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

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XMM-Newton and Chandra have boosted our knowledge about the X-ray emission of early-type stars (spectral types OB and Wolf-Rayet). However, there are still a number of open questions that need to be addressed in order to fully understand the X-ray spectra of these objects. Many of these issues require high-resolution spectroscopy or monitoring of a sample of massive stars. Given the moderate X-ray brightness of these targets, rather long exposure times are needed to achieve these goals. In this contribution, we review our current knowledge in this field and present some hot topics that could ideally be addressed with XMM-Newton over the next decade.

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1 Introduction

Early-type stars of spectral types O and Wolf-Rayet (WR) have been known since the *EINSTEIN* era to be rather soft and moderately bright X-ray sources (Seward et al. 1979). These stars have powerful stellar winds, associating mass-loss rates of order 10^{-6}–$10^{-4}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and velocities of several thousand $\mathrm{km\,s^{-1}}$. These winds play a crucial role both in stellar and galactic evolution. The existence of these winds must have an impact on the X-ray emission of early-type stars and the most popular paradigm for this X-ray emission indeed assumes that it arises from radiatively cooling shock-heated plasma embedded in the acceleration zone of the wind. Such shocks are thought to develop from the instability of radiatively driven mass-loss (e.g. Owocki, Castor & Rybicki 1988).

The X-ray luminosity of O-type stars scales with their bolometric luminosity (see below) whilst the X-ray luminosity of WR stars does not follow a clear $L_\mathrm{X}/L_\mathrm{bol}$ relation. Binary systems often display a variable excess X-ray emission compared to the canonical $L_\mathrm{X}/L_\mathrm{bol}$ which is thought to be the result of the collision between their winds. For a general review on the X-ray emission of early-type stars see e.g. Rauw (2006).

XMM-Newton and Chandra have significantly changed our view of the physics of early-type stars and of their X-ray emission, the most spectacular results coming from the first high-resolution spectra of these stars. The main contributions of XMM-Newton in the domain of early-type stars stem from (1) the RGS high-resolution spectroscopy, (2) the high sensitivity and the wide field of view of the EPIC cameras as well as (3) the capability to monitor variable sources.

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2 High-resolution spectroscopy

RGS and HETG spectra of a small sample of single O-type stars have revealed spectra that are extremely rich in broad emission lines (FWHM of the order 1000–$2500\,\mathrm{km\,s^{-1}}$). Well exposed high-resolution spectra of O-type stars (Fig. 1) provide many powerful diagnostics.

Very important information on the properties of the hot plasma comes from the successful line profile fitting with so-called exospheric models (e.g. Cohen et al. 2006). Assuming that the X-rays arise from wind-embedded shocks and that the hot plasma moves along with the cool wind, the shape of the line profiles should reflect the combination of the line formation radius in the wind, the overall wind motion and the absorption by the overlying cool wind material (see e.g. Fig. 2). In principle, the radial optical depth $\tau_{\lambda,*}$ of the overlying cool wind from R_0 outwards to infinity can be related to the mass-loss rate of the star. Application of this sort of analysis to observed HETG and RGS spectra of stars with known mass-loss rates (e.g. Cohen et al. 2006; Oskinova et al. 2006) yield the conclusion that the value of $\tau_{\lambda,*}$ is usually significantly smaller than expected from the mass-loss rate (assuming a smooth wind) and that the optical depth is essentially independent of λ. Both these features can be accounted for if the stellar winds are heavily clumped, up to a level where porosity sets in (Oskinova et al. 2006).

Another important piece of information comes from the f, i, r triplets of helium-like ions. Whilst the f/i ratio is a sensitive diagnosis of density in the coronae of late-type stars, it becomes essentially a measure of the dilution of the photospheric UV radiation field (hence of the distance between the hot plasma and the photosphere) in the case of early-type stars (see Porquet et al. 2001). Analysing a set of O-

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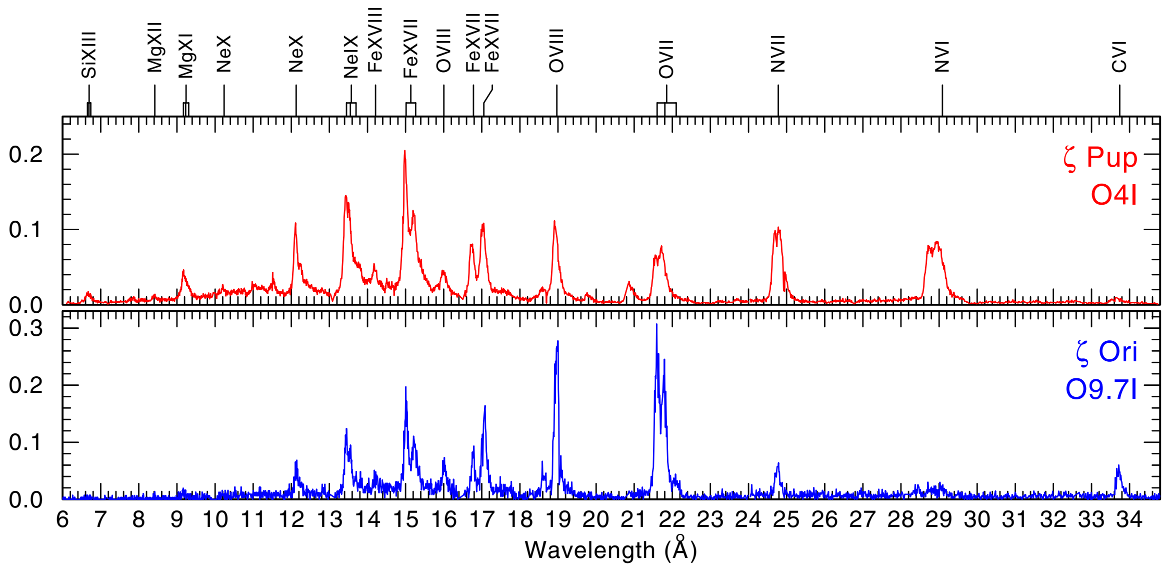

Fig. 1 (online colour at: www.an-journal.org) RGS spectrum of the O4 Ief star ζ Pup (*top panel*) and the O9.7 Ib star ζ Ori (*bottom panel*). These spectra are not corrected for interstellar absorption. The ζ Pup spectrum results from the combination of 12 separate exposures accumulating about 530 ks of useful exposure time. The most important emission lines are labelled. Note that in the case of ζ Pup, the strength of the nitrogen lines compared to the oxygen and carbon lines clearly indicates an overabundance of nitrogen.

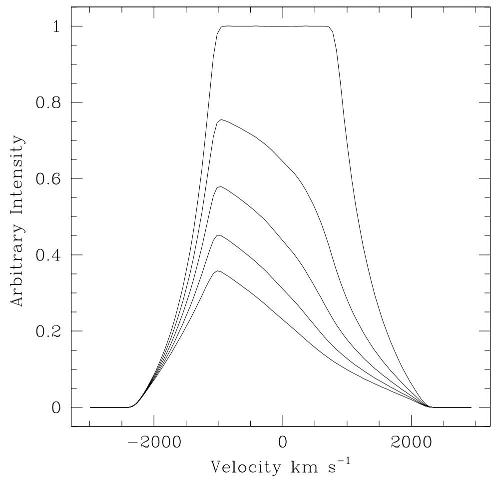

Fig. 2 Grid of synthetic line profiles computed for an inner radius of emission $R_0 = 1.8\,R_*$, a wind terminal velocity $v_\infty = 2300\,\mathrm{km\,s^{-1}}$ and assuming that the line emissivity scales as $\epsilon \propto \rho^2$ where ρ is the wind density. Flat-topped profiles correspond to radial optical depths from R_0 on outwards of $\tau_{\lambda,*} = 0.0$, whilst the other profiles computed for $\tau_{\lambda,*} = 0.5$, 1.0, 1.5, and 2.0 show an increasing blue-shift of the line centroid and a reduction of the line strength. The profiles are normalized with respect to the maximum intensity of the flat-topped profile.

type stars, Leutenegger et al. (2006) showed that the He-like triplets arise from regions between about 1.25 and 1.7 R_*, in very good agreement with the R_0 values inferred from the line profile fitting (Cohen et al. 2006).

The results highlighted above indicate that the wind-embedded shock model accounts for many of the properties of the X-ray spectra of single O-type stars. However, there are a few caveats. First of all, a few stars (θ^1 Ori C, Gagné et al. 2005; τ Sco, Mewe et al. 2003), known to have a measurable (and hence rather strong) magnetic field, probably have their winds confined into the equatorial plane of their magnetic field. The X-ray line profiles are narrower than expected from the wind-embedded shock scenario and their X-ray emission is brighter and harder. The latter features can be explained if the X-rays arise from the shock between the winds of both hemispheres of the star channeled by the magnetic field towards the magnetic equator (Donati et al. 2002). Finally, Pollock (2007) recently analysed the RGS spectrum of the O9.7 Ib supergiant ζ Ori and proposed an alternative scenario. In Pollock's paradigm, X-rays arise in the terminal velocity domain from collisionless shocks controlled by magnetic fields. In this scenario, the plasma should be out of equilibrium and the X-ray line emission would be triggered mostly by collisions with protons rather than electrons. The latter model predicts that the lines of a given star should all have the same shape and that the bremsstrahlung continuum should be significantly weaker than expected for an electron excited plasma in equilibrium.

In the ROSAT All Sky Survey (RASS), there are 11 O-type stars with a PSPC count rate of more than 0.2 cts s^{-1} (Berghöfer, Schmitt & Cassinelli 1996), which is the minimum required to collect about 20 000 RGS counts (i.e. the strict minimum number of counts needed in the entire RGS1 + 2 spectrum to perform a decent line profile analysis) in a 100 ks exposure. After almost seven years of operation, XMM-Newton and Chandra have observed all of these brightest O-type objects at high spectral resolution. However, several targets have only been observed with very short exposure times thus yielding too low a signal to noise ratio to perform a useful analysis of their line profiles. A

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significant increase of the sample of high-resolution spectra of early-type stars or a study of the variability of their line profiles will have to await for the quantum leap in collecting area expected for the next generation X-ray telescopes (XEUS, Con-X, ...). However, in the meantime, XMM could easily collect better quality spectra of those stars that are under-exposed. These data would provide information allowing to test the predictions of various models (e.g. the Pollock 2007 scenario) and hence significantly enhance our understanding of the X-ray emission of single O-type stars and help quantify the impact of magnetic fields on the stellar winds.

3 Observations of very young open clusters

Although the formation of stars more massive than $10\,M_\odot$ is still an unsolved question of modern astrophysics, it is well known that the vast majority of these stars form in open clusters. Thanks to their wide field of view and high sensitivity, the EPIC instruments aboard XMM-Newton have allowed to gather precious information on a number of very young (ages of a few million years) open clusters and their early-type star population.

One of the earliest results of the EINSTEIN satellite concerning O-type stars was the finding that their X-ray luminosity scales with their bolometric luminosity as $L_X/L_{bol} \simeq 10^{-7}$ (Long & White 1980). A number of studies have been devoted to this relation, the one benefiting from the most exhaustive data set being the Berghöfer et al. (1997) analysis of the RASS data on OB stars. The latter work revealed a large scatter around the best-fit relation and further indicated the existence of a break in the relation around spectral type B1–B1.5. The physical origin of the L_X/L_{bol} relation remains however unclear. In fact, Owocki & Cohen (1999) investigated the theoretical dependence of the X-ray emission of an O-type star on the main stellar and wind parameters. It was found that in order to reproduce the observed scaling, a delicate balance between emission and absorption is necessary. One of the results of XMM-Newton observations of the NGC 6231 open cluster was the establishment of a new L_X/L_{bol} relation (Sana et al. 2006). Whilst the NGC 6231 scaling relation is in good agreement with the one of Berghöfer et al. (1997), the most important difference is a significantly smaller dispersion (20 to 40%) around this relation.

It is quite likely that the low dispersion of the L_X/L_{bol} of the O-stars in NGC 6231 indicates the existence of an intrinsically very tight relation for a given stellar population. Indeed, the study of Sana et al. (2006) is based on a homogeneous sample of stars (same age, same distance, same metallicity), the X-ray luminosities were derived from a detailed fit of the EPIC spectra and the bolometric luminosities and the multiplicities of the stars have been established through an intensive optical spectroscopic monitoring. The RASS relation on the other hand was based on a larger, but extremely heterogeneous sample (mixture of stars from the field and inside clusters, at different distances, some stars with uncertain spectral types, ...) and the X-ray luminosities were simply derived from count rate conversion factors. The existence of such a tight relation sets stringent constraints on any scenario for the formation of X-rays in O-type stars. Therefore, it is very important to check whether stars in other open clusters (with different ages, binary fractions, metallicities, ...) also display a tight relation such as the one found for NGC 6231. A similar, although slightly larger, dispersion was found in a recent study of the O-stars in the Carina OB1 association (Antokhin et al. 2008).

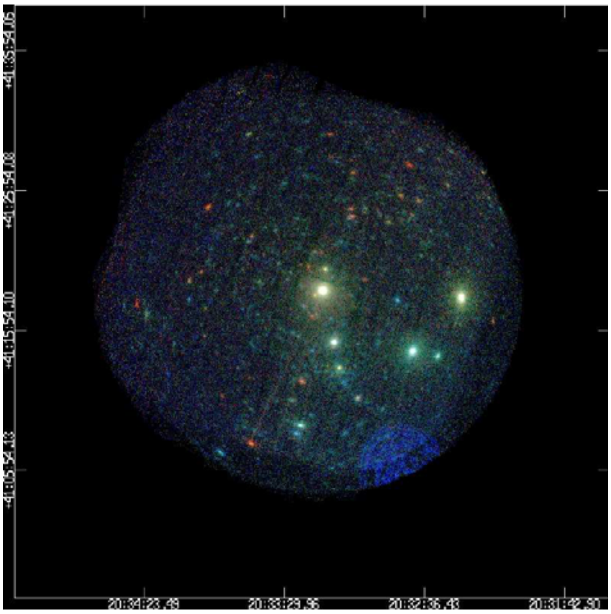

Fig. 3 (online colour at: www.an-journal.org) EPIC observation of the Cyg OB2 association. Whilst the brightest sources in the field of view are associated with O-type stars, there is a wealth of secondary sources most likely associated with pre-main sequence stars (from Rauw, De Becker & Linder 2005).

So far, 8 clusters containing at least 5 O-stars have been observed with XMM-Newton or Chandra, but not all of them are well suited for this purpose (spatial confusion, exposure times too short, lack of appropriate optical characterization of the cluster members, ...). In the WEBDA database, there are 8 more spatially resolved very young open clusters that are rich in O-stars and have not yet been observed. Some of them contain O-type stars over the full range of spectral types (and hence masses) from O2 to O9 and would be ideal for a detailed investigation with XMM-Newton.

The observations of these very young open clusters is also important for a deeper understanding of the low-mass star formation activity in an environment rich in early-type stars with their strong UV radiation (see e.g. Rauw et al. 2003; Sana et al. 2007; Guarcello et al. 2007). Indeed, X-ray observations of these clusters (e.g. Fig. 3) reveal a wealth of secondary sources (sometimes flaring) associated with a population of low-mass pre-main sequence objects (essentially weak-line T Tauri stars).

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4 Probing the X-ray variability of interacting wind binaries

To the level of accuracy of current and previous X-ray observations of early-type stars, X-ray variability is mainly a characteristic of colliding and/or interacting wind binaries. The main X-ray features of colliding wind binaries are (1) a higher X-ray luminosity than expected from the sum of the intrinsic contributions of the two components of the binary, (2) a modulation of the X-ray flux due either to the changing amount of wind absorbing material along the line of sight or to a changing orbital separation, and (3) a harder emission than the usual $kT = 0.5$ keV plasma.

A sample of Galactic O + O and WR + O binaries have been monitored (mainly with XMM-Newton) over a substantial part of their orbit, providing phase-resolved (CCD) X-ray spectroscopy of these systems (e.g. Sana et al. 2004; De Becker et al. 2006; Pollock & Corcoran 2006). These observations provide a unique data set for comparison with theoretical models. In relatively long-period binaries with a rather wide orbital separation, the spectra usually reveal a rather hot plasma (kT of order 2 keV) which is most likely heated by the shock resulting from the collision of the two stellar winds. However, the light curves reveal quite different behaviours. For instance, the O6f + O5.5(f) system Cyg OB2 #8a ($P_{\rm orb} = 21.9$ d, $e = 0.24$) displays its maximum X-ray flux when the secondary with the weaker (and hence less dense) wind is in front. This modulation thus most likely reflects the changing optical depth along the line of sight (De Becker et al. 2006). On the other hand, the WN6ha + O system WR 25 ($P_{\rm orb} = 208$ d, $e = 0.56$) displays variations of its X-ray emission by at least a factor 2 and the flux is maximum around periastron which, to first order, is indeed the $1/d$ behaviour (where d is the orbital separation) one would expect theoretically for a long-period colliding wind binary (Stevens, Blondin & Pollock 1992). Recently, XMM-Newton monitored, for the first time, the variations of the X-ray flux of an interacting wind system outside our Galaxy: Nazé et al. (2007) reported on phase-dependent variations of the X-ray flux of the Wolf-Rayet binary HD 5980 in the Small Magellanic Cloud. These data provide important insight into the wind interaction in this enigmatic binary that underwent an LBV-like eruption in 1994.

Phase-resolved XMM-Newton spectroscopy of interacting wind binary systems thus provides important information on the physics of these interactions, and can help us assess the actual mass-loss rates in these binaries.

5 Conclusions

Over the next decade, the main contributions of the XMM-Newton observatory to the field of early-type stars research most likely concern (1) the collection of higher quality RGS spectra of a limited sample of X-ray bright early-type stars, (2) the investigation of the overall X-ray properties of a large sample of stars through observations of spatially resolved open clusters, and (3) investigations of the time variability of early-type stars and more specifically of interacting wind binaries. XMM-Newton clearly has the potential to make major contributions to these fields.

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References

Antokhin, I.I., Rauw, G., Vreux, J.-M., van der Hucht, K.A., Brown, J.C.: 2008, A&A 477, 593
Berghöfer, T.W., Schmitt, J.H.M.M., Cassinelli, J.P.: 1996, A&AS 118, 481
Berghöfer, T.W., Schmitt, J.H.M.M., Danner, R., Cassinelli, J.P.: 1997, A&A 322, 167
Cohen, D.H., Leutenegger, M.A., Grizzard, K.T., Reed, C.L., Kramer, R.H., Owocki, S.P.: 2006, MNRAS 368, 1905
De Becker, M., Rauw, G., Sana, H., Pollock, A.M.T., Pittard, J.M., Blomme, R., Stevens, I.R., van Loo, S.: 2006, MNRAS 371, 1280
Donati, J.-F., Babel, J., Harries, T.J., Howarth, I.D., Petit, P., Semel, M.: 2002, MNRAS 333, 55
Gagné, M., Oksala, M.E., Cohen, D.H., Tonnesen, S.K., ud-Doula, A., Owocki, S.P., Townsend, R.H.D., MacFarlane, J.J.: 2005, ApJ 634, 712
Guarcello, M.G., Prisinzano, L., Micela, G., Damiani, F., Peres, G., Sciortino, S.: 2007, A&A 462, 245
Leutenegger, M.A., Paerels, F.B.S., Kahn, S.M., Cohen, D.H.: 2006, ApJ 650, 1096
Long, K.S., White, R.L.: 1980, ApJ 239, L65
Mewe, R., Raassen, A.J.J., Cassinelli, J.P., van der Hucht, K.A., Miller, N.A., Güdel, M.: 2003, A&A 398, 203
Nazé, Y., Corcoran, M.F., Koenigsberger, G., Moffat, A.F.J.: 2007, ApJ 658, L25
Oskinova, L.M., Feldmeier, A., Hamann, W.-R.: 2006, MNRAS 372, 313
Owocki, S.P., Castor, J.I., Rybicki, G.B.: 1988, ApJ 335, 914
Owocki, S.P., Cohen, D.H.: 1999, ApJ 520, 833
Pollock, A.M.T.: 2007, A&A 463, 1111
Pollock, A.M.T., Corcoran M.F.: 2006, A&A 445, 1093
Porquet, D., Mewe, R., Dubau, J., Raassen, A.J.J., Kaastra, J.S.: 2001, A&A 376, 1113
Rauw, G.: 2006, in: A. Wilson (ed.), *The X-ray Universe 2005*, ESA SP-604, p. 7
Rauw, G., De Becker, M., Linder, N.: 2005, in: G. Rauw et al. (eds.), *Massive Stars and High-Energy Emission in OB Associations*, JENAM 2005, p. 103
Rauw, G., De Becker, M., Gosset, E., Pittard, J.M., Stevens, I.R.: 2003, A&A 407, 925
Sana, H., Stevens, I.R., Gosset, E., Rauw, G., Vreux, J.-M.: 2004, MNRAS 350, 809
Sana, H., Rauw, G., Nazé, Y., Gosset, E., Vreux, J.-M.: 2006, MNRAS 372, 661
Sana, H., Rauw, G., Sung, H., Gosset, E., Vreux, J.-M.: 2007, MNRAS 377, 945
Seward, F.D., Forman, W.R., Giacconi, R., Griffiths, R.E., Harnden, F.R.Jr., Jones, C., Pye, J.P.: 1979, ApJ 234, L55
Stevens, I.R., Blondin, J.M., Pollock, A.M.T.: 1992, ApJ 386, 265

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