High-resolution X-ray spectroscopy of early-type stars

G. Rauw* [a], A.M.T. Pollock [b], & Y. Nazé† [a]

[a]Institut d'Astrophysique, Université de Liège, Allée du 6 Août, 17, Bât B5c, B-4000 Liège (Sart Tilman), Belgium

[b]ESA *XMM-Newton* Science Operation Centre, ESAC, 28080 Madrid, Spain

Although X-ray emission from massive, early-type stars has been known for almost thirty years, it is only with the advent of the high-resolution spectrographs aboard *Chandra* and *XMM-Newton* that a detailed investigation of the X-ray spectra of these stars has become possible. The existing observations of both single and binary early-type stars have been used to study the properties of their stellar winds. While some results agree with the expectations from theoretical models, other spectra show unexpected features. In this contribution, we review our current knowledge on the X-ray emission of stars of spectral type O and Wolf-Rayet and discuss the possibilities to test some new ideas with future high-resolution X-ray observations.

1. X-ray emission from early-type stars

Early-type stars of spectral type O or Wolf-Rayet (WR) are hot and luminous objects ($T_{\rm eff} \geq 30\,000$ K, $L_{\rm bol} \geq 4 \times 10^6\,L_\odot$) with initial masses on the main sequence of more than about $15\,M_\odot$. The strong radiation fields of these stars drive energetic stellar winds with mass loss rates in the range $\dot{M} \simeq 10^{-7} - 10^{-4}\,M_\odot\,{\rm yr}^{-1}$ and terminal velocities of order $v_\infty \simeq 1000 - 3000\,{\rm km\,s^{-1}}$. These winds not only affect the evolution of the stars themselves, but they have also a tremendous impact on their surroundings (see e.g. [1] for a general review). Stellar winds of O-type stars are driven by the transfer of momentum from the photospheric radiation field through photon scattering by strong UV resonance lines [2]. In this mechanism, only a fraction of the ions are directly accelerated. The other charged particles that constitute the stellar wind are dragged along by Coulomb interactions.

X-ray emission from early-type stars had been expected on theoretical grounds since the presence of certain ions (O VI and N V) in the UV spectra of these stars could be explained by Auger ionisation [3]. In the late seventies, when the *EINSTEIN* satellite observed regions near Cyg X-3 and η Car, a number of secondary X-ray sources were discovered and identified with O and WR stars of the Cyg OB2 and Car OB1 associations [4,5]. The first low-resolution broad-band X-ray spectra of these early-type stars indicated plasma temperatures of about $kT \simeq 0.5$ keV and luminosities of $\sim 10^{-7}\,L_{\rm bol}$. The first theoretical attempts to explain this X-ray emission supposed that it arises from a dynamo-driven corona at the base of a cool wind [3,6]. However, as the stellar winds of massive stars in high-mass X-ray binaries produce strong absorption of the X-ray emission from the compact companion [7], one would expect to see similarly strong absorption for X-rays arising from a base corona. Since this is not the case, alternatives to the base corona model were sought. The most popular current scenario for X-ray emission from single O-stars stems from the fact that the transfer of momentum via scattering by resonance lines is a highly unstable process (see e.g. [8,9]). This microscopic line-force instability is thought to trigger macroscopic hydrodynamic shocks distributed throughout the wind; X-rays from the shock-heated plasma could better account for the overall properties of the low-resolution spectra of early-type stars as seen with *EINSTEIN*, *ROSAT* and *ASCA* [10].

With the advent of *XMM-Newton* and *Chandra*, the current generation of X-ray observatories combine high throughput and high-resolution spectroscopy, and new insight into the X-ray emission of early-type stars has been obtained. Since this conference deals primarily with high-resolution X-ray spectroscopy, we will focus on the results that have been obtained with the *Chandra* and *XMM-Newton* grating instruments. A general review of X-ray properties of early-type

*Research Associate FNRS (Belgium)
†Postdoctoral Researcher FNRS (Belgium)

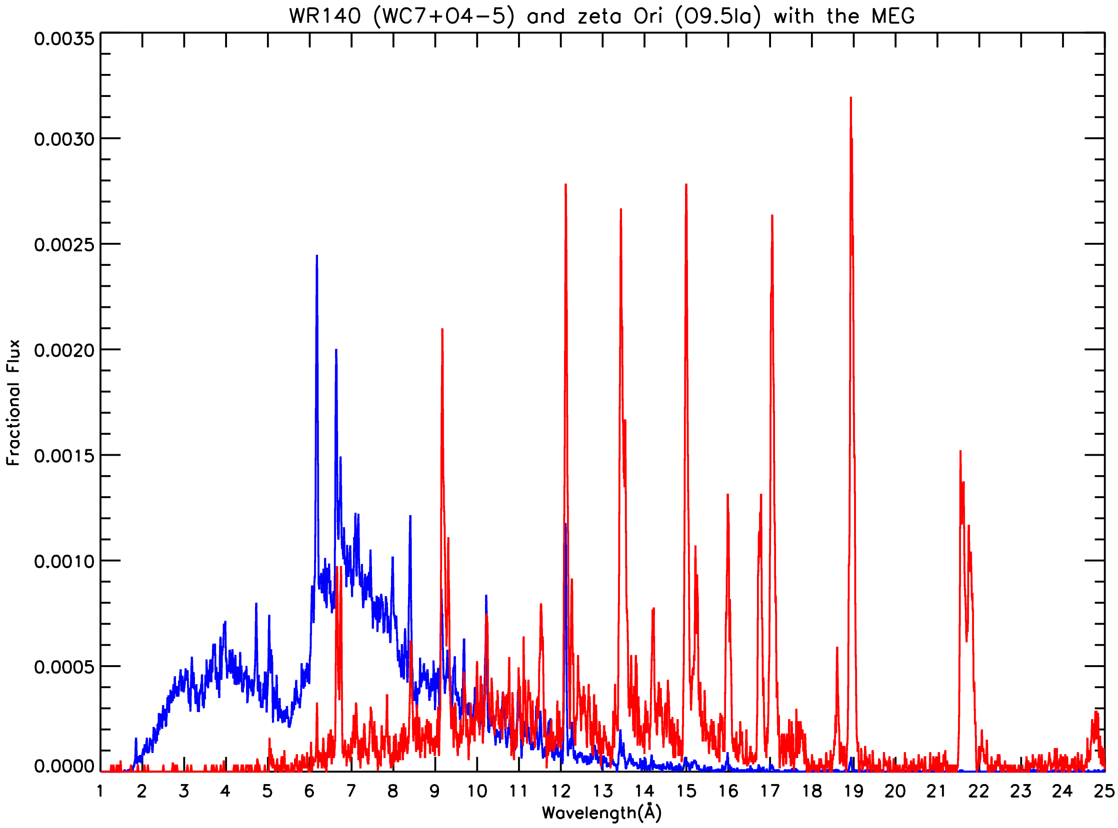

Figure 1. HETG-MEG spectra of ζ Ori (red) and the colliding wind binary WR 140 (blue). Note the prominent bremsstrahlung continuum in WR 140 and the obvious difference in plasma temperature between the two stars. The WR 140 spectrum is the pre-periastron observation discussed by [17].

stars can be found for instance in [11].

The first massive stars to be observed with these high-resolution spectrographs [1] were the supergiants ζ Pup (= HD 66811; O4 Ief) and ζ Ori (= HD 37742; O9.7 Ib) (see [12–14]), revealing X-ray spectra dominated by numerous emission lines (see Fig. 1). These individual lines or groups of lines provide for the first time the opportunity to apply detailed diagnostics of the physical properties of the X-ray emitting plasma. Half a dozen single O-stars have been observed to date with either HETG or RGS and their spectra show a variety of line morphologies, from rather narrow to broad, from symmetric to asymmetric, from blue-shifted to un-shifted, although there seems to be a reasonably smooth transition from ζ Pup at one extreme to σ Ori (= HD 37468; O9.5 V) at the other [15].

While single O-type stars are found to display intrinsic X-ray emission that scales roughly with bolometric luminosity (see e.g. [16] and references therein), some early-type binaries are considerably brighter, hotter and more variable. This is attributed to the interaction of the stellar winds of the binary components. A few of these systems (such as WR 140, [17] see also Fig. 1) are among the brightest hot-star X-ray sources and we review some of the results from high-resolution spectroscopy in Sect. 4.

2. The standard wind-shock model for single O stars

As outlined above, the most popular current interpretation of the intrinsic X-ray emission from

[1] $\Delta\lambda$ = 0.012, 0.024, $\sim$ 0.06Å for the HETG/HEG, HETG/MEG and the RGS instruments respectively

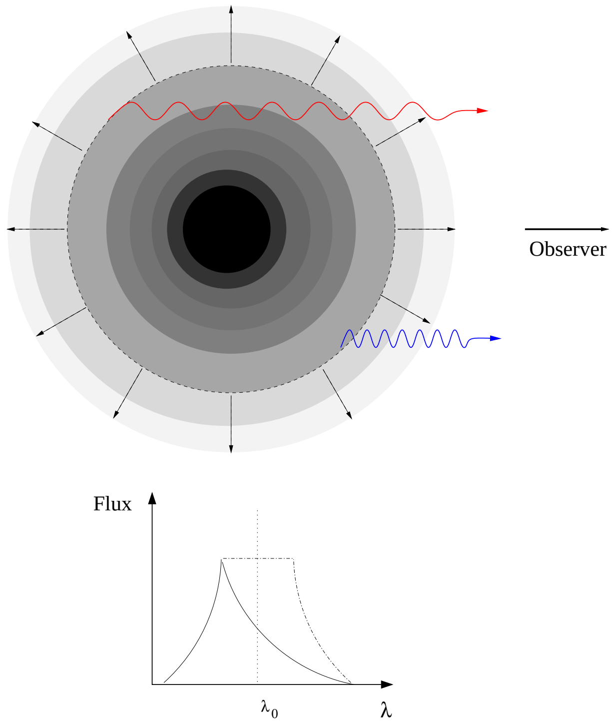

Figure 2. Schematic view of emission-line formation in the standard wind-shock model for a smooth spherically symmetric wind. Consider line photons arising on the dashed surface in an expanding wind. Since the X-ray emitting material is assumed to move along with the cool wind material, for an observer located to the right in our cartoon, a photon coming from the rear side of the wind will be red-shifted, whereas photons from the front side will be blue-shifted. In the absence of photoelectric absorption by the cool wind material, we expect to observe a roughly flat-topped line profile (dash-dotted line profile). However, as a result of the much larger column density seen by the red photons, the red part of the line suffers much stronger absorption than the blue and the resulting profile is blue-shifted and asymmetric, as shown by the solid line profile.

single early-type stars relies on the wind-shock model based on the idea that stellar winds driven by the transfer of momentum from the radiation field through scattering in UV resonance lines are highly unstable. In this scenario, the X-ray emitting plasma should be distributed across the stellar wind and as a result of the bulk expansion of the wind material the spectral lines are expected to be significantly broadened. In addition, photoelectric absorption by the overlying cool wind, assumed smooth and spherically symmetric, should mostly affect the emission coming from the wind material that is moving away from the observer. Hence the red wing of an X-ray line should be more heavily absorbed than the blue wing (see Fig. 2). The lines are thus expected to be broad, blue-shifted and asymmetric with a steeper blue wing (see Fig. 2). Moreover, the line emission is expected to arise from radii above the surface of optical depth unity ($\tau = 1$). Due to the wavelength dependence of photoelectric absorption, longer wavelength transitions should come from farther out in the wind than lines at shorter wavelengths.

There is growing evidence (e.g. [18]) that stellar winds of O-type stars are not smooth but clumpy. This can have important consequences on the wind absorption, as discussed further below. Several authors have computed synthetic line profiles for various situations (optically thin vs. optically thick lines, homogeneous vs. clumped stellar wind,...) based on the wind-shock model ([19–21]; see also Oskinova *et al.*, these proceedings).

The high-resolution X-ray spectra of the supergiant ζ Pup [13,14] are reasonably well reproduced by these models: the broad emission lines are resolved by the RGS and HETG instruments and appear significantly blueshifted and skewed. The broadening implies Doppler velocities of less than v_∞, indicating that the lines originate from within the wind acceleration zone. The observed line morphologies agree with the theoretical profiles computed for a standard model configuration. Eight individual spectral lines were fitted with a simple spherically symmetric wind-shock line profile model by [22]. The free parameters of their model were

- the inner radius of the emission zone R_0. All the X-ray line emission is assumed to arise from plasma located at $r \geq R_0$.
- the filling factor of the hot plasma (assumed to vary as r^{-q} with q being a fitting parameter.
- the typical wind optical depth τ_* at the wavelength of the line. For a smooth

spherically symmetric wind, this parameter should be equal to $\frac{\kappa\,\dot{\rm M}}{4\,\pi\,v_\infty\,R_*}$, where κ is the absorption coefficient of the overlying cool wind material.

While for most lines the values of R_0 cluster around $1.4\,R_*$, the most surprising result from this study was that the wind attenuation parameter τ_* was found to be significantly smaller than might have been expected from the commonly adopted $\dot{\rm M}$ and assuming a spherically symmetric homogeneous wind. Moreover, no obvious dependence of τ_* on the line wavelength was found, suggesting that over the observed wavelength domain between 6 and 25Å, the absorption is essentially grey [22].

Another diagnostic of the plasma conditions is provided by the ratio of the intensities of the forbidden and intercombination lines of He-like triplets. For X-ray emitting plasmas surrounding early-type stars which have a strong UV radiation field, this ratio is essentially determined by the dilution of the UV radiation field [23,24]. For the RGS and HETG spectra of ζ Pup this technique indicates that the lines form at several stellar radii above the photosphere as expected for plasma embedded in the wind.

While ζ Pup seems to fit well into the wind-shock paradigm, the morphology of the X-ray line profiles of some other O-type stars observed with the HETG and RGS spectrographs does not conform at first sight so well to expectations. A controversial case is ζ Ori, whose lines are narrower than those of ζ Pup [12,25–27]. In the first paper dealing with the HETG spectra of this star [12], it was argued that the Si XIII He-like triplet arises very close to the stellar surface and that the strongest X-ray lines are symmetric and do not show any evidence of blue-shifted line centroids. They concluded that this result was at odds with the wind-shock model and they proposed instead that the X-ray emission comes from magnetic loops near the stellar surface. Recently, the same data have been reanalysed in a variety of ways, yielding quite different conclusions [27,25–27]. [27] obtained a good fit to the entire spectrum with the same asymmetric triangular velocity profile for every line. They found that the X-ray lines of ζ Ori show some asymmetry with the line centre being blue-shifted by $\sim -300\,{\rm km\,s^{-1}}$. Similarly, it has been shown by [25] that Gaussian fits with zero velocity shift such as used by [12] produce systematic residuals that can be reduced if the Gaussians are allowed to have a blue-shifted centroid. [25] also went on to use a model-independent non-parametric method, based on the moments of the lines, to confirm the existence of a significant blue-shift. Finally, they used the same method as [22] to fit seven individual lines with synthetic profiles for a spherically symmetric wind-shock model (see above). Good fits were obtained that indicated values of R_0 of about $1.5\,{\rm R}_*$, a roughly constant filling factor and a typical optical depth parameter of $\tau_* \simeq 0.25 - 0.5$, about one order of magnitude lower than expected for a homogeneous wind with the assumed mass loss rate. The R_0 parameter indicates that much of the line emission actually arises from regions in the wind below the $\tau = 1$ surface for a homogeneous wind (see Fig. 3). This situation, along with the fact that, once again, no obvious trend of the optical depth with wavelength was observed (as for ζ Pup [22], see also Fig. 3) could indicate that the mass loss rate of ζ Ori is lower than previously reported and that clumping impacts significantly on the value of τ_*.

The effect of clumping has been investigated further by several authors [26,29,30]. [26,29] fitted the observed HETG spectral lines of ζ Pup, ζ Ori, ξ Per (= HD 24912; O7.5 III(n)((f))) and ζ Oph (= HD 149757; O9.5 V) with a clumped wind model. From these studies, it appears that clumping can have serious effects on the shape of the X-ray lines in the standard model.

First of all, mass loss rates of early-type stars are mostly determined by fitting the optical, UV and near-IR spectra with a model atmosphere code. Accounting for the clumping of a fragmented stellar wind reduces the mass loss rates by a factor of a few to a few tens compared to smooth wind models. This will obviously lead to a reduced optical depth for X-ray photons. The line emission will thus be less attenuated and the line asymmetry will be less pronounced than in a smooth wind.

Second, if the clumps are nearly optically thick, the dependence of τ_* on λ vanishes and the opacity eventually becomes grey. This can easily be understood if we consider that the optical depth now reflects the probability that any line of sight

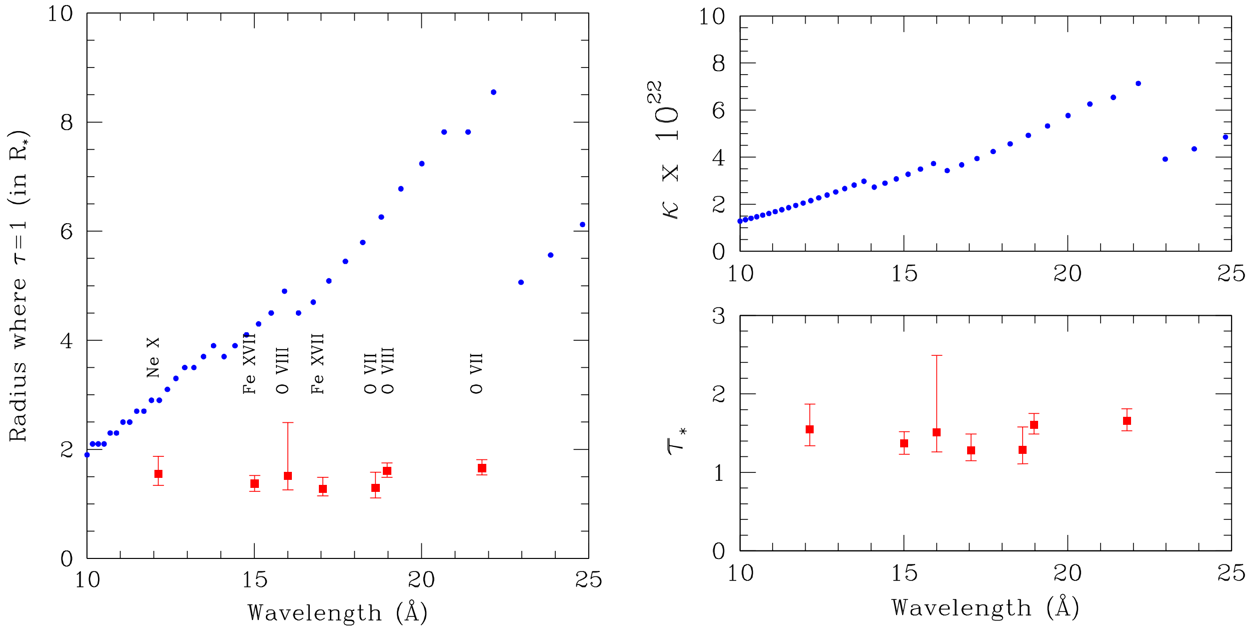

Figure 3. *Left:* comparison of the observed minimum radii of line formation with the 'X-ray photosphere' of ζ Ori. The square dots with error bars indicate the R_0 parameter from the fits of [25] to the line profiles observed in the HETG spectrum as a function of wavelength. The dotted line yields the theoretical radius of $\tau = 1$ for the stellar and wind parameters of ζ Ori ($T_{\rm eff} = 28\,500$ K, $\dot{M} = 2.5 \times 10^{-6}\,M_\odot\,{\rm yr}^{-1}$, $v_\infty = 2100\,{\rm km\,s^{-1}}$, $R_* = 31\,R_\odot$, $M_* = 49\,M_\odot$) calculated with the wind opacity model of [28]. *Right, upper panel:* predicted photoelectric absorption coefficient of the wind material around ζ Ori using the same wind opacity model as for the left panel. *Right, lower panel:* effective wind optical depth of ζ Ori as determined from the fits of individual lines [25].

from the X-ray emission zone outwards intersects a clump. This probability obviously depends on the average separation between the fragments, which is a wavelength independent, purely geometrical parameter. For a large enough spacing between the clumps, the stellar wind becomes porous and the shape of an emission line is sensitive to the spatial distribution of the clumps rather than to the amount of material along the line of sight. A detailed investigation of the effects of porosity has been presented by [30]. These authors show that in order to produce a substantial reduction of the effective optical depth, the so-called porosity length $h = l/f$ must be large. In this relation, l is the characteristic size of the clumps, whilst $f = l^3/L^3$ is the clumping factor, L being the mean distance between the clumps. A long porosity length implies that either the clumps must have very large characteristic sizes, or the volume filling factor must be small or a combination of both properties. These requirements on the clump sizes and filling factors seem *a priori* at odds with the properties of the small-scale wind structures expected from 1-D hydrodynamical simulations of the intrinsic instability of line driven stellar winds.

At this stage, it is worth emphasizing that any conclusions about the opacity of stellar winds should also be able to account for the wind absorption in high-mass X-ray binaries such as Vela X-1 (see e.g. Paerels, these proceedings). In these systems, the wind of an apparently normal O star provides material for both accretion and absorption, the absorption showing no obvious signs of anything but a normal photoelectric law.

Understanding the nature of wind opacity is also highly relevant for the study of chemical abundances and vice-versa. As a result of the combined action of stellar evolution and mass loss through the stellar wind, the surface composition of evolved massive stars is significantly altered. In principle, high-resolution X-ray spectroscopy offers the possibility to constrain abundances of some elements that are difficult to derive from other wavelength domains. The relative emission measures of various lines in the RGS spectrum of ζ Pup were investigated by [14]. They found that the abundances of CNO elements were non-solar with nitrogen overabundant, and carbon and oxygen depleted. It should be stressed that this kind of analysis strongly depends on the knowledge of the wavelength dependence of the optical depth. In fact, if the wind is clumpy and the optical depth effectively grey [25,26], then no correction of the wind absorption is needed, although corrections are still required for ISM absorption. If on the other hand, the opacity is non-grey, the differences in optical depth for the different lines must be accounted for. Another crucial point is the fact that the X-ray emitting plasma is usually not isothermal. Therefore, the conversion of line strength into actual abundances critically depends upon our knowledge of the emission measure distribution (see e.g. Behar, these proceedings).

Finally, we stress that the X-ray emission from embedded shocks is usually expected to be rather soft. This is because the X-rays arise from within the wind acceleration zone where the winds have not yet reached v_∞, thus reducing the velocity jump (and hence the increase in plasma temperature) across a hydrodynamical shock. In ζ Pup, for instance, both the line spectrum and the continuum emission, modelled as thermal bremsstrahlung, are consistent with $kT \simeq 0.6$ keV [29]. It is thus usually considered that the wind-shock model cannot explain the existence of significant quantities of X-ray emitting plasma at temperatures above ~ 1 keV in early-type stars. When such hard emission dominates the X-ray spectrum, it is often interpreted in terms of either a magnetically confined wind or a wind-wind collision in a binary system (see e.g. Fig. 1).

3. Magnetically confined winds

In the early 1990's, extensive optical as well as UV monitoring campaigns of θ^1 Ori C (= HD 37022; O4-6 Vp) revealed a periodic (P = 15.42 days) modulation of its spectrum ([31] and references therein). It was suggested that these variations could indicate a rotational modulation of the emission in an oblique magnetic rotator [31]. The same periodicity was subsequently discovered in the *ROSAT* HRI X-ray count rate of this extremely young star [32]. To explain these features, a model where a large-scale dipolar magnetic field confines the stellar wind near the magnetic equator has been proposed [33] (see Fig. 4). This model quantitatively reproduces the X-ray and optical variations of θ^1 Ori C. The existence of a dipolar magnetic field with an equatorial field strength of $B_0 = 530$ G and inclined by $\sim 45°$ with respect to the rotation axis was discovered by [34]. The magnetic field channels wind material from both hemispheres towards the magnetic equator thereby producing a head-on collision of two high velocity flows that heats the plasma to temperatures of $\sim 30 \times 10^6$ K. As the star rotates, our viewing angle towards the confined wind varies, thus resulting in a modulation of the observable X-ray flux as well as of the optical emission lines [33,35]. Recently, [36] reported on four *Chandra* HETG spectra that were obtained in such a way as to sample the 15.42 days cycle. These four spectra display narrow spectral lines with Doppler widths ranging from ~ 250 to ~ 625 km s^{-1}. Furthermore, the line strengths of the He-like triplets seen in the HETG spectra indicate that the X-ray emitting plasma must be located rather close to the stellar surface (between about 1.5 and 2.0 R$_*$). As shown by [36], these are actually the properties expected for the X-ray emission of a magnetically channeled wind.

The question that comes to mind is how unique an object θ^1 Ori C is. So far, there are two other massive stars for which the detection of a large-scale magnetic field has been claimed in the literature. These are the peculiar Of?p object HD 191612 for which [37] reported a dipolar field strength of 1.5 ± 0.2 kG and the very young B0.2 V star τ Sco (= HD 149438) which has an average field strength of 300 G over the stellar surface [38]. High-resolution X-ray spectra of τ Sco and HD 191612 have been obtained and discussed by [39,40] and [41] respectively. The X-ray properties of τ Sco fit indeed rather well into the overall picture of the magnetically confined wind scenario. In fact, the star displays an unusually hard X-ray spectrum (with temperatures up to 20×10^6 K) and a comparatively large X-

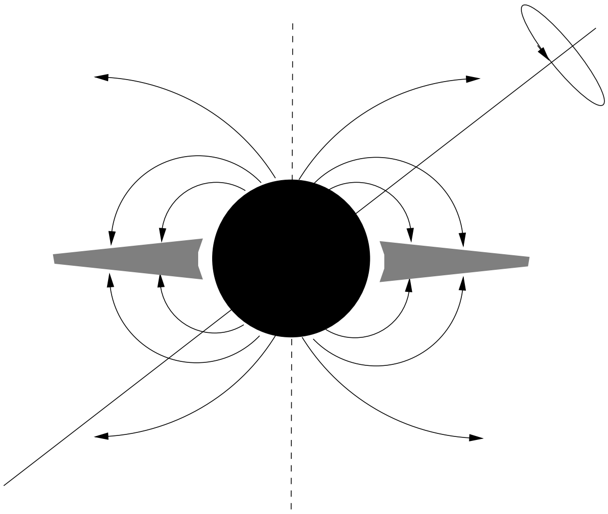

Figure 4. Schematic view of the magnetically confined wind model for an oblique magnetic rotator such as θ^1 Ori C. The magnetic axis (dashed line) is inclined with respect to the rotation axis (solid line). The dipolar magnetic field channels the wind material towards the magnetic equator where it collides with the material from the opposite magnetic hemisphere. This collision generates a hot, high-density plasma near the magnetic equator, where copious amounts of relatively hard X-rays are emitted. During the rotational cycle the viewing angle towards the confined wind region changes resulting in the observed modulation of the X-ray emission as well as of the emission at other wavelengths.

ray luminosity ($\sim 3 \times 10^{31}\,\mathrm{erg\,s^{-1}}$) for a B0-type object. The average HWHM of the lines in the HETG and RGS spectra is $\sim$ 300 km s^{-1} (much less than $v_\infty \simeq 2400\,\mathrm{km\,s^{-1}}$), even less than for θ^1 Ori C. The Si XIII He-like triplet of τ Sco indicates a formation radius of less than 1.5 R$_*$ [39,40]. Therefore, [39] pointed out the similarities between τ Sco and θ^1 Ori C. The discovery of a magnetic field [38] lends further support to this interpretation, although the magnetic topology of τ Sco appears significantly more complex than a simple dipole. Such a complex magnetospheric structure results in a heavily distorted torus of closed magnetic loops where the wind flows collide and produce a hot X-ray emitting plasma. Thus the magnetosphere of τ Sco might resemble that of the Solar corona, although the mechanism responsible for the heating of the plasma would obviously be different [38].

The situation is however quite different for HD 191612. RGS spectra of this star at three different phases of its 538 day cycle were obtained by [41]. While the overall spectrum of the star is rather hard, including emission at temperatures of 12 – 18 $\times$ 10^6 K, it appears significantly cooler than θ^1 Ori C, where plasma as hot as 30 $\times$ 10^6 K has been observed. In addition, the O VIII Lyα and Fe XVII λ 15.014 lines have FWHM of 2000 – 2600 km s^{-1}, whilst the average FWHM of the X-ray lines of HD 191612 amounts to 1800 $\pm$ 400 km s^{-1}. These lines are thus significantly broader than those of τ Sco or θ^1 Ori C. These properties are therefore at odds with the X-ray emission of HD 191612 arising from a magnetically confined wind. While [37] suggested that the confinement of the stellar winds in θ^1 Ori C and HD 191612 as estimated from the parameter $\eta = \frac{(B_0^2\,R_*^2)}{(\dot{M}\,v_\infty)}$ should be similar, we caution that the large mass loss rate of HD 191612 probably means that the optical depth of the wind is also significantly larger. Therefore, it could be possible that the larger optical depth prevents us from seeing the X-rays from the magnetically compressed wind that should essentially be located below the Alfvén radius. However, this interpretation would contrast with the idea that the X-ray wind attenuation is reduced by wind clumpiness and that most of the X-ray lines form between $\sim$ 1.5 and $\sim$ 2.5 R_* as inferred for ζ Pup and ζ Ori for instance.

4. Colliding Wind binaries

In early-type binaries, the interaction of stellar winds can produce X-ray emission that comfortably exceeds the intrinsic emission of the companion stars (see e.g. [42]). The eccentric ($e = 0.88$) long-period (P = 7.94 yrs) WC7 + O4-5 binary WR 140 (= HD 193793) probably provides the best example of a colliding wind binary system. Signatures of the wind interaction can be seen in wavelengths ranging from radio to X-rays. For instance, the system is known to display non-thermal synchrotron radio emission that varies as a function of orbital phase. Spectacular images of the radio emission obtained with the *VLBA* [43] show clearly that the non-thermal radio emission comes from the wind-wind collision zone between the stars.

The X-ray emission of WR 140 [17] is also highly variable as a function of orbital phase because of both the changing orbital separation and variable absorption along the line-of-sight to the shock region. WR 140 was observed twice with the *Chandra* HETG close to the 2001 peristron, once before and once after. The spectra reveal a strong continuum ($kT \sim 4$ keV) and many emission lines (see Fig. 1). The pre-periastron X-ray luminosity in the energy range 0.5 – 10 keV was $\sim 1.5 - 2.0 \times 10^{34}$ erg s^{-1}, about a factor of 10 – 100 larger than the typical X-ray luminosity of single O stars.

The remarkably strong neon lines in the X-ray spectrum of WR 140 are probably due to the chemical enrichment of the stellar wind of the WC component. Since the strong bremsstrahlung continuum is largely produced by free electrons from carbon and helium, the most abundant elements in the WC wind, the equivalent widths of lines directly reflect the relative abundance of the corresponding elements with respect to He and C, allowing accurate abundances to be derived.

The spectral lines of WR 140 were blue-shifted during the pre-periastron observation with velocity widths increasing with ionization potential. Given the orbital configuration of the binary at the time of the observation, the blueshift directly indicates that the X-ray emission arose from material flowing along the shock cone wrapped around the O-star. The changing linewidths, on the other hand, were interpreted as a consequence of the lack of equilibrium caused by the slowness of relaxation behind collisionless shocks in the low-density interacting flows between the stars.

Beside the long-period colliding wind binaries like WR 140 and η Car ([44]), many other shorter period early-type interacting wind binaries have been observed with *XMM-Newton*, mainly O + O systems with periods of days to weeks. In these close systems, the winds interact before they have reached their terminal velocities and many display phase-modulated X-ray flux [45–48]. Because of the lower pre-shock wind velocities, the X-ray emission from the wind interaction zone is softer and weaker than in wider systems such as WR 140. For a review of the X-ray observations of these systems, we refer to [11].

5. A new paradigm for X-ray emission from single early-type stars

Some of the thinking applied to WR 140 has triggered the development of a alternative interpretation to the standard wind-shock model [27,49] that could be far-reaching in its implications. The ions and electrons of the stellar wind interact through slow, long-range Coulomb collisions. As pointed out above, these are relevant in the wind-driving mechanism for transferring momentum from the small minority of directly driven ions to the flow of all ions and electrons. In addition, they will also help determine the way in which any shocks in the wind might develop. [27,49] drew attention to the fact that the ion-ion collisional mean free path scales as v^4/n_i, where v is the ion velocity and n_i the density. Whilst this mean free path is small near the stellar photosphere, it increases rapidly with radius in the stellar wind as v increases and n_i decreases. For instance, in ζ Ori, it reaches about 1 R_* at $r = 10\,R_*$. These authors suggest, therefore, that in common with most other astrophysical plasmas, much of a stellar wind is a collionless plasma and that any shocks which develop are regulated instead by plasma waves and are thus of magnetic origin. In such collisionless shocks, it is expected that predominantly ions are heated, whilst electrons remain cold. Given the even slower rate of energy exchange between ions and electrons, equilibrium is unlikely to be established and X-ray ionization could be due to protons rather than electrons. The width of the emission lines would then result from the thermalized motion of the ions in the post-shock region, rather than reflecting the bulk motion of the emitting plasma. [27,49] also discussed the possibility that the sluggishness of Coulomb interactions could prevent the microscopic instability of the driving mechanism developing into macroscopic shocks. If the shocks producing the X-rays in both single and binary stars are indeed collisionless, high-resolution X-ray observations of early-type stars provide a novel testbench for the study of magnetic fields and plasma physics.

6. Conclusions and Future Prospectives

High-resolution spectroscopy with *Chandra* and *XMM-Newton* has opened up an entirely new view on the X-ray emission of early-type stars. However, there is still a long way to go before the X-ray spectra of hot stars reach the same level of accuracy as in *IUE* UV spectra. Moreover, high-resolution X-ray spectroscopy of early-type stars is so far restricted to only about a dozen objects. In order to formulate general conclusions, it is mandatory to enlarge this sample. This is especially true since different objects apparently require different models to account for their X-ray spectra. Using longer integration times with the current facilities to observe fainter sources is not enough. Instead, a quantum leap in effective area is required, such as expected for the *XEUS* and *Con-X* , in order to increase significantly the number of early-type stars that can be studied at high resolution.

Beside the large effective area and good spectral resolution, future X-ray spectrographs should also have angular resolution at least as good as that of the current EPIC instruments aboard *XMM-Newton*. As the majority of the early-type stars are located in open clusters, poor angular resolution would condemn X-ray spectroscopists to work with spectra suffering from confusion by the light from either neighbouring massive stars or from the abundance of low-mass pre-main sequence stars that congregate around early-type stars.

Future high-resolution spectra of massive stars will provide the first detailed X-ray line profiles, possibly allowing the study of variability on time-scales down to the hours typical wind flow times. In the UV and optical domain, emission-line-profile variability on such time-scales is common and has been attributed to either small-scale, such as clumps, or large-scale structures in the winds.

XEUS and *Con-X* observations will also provide tests for the various ideas outlined above. For instance, they will allow to search for satellite lines that could indicate the presence of non-thermal electrons via inner-shell ionization. Relativistic particles are expected to be accelerated in the shocks probably responsible for the X-ray emission in both single and binary stars. All-in-all, these observations promise deeper insight into the high-energy mechanisms that occur inside the stellar winds of hot stars and will provide fundamental information on many processes that occur in astrophysical plasmas. In many respects, the *golden age* of X-ray astronomy of early-type stars is yet to come.

REFERENCES

1. Nazé, Y. 2006, Bulletin of the Royal Scientific Society Liège, 75, 20, `http://www.srsl-ulg.net/`
2. Lamers, H.J.G.L.M., & Cassinelli, J.P. 1999, *Introduction to Stellar Winds*, Cambridge University Press
3. Cassinelli, J.P., & Olson, G.L. 1979, ApJ, 229, 304
4. Harnden, F.R.Jr., Branduardi, G., Elvis, M., *et al.* 1979, ApJ, 234, L51
5. Seward, F.D., Forman, W., Giacconi, R., *et al.* 1979, ApJ, 234, L55
6. Waldron, W.L. 1984, ApJ, 282, 256
7. Sato, N., Hayakawa, S., Nagase, F., *et al.* 1986, PASJ, 38, 731
8. Lucy, L., & White, R.L. 1980, ApJ, 241, 300
9. Dessart, L., & Owocki, S.P. 2005, A&A, 437, 657
10. Feldmeier, A., Puls, J., & Pauldrach, A.W.A. 1997, A&A, 322, 878
11. Rauw, G. 2006, in *The X-ray Universe 2005*, ESA SP-604, 7
12. Waldron, W.L., & Cassinelli, J.P. 2001, ApJ, 548, L45
13. Cassinelli, J.P., Miller, N.A., Waldron, *et al.* 2001, ApJ, 554, L55
14. Kahn, S.M., Leutenegger, M.A., Cottam, J., *et al.* 2001, A&A, 365, L312
15. Pollock, A.M.T. 2005, in *6 Years of Science with Chandra*, `http://cxc.harvard.edu/symposium_2005/proceedings/files/pollock_andy.pdf`
16. Sana, H., Rauw, G., Nazé, Y., *et al.* 2006, MNRAS, in press
17. Pollock, A.M.T., Corcoran, M.F., Stevens, I.R., & Williams, P.M. 2005, ApJ, 629, 482
18. Fullerton, A.W., Massa, D.L., & Prinja, R.K. 2006, ApJ, 637, 1025
19. Owocki, S.P., & Cohen, D.H. 2001, ApJ, 559, 1108
20. Ignace, R., & Gayley, K.G. 2002, ApJ, 568, 954
21. Feldmeier, A., Oskinova, L., & Hamann, W.-R. 2003, A&A, 403, 217
22. Kramer, R.H., Cohen, D.H., & Owocki, S.P. 2003, ApJ, 592, 532
23. Blumenthal, G.R., Drake, G.W.F., & Tucker, W.H. 1972, ApJ, 172, 205

24. Porquet, D., Mewe, R., Dubau, J., *et al.* 2001, A&A, 376, 1113
25. Cohen, D.H., Leutenegger, M.A., Grizzard, K.T., *et al.* 2006, MNRAS, in press, astro-ph/0602599
26. Oskinova, L.M., Feldmeier, A., & Hamann, W.-R. 2006, MNRAS, submitted, astro-ph/0603286
27. Pollock, A.M.T., & Raassen, A.J.J. 2005, in *Massive Stars and High Energy Emission in OB Associations*, Proc. JENAM 2005 *Distant Worlds*, eds. G. Rauw et al., 35
28. Nazé, Y., Rauw, G., Vreux, J.-M., *et al.* 2004, A&A, 417, 667
29. Oskinova, L.M., Feldmeier, A., & Hamann, W.-R. 2006, in *The X-ray Universe 2005*, ESA SP-604, 57
30. Owocki, S.P., & Cohen, D.H. 2006, ApJ, submitted, astro-ph/0602054
31. Stahl, O., Kaufer, A., Rivinius, T., *et al.* 1996, A&A, 312, 539
32. Gagné, M., Caillaut, J.-P., Stauffer, J.R., *et al.* 1997, ApJ, 478, L87
33. Babel, J., & Montmerle, T. 1997, ApJ, 485, L29
34. Donati, J.-F., Babel, J., Harries, T.J., *et al.* 2002, MNRAS, 333, 55
35. ud-Doula, A., & Owocki, S.P. 2002, ApJ, 576, 413
36. Gagné, M., Oksala, M.E., Cohen, D.H., *et al.* 2005, ApJ, 628, 986 (Erratum ApJ, 634, 712)
37. Donati, J.-F., Howarth, I.D., Bouret, J.-C., *et al.* 2006a, MNRAS, 365, L6
38. Donati, J.-F., Howarth, I.D., Jardine, M.M., *et al.* 2006b, MNRAS, submitted
39. Cohen, D.H., de Messières, G.E., MacFarlane, J.J., *et al.* 2003, ApJ, 586, 495
40. Mewe, R., Raassen, A.J.J., Cassinelli, J.P., *et al.* 2003, A&A, 398, 203
41. Nazé, Y., Rauw, G., Pollock, A.M.T., *et al.* 2006, in preparation
42. Stevens, I.R., Blondin, J.M., & Pollock, A.M.T. 1992, ApJ, 386, 265
43. Dougherty, S.M., Beasley, A.J., Claussen, *et al.* 2005, ApJ, 623, 447
44. Leutenegger, M.A., Kahn, S.M., & Ramsay, G. 2003, ApJ, 585, 1015
45. Rauw, G., Vreux, J.-M., Stevens, I.R., et al. 2002a, A&A, 388, 552
46. Sana, H., Stevens, I.R., Gosset, E., Rauw, G., & Vreux, J.-M. 2004, MNRAS, 350, 809
47. Sana, H., Antokhina, E., Royer, P., et al. 2005a, A&A, 441, 213
48. De Becker, M., & Rauw, G. 2005, in *Massive Stars and High Energy Emission in OB Associations*, Proc. JENAM 2005 *Distant Worlds*, eds. G. Rauw et al., 73
49. Pollock, A.M.T., & Raassen, A.J.J. 2006, A&A, submitted

ACKNOWLEDGEMENTS

The authors are grateful to the organisers of this workshop for the invitation to present this review. GR and YN are supported by the FNRS (Belgium), through contract P5/36 IAP (Belspo) and through PRODEX grants linked to the ESA *XMM-Newton* and *INTEGRAL* missions.