD 159176. Most of them have optically faint counterparts with optical and near-IR colours indicating that they are likely PMS stars. The X-ray brightest of these PMS candidates have quite hard spectra and at least in one case the light curve displays a strong flare (Rauw et al. 2003).

2.4. The surroundings of massive stars

Early-type stars frequently belong to young (a few Myr) open clusters. *XMM-Newton* and *Chandra* observations of these stars often reveal a wealth of faint serendipitous sources. These faint X-ray sources exhibit properties (flares, high spectral temperatures, large $\mathrm{L_X/L_{bol}}$ ratios) quite typical of low-mass pre-main sequence (PMS) stars (e.g. NGC 6383, Rauw et al. (2003), see Fig. 3; NGC 6530, Rauw et al. (2002c), Damiani et al. (2004); NGC 6231, Sana et al. (2006); Cyg OB2, Rauw et al. (2005b)). The study of the counterparts of these sources allows to investigate the star formation history of the clusters and the relationship between low-mass and massive members. Interestingly enough, it is often found that low-mass stars apparently form prior to the massive stars. These observations are crucial to constrain the still ill-defined formation mechanisms of the most massive stars.

Some clusters of massive stars are surrounded by an apparently diffuse X-ray emission. This feature is expected as a result of the shocked gas that fills the superbubble blown by the combined stellar winds of the cluster members into the ambient interstellar medium. However, in many cases, simple models based on the energetics of the stellar winds cannot explain all the properties of this diffuse emission. For instance, in the case of the giant H II region N 11 in the LMC, several other ingredients likely contribute to the apparently diffuse soft X-ray emission. In addition to the emission from the superbubble, hidden supernova remnants (SNRs), as well as unresolved point sources associated with either massive stars or PMS objects probably play a role (Nazé et al., 2004b).
Townsley et al. (2004) review the diffuse X-ray emission observed with *Chandra* from the star forming regions M 17 and RCW 49. M 17 hosts a blister H II region that is triggering star formation in an associated giant molecular cloud. M 17 contains about 100 OB stars, among which there are 14 O-type stars. A 40 ksec *Chandra* observation revealed 900 point sources around the so-called 'ring of fire' (consisting of a concentration of early O stars). The diffuse emission does not display an appreciable temperature gradient with distance from the O-stars, thus indicating that the hot gas flows into the interstellar medium without substantial cooling. In the case of RCW 49, over 500 X-ray point sources were found with *Chandra* and the diffuse X-ray emission appears centered on the open cluster Westerlund 2 at the core of RCW 49. The spectrum of this diffuse emission can be modelled by a three temperature thermal emission. The hardest ($kT = 3.1\,\mathrm{keV}$) component may also be fitted with a non-thermal model (power-law with $\Gamma = 2.3$). If thermal, the hard component might be due to the concentration of stars in Westerlund 2. On the other hand, if non-thermal, it could reveal the signature of embedded SNRs.

3. WHAT WE STILL DON'T KNOW

Over the first six years of their missions, *XMM-Newton* and *Chandra* have already contributed significantly to our understanding of the X-ray emission of massive stars. Much progress has been achieved, but a lot more work remains to be done. Indeed, the new results discussed above have also led to new challenges, that call for additional observations as well as for new theoretical models.

To date, roughly half a dozen presumably single O-type stars have been observed at high spectral resolution. These data reveal a variety of line profiles, some of which are in agreement with the expectations of either the standard wind-shock model or the magnetically channeled wind model. However, more data are needed to put these results on firmer grounds and to find out which of the two situations is the most typical. In the framework of the second model, high-resolution X-ray spectroscopy could provide unprecedented information on the importance of large scale magnetic fields in early-type stars, thereby helping to solve the long-standing issue of magnetic fields in early-type stars. Alternative sce-

narios to the ‘standard’ model and the channeled wind model are currently being developed (Pollock & Raassen, 2005). High-quality high-resolution spectra will be crucial to test these new ideas.
As pointed out in the introduction, hydrodynamical simulations of the intrinsic instabilities of O-star winds often predict a short-term variability of the X-ray emission (e.g. Feldmeier et al. (2003)). However, observations of presumably single O-stars reveal a rather constant X-ray flux. A possible exception to this rule is ζ Oph (O9.5 V) for which Oskinova et al. (2001) found a 20% modulation of the X-ray flux as observed with *ASCA*. The time-scale (0.77 day) of this variation might be related to the recurrence time of discrete absorption components (DACs) seen in the UV lines of this star. If confirmed, such a correlation would provide important clues on the connection between the X-ray emission and the large-scale wind structures that are thought to produce recurrent DACs.
While the O-star $\mathrm{L_X} - \mathrm{L_{bol}}$ relation inferred from the *ROSAT* All Sky Survey (Berghöfer et al., 1997) displays a considerable scatter, the corresponding relation obtained from *XMM-Newton* observations of the open cluster NGC 6231 (Sana et al. (2005b), see also Sana et al., these proceedings) reveals an amazingly small scatter. Could this feature be explained by the fact that the Sana et al. relation is drawn from a homogeneous population of O-stars, while the *ROSAT* results refer to a mix of stars all over the Galaxy? Future observations of open clusters harbouring massive stars should allow to further constrain this relationship and to find out whether other parameters (such as metallicity, age, galactocentric distance...) play a role in this relation.

XMM-Newton and *Chandra* have allowed for the first time to collect high quality observations for a number of colliding wind binaries. These data have shed new light on the orbital variability of the X-ray flux of these systems, thereby providing a better description of the colliding wind interaction over a broad range of physical parameters. Many features that have been found are in excellent agreement with the theoretical expectations for colliding wind systems. Some other properties, such as the role of non-thermal processes are as yet more difficult to interpret. A key question that remains to be answered is what happens to the kinetic power in radiative shocks and what fraction of it is used to accelerate relativistic particles. Another issue concerns the nature of the shocks. Pollock et al. (2005) and Pollock & Raassen (2005) suggest that the shocks are collisionless and that the post-shock plasma is not in equilibrium. If this is the case, then the qualitative interpretation of the X-ray spectra of colliding wind binaries (and probably early-type stars in general) requires the design of new dedicated models including collisionless shocks, particle acceleration as well as non-equilibrium plasma conditions.
Finally, hard X-ray emission in early-type stars is often attributed to the presence of a wind interaction zone. However, in some cases, stars that display a hard X-ray emission and that are X-ray overluminous (e.g. the Of?p star HD 108, Nazé et al. (2004a), see also Nazé et al., these proceedings) do not show any obvious indication of multiplicity at other wavelengths. More data, both in X-rays and other energy domains, are needed to clarify the origin of this hard emission.

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