X-rays from massive OB stars: thermal emission from radiative shocks

Svetozar A. Zhekov1* and Francesco Palla2⋆

1Space Research Institute, Sofia-1000, Moskovska str. 6, Bulgaria
2INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy

ABSTRACT

Chandra grating spectra of a sample of 15 massive OB stars were analysed under the basic assumption that the X-ray emission is produced in an ensemble of shocks formed in the winds driven by these objects. Shocks develop either as a result of radiation-driven instabilities or due to confinement of the wind by a relatively strong magnetic field, and since they are radiative, a simple model of their X-ray emission was developed that allows a direct comparison with observations. According to our model, the shock structures (clumps, complete or fractional shells) eventually become ‘cold’ clouds in the X-ray sky of the star. As a result, it is expected that for large covering factors of the hot clumps, there is a high probability for X-ray absorption by the ‘cold’ clouds, resulting in blueshifted spectral lines. Our analysis has revealed that such a correlation indeed exists for the considered sample of OB stars. As to the temperature characteristics of the X-ray emission plasma, the studied OB stars fall in two groups: (i) one with plasma temperature limited to ∼0.1–0.4 keV and (ii) the other with X-rays produced in plasmas at considerably higher temperatures. We argue that the two groups correspond to different mechanisms for the origin of X-rays: in radiation-driven instability shocks and in magnetically confined wind shocks, respectively.

Key words: shock waves – stars: early-type – stars: winds, outflows – X-rays: stars.

1 INTRODUCTION

The present concept on the origin of X-rays in massive OB stars posits that they are emitted by hot gas heated by shocks (Lucy & White 1980; Lucy 1982). OB stars possess massive and fast winds driven by radiation pressure (e.g. Castor, Abbott & Klein 1975) and subject to instabilities [radiation-driven instabilities (RDI), Owocki & Rybicki 1984] which may give rise to the formation of strong shocks (Owocki, Castor & Rybicki 1988; Feldmeier, Puls & Pauldrach 1997). The resulting emission is expected to be relatively soft (plasma temperatures $kT < 1$ keV), while the X-ray lines formed in the optically thick outflowing gas are predicted to be blueshifted and asymmetric due to the different absorption of the red and the blue part of the line profiles (Ignace 2001; Owocki & Cohen 2001).

Recently, it has been suggested that the presence of magnetic fields may be an important ingredient for the X-ray production mechanism in very young massive stars (Babel & Montmerle 1997; ud-Doula & Owocki 2002). The main physical effect of an ordered magnetic field is to channel the stellar wind towards the equatorial plane where the flows from the opposite stellar hemispheres collide, leading to the formation of strong shocks. The basic feature of the so-called magnetically confined wind shock model (MCWS) is that the X-ray emission should be much harder (plasma temperatures $kT > 1$ keV) than that originating from the RDI shocks, and that the X-ray line profiles should be narrower (linewidths as small as one-fourth of the stellar wind velocity).

With the launch of the Chandra and XMM–Newton observatories, the quality of the X-ray data on OB stars has improved considerably, making it possible to test models of the origin of X-ray emission. Amongst the more than a dozen OB stars with gratings spectra of acceptable quality, only one object, ζ Puppis, shows unambiguous blueshifted spectral lines with asymmetric profiles (Cassinelli et al. 2001; Kahn et al. 2001). On the other hand, there are two objects, θ1 Ori C (Schulz et al. 2000, 2003; Gagne et al. 2005) and r Sco (Cohen et al. 2003), in which a clear manifestation of the MCWS effects is observed. While the scarcity of the MCWS-type objects might be accounted for by their youth and the expected decay of the magnetic field strength with the age of the massive star (Schulz et al. 2003), the standard RDI shock model needs further refinements to bring theory in accord with observations.

The fact that most OB stars show no appreciable line shifts and asymmetric profiles is an obvious indication that their winds are much more transparent in X-rays than originally believed. This result, along with the small filling factors of the X-ray emitting plasma in OB stars as found in previous (ROSAT) studies (Kudritzki et al. 1996), lends support to a physical picture in which the stellar winds are clumpy and/or porous. Alternatively, if the winds are smooth and homogeneous, the mass-loss rates should have values

*E-mail: szhekov@space.bas.bg (SAZ); palla@arcetri.astro.it (FP)
Wind clumping and porosity effects on the X-ray emission from OB stars, and specifically on the shape of the line profiles, have been explored in recent analytical and numerical models (e.g. Feldmeier, Oskinova & Hamann 2003; Oskinova, Feldmeier & Hamann 2004, 2006; Owocki & Cohen 2006). It has been shown that under given conditions (such as reduced mass loss and assumed ‘typical’ distance between clumps) their inclusion may lead to results much more consistent with the observations. Given the complexity of these models and the fact that they are not yet fully self-consistent, it is important to gather empirical information about the physical conditions in the regions responsible for the X-ray emission to put further constraints on numerical models.

Various diagnostics have been used in this respect: analysis of helium-like triplet ratios, global fits with discrete-temperature models, constructing a distribution of emission measures (DEMs) as a function of temperature, based on fits to individual-line fluxes and to the total X-ray spectra (Waldron & Cassinelli 2000; Cassinelli et al. 2001; Kahn et al. 2001; Miller et al. 2002; Cohen et al. 2003; Schulz et al. 2003; Sanz-Forcada, Franciosini & Pallavicini 2004; Wodjowski & Schulz 2004; Gagne et al. 2005; Wodjowski & Schulz 2005; Leutenegger et al. 2006). These studies indicate that X-rays are produced close to the stellar surface (likely, in the wind acceleration zone), and that the corresponding hot plasma has a temperature stratification. The latter point reinforces the idea that the X-ray emission originates in an ensemble of shocks.

Guided by this background, we have developed a simple model which bears all the basic characteristics of the X-ray production in wind shocks. The model is described in Section 2; the data sample is given in Section 3; the results are presented in Section 4 and discussed in Section 5. The conclusions close this paper.

2 MODEL

As in the case of the RDI and the MCWS models, our basic assumption is that the X-ray emission of hot massive stars originates in shocks. Given the relatively high densities in the wind, the energy losses by the shock-heated plasma are considerable: thus, shocks should be radiative. This conclusion follows from simple estimates which show that the typical cooling time of a parcel of gas at the post-shock temperature and density is smaller than the typical dynamical time of the flow. Namely, for the shock position at a distance \( r \) from the star, the ratio of the cooling time \( t_c = \frac{\tau}{\rho v}/Q_c \) to the dynamic time of the flow \( (t_d = R/c) \) is

\[
\frac{t_c}{t_d} = 1.58 \times 10^{-2} \tau_{16} \left( \frac{r}{R_\odot} \right) \frac{v_{1000} M_6}{T_{sh}^2},
\]

and the ratio of the thickness of the radiative shock (i.e. the cooling length of a parcel of hot gas at the post-shock temperature: \( l_c = \frac{2}{3} \log_2(t_c) \) and shock ‘radius’ is:

\[
\frac{l_c}{r} = 3.59 \times 10^{-3} \tau_{16} \left( \frac{r}{R_\odot} \right) \frac{v_{1000} M_6}{T_{sh}^3},
\]

where \( T_{sh} \) is the post-shock temperature given in keV, \( v_{1000} \) is the terminal stellar wind velocity (in units of 1000 km s\(^{-1}\)) and \( M_6 \) is the stellar mass loss (in units of \( 10^{-6} M_\odot \) yr\(^{-1}\)). For a strong shock, the relation between the post-shock temperature (in keV) and the shock velocity (in units of 1000 km s\(^{-1}\)) is given by \( T_{sh} = 1.956 v_{1000}^2 \mu M_6 \), and \( \mu \) is the mean atomic weight. The relative number density of hydrogen is assumed \( n_H = 0.9 \); thus, the relative electron number density is \( n_e = 1.1 \) for a fully ionized plasma. The gas-dynamical quantities and the cooling function are described in Section 2.1.

For typical mass-loss rates \( (M_6 \approx 0.1−1) \) and wind velocities \( (v_{1000} \approx 1.5−2.5) \), the cooling time and the cooling length of a shock developed in a wind are appreciably smaller than the corresponding typical characteristics of the flow (see equations 1 and 2). This is true for post-shock temperatures below 1 keV (i.e. shock velocities smaller than 1000 km s\(^{-1}\) for solar abundances) and shock locations from a few to several tens of stellar radii. Therefore, the assumption of a steady state, plane–parallel, radiative shock is a good approximation for our analysis. This conclusion finds support in numerical simulations of both the RDI and the MCWS models. In fact, as a result of efficient cooling, the shocks ‘collapse’ in geometrically thin shells and disc-like structures, respectively (e.g. Feldmeier et al. 1997; ud-Doula & Owocki 2002; Gagne et al. 2005).

The description of our shock model and the ensemble of shocks is given below. The models were then used in the recent version (11.3.2) of the software package for analysis of X-ray spectra, XSPEC (Arnaud 1996). A global-fit approach was adopted in our analysis for the following reasons: (i) the fit can automatically take into account the quasi-continuum due to numerous weak lines; (ii) by fitting the shape of the underlying continuum, the model places additional constraints on the plasma temperature; (iii) the model can constrain the column density of the X-ray absorbing gas and (iv) it can yield estimates of relative element abundances. Finally, the X-ray emission is assumed to originate from a hot optically-thin plasma in collisional ionization equilibrium (CIE), as is the case for various types of astrophysical objects, including hot massive stars (e.g. Paerels & Kahn 2003).

2.1 Shock model

We consider a steady state, plane–parallel, radiative shock moving in a gas with adiabatic index \( \gamma = 5/3 \). The basic physical quantities of the flow (density or nucleon number density, velocity and pressure) have their standard post-shock values for a strong shock:

\[
\rho_s = 4 \rho_0 n_{ab} = 4n_0,
\]

\( v_s = \frac{v_0}{4} \), and \( p_s = \frac{3}{4} \frac{\rho v_0^2}{\gamma - 1} \), where the subscript ‘0’ denotes the pre-shock values (the gas velocity is given in the rest frame of the shock front). The mass and momentum conservation equations that describe the downstream flow are:

\[
\begin{align*}
\frac{d}{d\xi} \left( \frac{\rho v^2 + \rho \frac{v^2}{2}}{\gamma - 1} \right) &= -Q_c, \\
\frac{d}{d\xi} (\rho v) &= 0, \\
\frac{d}{d\xi} (\rho v^2) &= 0,
\end{align*}
\]

where \( \xi \) is the distance downstream from the shock front and \( Q_c \) is the cooling due to the optically thin, hot plasma in CIE.

In the steady-state case, when cooling is efficient, the temperature decreases and the density increases downstream from the shock front. The cooling layer eventually ‘collapses’, that is, the gas velocity asymptotically reaches zero. It follows (see the momentum equation) that the gas pressure does not experience large variations in the post-shock plasma \( (3/4 \leq p_s/\rho_s v_s^2 \leq 1) \). Thus, we adopt a constant-pressure approximation (CPA) to describe the physical parameters of the post-shock plasma. As we will see below, this allows us to easily make use of the radiative shock model in the analysis of the X-ray emission. Under the CPA, the energy equation reads

\[
\frac{d}{d\xi} \left( \frac{\rho v^2 + \rho \frac{v^2}{2}}{\gamma - 1} \right) = -Q_c,
\]

where the cooling term is given explicitly, \( T \) is the plasma temperature, \( k \) is the Boltzmann constant, \( n_e = n_t/n \) is the relative electron
number density, \( n_h = n_0/\epsilon \) is the relative number density of hydrogen and \( \varLambda(T) \) is the cooling function at CIE (e.g. Raymond, Cox & Smith 1976). To facilitate the calculations, we followed a standard approach and made use of a piece-wise power-law approximation to the cooling curve: \( \varLambda(T) = \varLambda_0 T^\beta \). In the high-temperature interval \( (10^7 \leq T \leq 10^7) \), the adopted values of the constants are \( \varLambda_0 = 7 \times 10^{-19}, 3 \times 10^{-27} \) and \( \beta = -0.6, 0.5 \) (e.g. Myasnikov, Zhekov & Belov 1998).

Fig. 1 shows a comparison between the exact and the CPA solutions for the radiative shock, and illustrates that our choice (CPA) is acceptable for the purpose of this study. Moreover, as we will see below, the CPA allows an easy incorporation of the radiative shock model in XSPEC which, unfortunately, is not the case for the exact solution of the problem.

To determine the X-ray spectrum from a steady state, plane-parallel, radiative shock (with ‘surface’ \( A \)), we must integrate the hot plasma emissivity over a range of plasma temperatures in the temperature-stratified post-shock zone (Fig. 1):

\[
Sp(E) = A \int_0^{T_n} \epsilon(E, T) n_x n_H^2 \, d\xi, \tag{4}
\]

where \( \epsilon(E, T) \) is the specific emissivity at given photon energy \( E \) and plasma temperature \( T \) (its integral over the entire energy/spectral range gives the value of the cooling curve at \( T \)), \( \xi \) is the distance from the shock front, and \( T_n \) is the post-shock temperature in keV. Using equation (3), we can then write:

\[
Sp(E) = \varGamma_{sh} \int_0^{T_n} \epsilon(E, T) T^{1-\alpha} \, d\ln T, \tag{5}
\]

where for numerical convenience, we integrate over \( \ln T \) instead of \( T \), and \( \varGamma_{sh} \) is the normalization parameter. In this form, the X-ray spectrum from a radiative shock is well suited for modelling with XSPEC: namely, we simply have a known power-law DEM at various temperatures, and we adopt an optically-thin plasma model (model \textsc{vpe} in XSPEC) for the plasma spectrum at temperature \( T \) (given by the quantity \( \epsilon(E, T) \)). Thus, our XSPEC shock model has the following parameters: the post-shock temperature \( T_{sh} \), chemical abundances and the normalization factor \( \varGamma_{sh} \), which is related to the total emission measure in the shock (some technical details are found in Appendix A).

2.2 Global model

Our global model assumes that X-rays are produced in radiative shocks which are randomly (and uniformly) distributed in the stellar wind, most likely in the acceleration zone. Therefore, the spectral lines in the total (integrated) X-ray spectrum from shocks are broadened by the bulk (wind) gas velocity, but are not shifted without including absorption. Qualitative physical considerations, also demonstrated by numerical modelling (e.g. Owocki & Cohen 2001), show that the X-ray absorption effects in the stellar wind result in blueshifted spectral lines with asymmetric line profiles.

To describe this physical situation, we have constructed a new XSPEC model, whose technical aspects are given in Appendix A. The main features of the model are as follows. (i) Shocks are characterized by their post-shock temperature, and the distribution of the total emission measures in the shocks is determined from the Chebyshev polynomial algorithm, as is used in the standard XSPEC model \textsc{c6vpmkl} (Lemen et al. 1989). We note that a similar approach was successfully adopted in fitting the X-ray emission from an ensemble of adiabatic shocks (Zhekov et al. 2006). (ii) The basis vectors for X-ray emission from the shock ensemble are those from the radiative shock model incorporated in XSPEC (see Section 2.1). (iii) All shocks have the same elemental abundances and share the same spectral line shifts. Thus, the basic model parameters are: the DEM of radiative shocks; chemical abundances and the global line shift for the spectrum.

The profile asymmetry is handled through two (half) Gaussians each approximating the blue and the red halves of the line profile. The Gaussian widths can vary with wavelength (in the same manner as in the XSPEC model \textsc{gsMOOTH}: \( \Delta E \propto E^\beta \)). Although the goal of our approach is just to obtain best fits to the line profiles over the entire spectrum, it is worth noting that the wavelength dependence of the linewidth represents the physical notion that faster shocks produce higher-temperature plasma whose emission is dominated by lines at shorter wavelengths.

3 X-RAY DATA

For our study, we selected a sample of OB stars with available gratings observations in the Chandra data archive. We extracted first-order spectra for each object according to the procedure described in the Science Threads for Grating Spectroscopy in the CIAO data analysis software. The ancillary response functions for all spectra were generated using the Chandra calibration data base CALDB v3.2. Table 1 gives some basic information about the stars of the sample and the X-ray observations. Our analysis is based on the Medium Energy Grating (MEG) spectra to take advantage of their higher sensitivity compared to the High Energy Grating (HEG) spectra. One object (Spica) was observed with the Chandra Low Energy Transmission Grating (LETG).

Depending on the quality of the data (the total number of photons), the MEG spectra were rebinned to have between 15 and 30 counts per bin. The spectra near the intercombination and the forbidden lines in the helium-like triplets (\( \text{Si}^{\text{XIII}}, \text{Mg}^{\text{XI}}, \text{Ne}^{\text{IX}} \) and \( \text{O}^{\text{VII}} \)) were rebinned so that these two lines fall into one large bin. This technical approach is aimed at improving the quality of the fit when optically thin plasma models (as those available in XSPEC) are used that do not take into account the effects of a strong external ultraviolet (UV) field. In the case of hot massive stars, such a UV field is
Table 1. OB stars with Chandra grating spectra.

| Numbers | HD   | Name  | Typea | Distanceb (pc) | Observation IDs | Counts c (MEG) | Data d |
|---------|------|-------|-------|----------------|----------------|---------------|--------|
| 1       | 150136 | ζ Pup | O3    | 1300           | 2569           | 8569          | 8      |
| 2       | 66811 | θ 1 Ori C | O4-6p | 450            | 3, 4           | 28719; 13706  | 3, 6, 7, 11 |
| 3       | 37022 | η Ori A | O9V   | 140            | 2571, 4367    | 5915          |        |
| 4       | 149757 | ζ Oph | O9i   | 501            | 639            | 6116          | 4, 11  |
| 5       | 39486 | δ Ori A | O9.5 II | 501           | 610            | 9220          | 10, 11 |
| 6       | 37742 | ζ Ori A | O9.7 Iib | 412        | 3753           | 6811          |        |
| 7       | 37128 | δ Ori | B0lab | 132            | 638            | 16838         | 2, 11  |
| 8       | 149438 | τ Sco | B0.2 V | 800            | 1888, 1889    | 1597          | 5, 11  |
| 9       | 206267A | O6.5 V | 767            | 5401, 6247    | 1631          |        |
| 10      | 47839 | 15 Mon | O7 V   | 480            | 2525, 2526     | 1470          | 5, 11  |
| 11      | 57061 | η CMa | O9 II  | 440            | 599, 2420     | 4934          | 11     |
| 12      | 37043 | ι Ori | O9 III | 353            | 3738           | 1893          | 9      |
| 13      | 37468 | ζ Ori AB | O9.5 V | 110            | 2575           | 1830          | 11     |
| 14      | 111123 | θ Cru | B0.5 III | 80            | 4509           | 3041          |        |
| 15      | 116658 | Spica | B1 III-IV | 80           | 4509           | 3041          |        |

aSpectral type is from Wojdowski & Schulz (2005) except for HD 150136, ζ Oph, ϵ Ori, 15 Mon, σ Ori AB and Spica whose spectral type is from SIMBAD.
bValues of the distance are taken from Wojdowski & Schulz (2005) except for HD 150136 (Herbst & Havlen 1977), and ζ Oph, ϵ Ori, 15 Mon, σ Ori, and Spica (from the Jim Kaler’s ‘STARS’ web site: http://www.astro.uiuc.edu/~kaler/sow/sowlist.html).
cThe total number of counts in the Chandra MEG background-subtracted spectra. Thanks to the X-ray brightness of θ 1 Ori C, the two observations were analysed separately. The data for Spica were obtained with the Chandra LETG.
dReferences to the articles where the X-ray spectra of the stars are discussed in detail: (1) Cassinelli et al. (2001); (2) Cohen et al. (2003); (3) Gagne et al. (2005); (4) Miller et al. (2002); (5) Schulz (2003); (6) Schulz et al. (2000); (7) Schulz et al. (2003); (8) Skinner et al. (2005); (9) Skinner et al. (in preparation); (10) Waldron & Cassinelli (2000); (11) Wojdowski & Schulz (2005).

4 RESULTS

The X-ray spectra (MEG) of the stars from our sample (see Table 1) were fitted with the global model that assumes a distribution of radiative shocks in the stellar wind (Section 2.2). To determine the elemental abundances, we varied only those having strong emission lines in the observed spectrum of a given object. These usually include N, O, Ne, Mg, Si and Fe, while for some objects C and S were also varied. For the abundance of all the other elements, the solar value was adopted (Anders & Grevesse 1989). Finally, to derive the X-ray absorption column density towards each object, we made use of Morrison & McCammon (1983) cross-sections (XSPEC model WABS).

Table 2 presents some basic results from the fits to the spectra of the studied stars: the total χ² and the degrees of freedom for the fit (2nd column); the X-ray absorption column density (3rd column); the individual elemental abundance relative to the solar value (columns 4–10); the observed and unabsorbed X-ray flux (last columns). The corresponding distributions of emission measure of the radiative shocks in the stellar winds are shown in Fig. 2. The quality of the global fits in the vicinity of some strong emission lines is illustrated in Fig. 3. A few properties are worth noting.

There is an indication that the metal abundances are subsolar in the sample of OB stars with grating spectra, and this trend is well demonstrated by the iron abundance being a factor of 2–3 below the solar value. Nitrogen might be considered an exception but we note that the poor quality of the data in the soft part of the X-ray spectra, where the nitrogen lines are found, prevents a firm conclusion. The values of the column density of the X-ray absorption material are consistent with those derived from the visual extinction to each object, using data from Berghofer, Schmitt & Cassinelli (1996) and the Gorenstein (1975) conversion formula. The only object showing a clear sign of excess absorption with respect to its interstellar value is ζ Pup which may suggest that wind absorption effects play an important role in this object.

We see that most stars display the same DEM of the radiative shocks, peaked at ~0.1–0.4 keV and with a very low level of high-temperature tail extending above 1.0 keV. Thus, in most cases X-rays are produced in low-velocity shocks. This finding is consistent with the radiation-driven instabilities scenario. The two most notable exceptions are θ 1 Ori C and τ Sco. In the former case, the main peak is at energy ~4–5 keV with a weaker component at ~0.8 keV. The case of τ Sco is more peculiar since there appear to be three peaks: one at very low energies, the main one at ~0.7 keV and some emission above ~3 keV. One could argue that the hot tail in the DEM in these objects is due to the MCWS while the cool component comes from the RDI shocks. For example, the shape of the emission measure distribution in θ 1 Ori C is stable between the two data sets (taken at two different times) and only the total amount of the hot gas changed mostly in the high-temperature component (Fig. 2). We note that this finding is in accord with the previous analysis of Chandra data (Schulz et al. 2003; Gagne et al. 2005). Such a different behaviour of the hot and the cool components might be an indication of their different origin, as mentioned above. However, it is necessary to obtain more data also on τ Sco, in order to establish whether such a behaviour is typical only for one object or has much more general validity. It should be noted that there is a third object in our sample of OB stars, ζ Oph, whose distribution of radiative shocks is relatively ‘hot’ and it peaks at ~0.5–0.6 keV.

The presence of considerably hotter plasma (therefore, fast velocity shocks), as definitely seen in θ 1 Ori C, τ Sco and ζ Oph,
in combination with the relatively narrow lines observed in their spectra could be assumed as a clear manifestation of the magnetically confined wind effects. It was recently proposed by Schulz et al. (2003) that the efficiency of the MCWS mechanism correlates with the age of the massive star. The relative youth of the first two objects (0.3 and ~1 Myr, see their table 4) and the small kinematic age of ζ Oph (~1 Myr, Hoogerwerf, de Bruijne & de Zeeuw 2001) indeed support this suggestion.

5 DISCUSSION

The radiative shock model introduced in this study allows us to deduce some important information on the global physical state of the X-ray emitting region of massive stars. As one can see from equation (A1), the normalization factor of the flux, $\Gamma_{ab}$, depends on the shock temperature ($T\text{sh}$), stellar wind parameters ($M_\ast$, $v_{\infty}$), and the distance to the object ($d_{\text{kpc}}$): $\Gamma_{ab} = 2.444 \left( \frac{M_\ast}{v_{\infty}} \right)^{\frac{3}{4}} \sqrt{T\text{sh}}$, so $\delta$ gives the effective surface of the shock.

Thus, from the results of the fits to the X-ray spectra, namely, using the $\Gamma_{ab}$ value and knowing the distance to each star, we can deduce some useful information on the structure of the stellar winds. To do so, we introduce a new quantity, $\delta \left( \frac{M_\ast}{v_{\infty}} \right)$, that is related to a specific shock, or to a group of shocks with the same velocity. We will refer to this quantity as the specific stellar ‘cloudiness’.

In our picture, the winds of hot massive stars are clumpy and the clumps are likely generated by radiation-driven instabilities, particularly efficient in the inner acceleration zone. The instabilities develop into strong shocks which are the source of X-rays. Since the shocks are radiative, the gas density in the cooling zone is much larger (probably by a factor of a few tens and more) than the local density of the smooth wind. Away from the acceleration zone, these shock structures (clumps, complete or fractional shells) expand and cool down even further, but the density contrast in their ‘tail’ zone will remain appreciably high. Eventually, the clumps become ‘cold’ clouds in the X-ray sky of the hot massive star, and in a steady-state picture there will be a correlation between their characteristics: for example, the higher the number of the hot clumps, the more numerous the ‘cold’ clouds; the higher the clumps’ covering factor, the higher the chance for X-ray absorption by the ‘cold’ clouds.

The specific stellar ‘cloudiness’ defined above is proportional to the quantities that determine the X-ray absorption efficiency of the cooling zones in the clumps and the cold clouds: namely, the geometrical extension of a cloud (the quantity $\delta$) and the cold gas density. The latter is proportional to the density of the smooth stellar wind, i.e. to the ratio of the mass loss to the wind velocity. Thus, one can use the total stellar ‘cloudiness’$^2$ in a given object, given by the sum of all the specific values, as a measure of the overall efficiency of the cold X-ray absorbers in the wind. In such a case, a correlation between the total ‘cloudiness’ and the line shift of the spectral lines might be altered appreciably, resulting in a blueshift of the spectral lines.

Notes: Fit results from the XSPEC model: WABS (gsim) (gsim states for the global shock model as described in Section 2.2). Derived for the each object emission measure distributions of radiative shocks are given in Fig. 2. The errors in the Table are 1σ. All abundances are expressed as ratios to their solar values (Anders & Grevesse 1989). Those without associated errors were kept fixed at their solar value.

$^a$The X-ray column density is in units of $10^{22}$ cm$^{-2}$.

$^b$Flux units are $10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The observed X-ray flux (0.3–8 keV) is followed in parentheses by the unabsorbed value.

$^c$The results are from a simultaneous fit to the both observations of this object. Such a model shares the same abundances for the both spectra and the other model parameters were varied individually for each data set.

$^d$The model fit is to the first-order LETG spectrum. Carbon abundance is C = 0.22 ± 0.10.
should be expected, in the sense that the larger the total ‘cloudiness’ the higher the amount of blueshift of the X-ray spectrum of the star.

Fig. 4 presents the results of our estimate of the total stellar ‘cloudiness’ versus the global line shifts in the X-ray spectra of the massive stars of our sample. These results indicate that the expected correlation does exist: winds from stars with high values of the covering factor display a larger amount of blueshift in the X-ray line profiles. Note that for many objects the errors derived from the fit can be appreciable. Unfortunately, the complexity of the model fits and the non-uniform quality of the data limit the accuracy on the derivation of the plotted quantities. An additional source of uncertainty comes from the ‘cloudiness’ parameter that depends on the accuracy of the cooling curve (see equation 5). However, the key point is that all the objects were analysed in a uniform way. Thus, future improvements in the atomic data (i.e. cooling curve) might only shift the scale, but they will not affect the observed trend that we believe is rather robust. More importantly, as can be seen in Fig. 4 appreciable redshifts of the spectral lines are not observed.

The observed correlation between the total stellar ‘cloudiness’ and the spectral line shifts reveals additional details about the

Figure 2. Emission measure distribution of radiative shocks in the OB stars of our sample. Horizontal axes are the immediate post-shock temperature in keV; vertical axes are the emission measure in units of $10^{56}$ cm$^{-3}$. In the case of $\theta^1$ Ori C, the results for ObsId 3 and ObsId 4 are shown by dotted and dashed lines, respectively.
X-ray emitting zone in hot massive stars. For example, from Fig. 4 and for typical mass-loss rates ($\dot{M}_b \approx 0.1–1$) and wind velocities ($v_{1000} \approx 1.5–2.5$), in most cases the ‘cloudiness’ parameter is small ($\delta \lesssim 1$). In other words, dense clumps/clouds do not completely cover the X-ray ‘sky’ of massive stars. This also means that the RDI instabilities (and the MCWS as well) do not affect a big part of their stellar winds.

Comparing the results for single and multiple systems, we note that the latter show higher values of the ‘cloudiness’ parameter; this could result from additional sources of X-ray emission, such as colliding wind shocks in binary stars (Luo, McCray & MacLow 1990; Stevens, Blondin & Pollock 1992; Myasnikov & Zhekov 1993). We have to keep in mind that the ‘cloudiness’ parameter is also a measure of the efficiency of the X-ray production. Therefore, if an extra source of X-rays exists in some object, then it will result in an effectively larger number of shocks representing the additional emission. This is the case for a binary system, where a higher value of that parameter is expected in comparison to a single star with the same spectral line shift.

Finally, the fact that no appreciable redshift of the X-ray line profiles is observed in any object indicates that the distribution of the absorbers in OB stars likely has a spherical (or axial) symmetry.
emitted by the underlying shocks. In such a case, the spectral lines of high coverage, these clouds can effectively absorb the X-rays eventually become ‘cold’ clouds in the X-ray sky of the star. In case structures (clumps, complete or fractional shells) cool down and zone of the stellar wind. Far from the formation region the shock from an ensemble of shocks that are most efficient in the acceleration the clouds in the stellar wind. Our analysis reveals that despite the ‘cloudiness’, which represents the X-ray absorption efficiency by numbers as in Table 1. The data point for objects with good photon statistics (total number of counts in the spectrum to the studied object are not taken into account in the error propagation). The errors of the total stellar ‘cloudiness’ follow from the 1σ errors for the total emission measure as derived in the fit, and the uncertainties of the distance.

Future observations with a high spectral resolution and a good photon statistics will give us an opportunity to further test these conclusions and to study the X-ray gas kinematics in greater detail. They will also show whether the ‘cloudiness’ parameter for a given object changes with time which might be an important characteristic of the mechanism that drives the wind instabilities responsible for the X-ray emission from massive stars.

6 CONCLUSIONS

Using the Chandra public archive, we have analysed the X-ray spectra of a sample of 15 massive OB stars. The basic assumption in this study is that the X-ray emission from such objects originates in shocks which develop in the stellar wind either as a result of radiation-driven instabilities or due to confinement of the wind by relatively strong magnetic field. The main results and conclusions are as follows.

(i) Based on the fast shock cooling in the winds of hot massive stars, we have developed a simple model of a steady state, plane-parallel radiative shock which has been incorporated in the software package for analysis of X-ray spectra, XSPEC.

(ii) The model is then used in a global analysis of the X-ray emission from the sample of OB stars with high-quality spectra obtained by Chandra. We assume that the X-ray emission originates from an ensemble of shocks that are most efficient in the acceleration zone of the stellar wind. Far from the formation region the shock structures (clumps, complete or fractional shells) cool down and eventually become ‘cold’ clouds in the X-ray sky of the star. In case of high coverage, these clouds can effectively absorb the X-rays emitted by the underlying shocks. In such a case, the spectral lines in the X-ray spectrum of the massive star will be blueshifted.

(iii) Using our model, we define a new quantity, the stellar ‘cloudiness’, which represents the X-ray absorption efficiency by the clouds in the stellar wind. Our analysis reveals that despite the large intrinsic uncertainties, there is a correlation between the stellar ‘cloudiness’ and the global line blueshifts in the observed X-ray spectra of the sample stars.

(iv) For each star, the model gives the DEM of the radiative shocks responsible for the observed X-rays. The sample of OB stars with good spectra is distinguished in two groups: (i) one with the DEM peaked at ~0.1–0.4 keV and with a very low level of high energy tail above 1.0 keV and (ii) one with the maximum of the DEM that falls at considerably higher temperatures. In the former case, the radiation-driven instability shocks are the likely mechanism for the production of X-rays, while in the latter (θ¹ Ori C, τ Sco and ζ Oph) the X-ray emission originates in magnetically confined wind shocks.

(v) The derivation of metal abundance indicates a subsolar metallicity for all the stars of the sample, with iron a factor of 2–3 below the solar value.

ACKNOWLEDGMENTS

Partial financial support from the Bulgarian Academy of Sciences – Consiglio Nazionale delle Ricerche bilateral cooperation programme is acknowledged. This research has made use of the NASA’s Astrophysics Data System, and the SIMBAD astronomical data base operated by CDS at Strasbourg, France.

REFERENCES

Anders E., Grevesse N., 1989, Geochimica et Cosmochimica Acta, 53, 197
Arnaud K. A., 1996, in Jacoby G., Barnes J., eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems. Astron. Soc. Pac., San Francisco, p. 17
Babel J., Montmerle T., 1997, ApJ., 485, L29
Berghöfer T. W., Schmitt J. H. M. M., Cassinelli J. P., 1996, A&AS, 118, 481
Cassinelli J. P., Miller N. A., Waldron W. L., MacFarlane J. J., Cohen D. H., 2001, ApJ, 554, L55
Castor J. I., Abbott D. C., Klein R. I., 1975, ApJ, 195, 157
Cohen D. H., de Messieres G. E., MacFarlane J. J., Miller N. A., Cassinelli J. P., Owocki S. P., Liedahl D. A., 2003, ApJ, 586, 495
Cohen D. H., Leutenegger M. A., Grizzard K. T., Reed C. L., Kramer R. H., Owocki S. P., 2006, MNRAS, 368, 1905
Feldmeier A., Puls J., Pauldrach A. W. A., 1997, A&A, 322, 878
Feldmeier A., Oskinova L., Hamann W.-R., 2003, A&A, 403, 217
Gagne 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, 628, 986
Gorenstein P., 1975, ApJ, 98, 95
Herbst W., Havlen R. J., 1977, A&AS, 30, 279
Hoogerwerf R., de Bruijne J. H. J., de Zeeuw P. T., 2001, A&A, 365, 49
Ignace R., 2001, ApJ, 549, L19
Kahn S. M., Leutenegger M. A., Cottam J., Rauw G., Vreux J.-M., den Boggende A. J. F., Mewe R., Güdel M., 2001, A&A, 365, L312
Kramer R. H., Cohen D. H., Owocki S. P, 2003, ApJ, 592, 532
Kudritzki R. P., Palsa R., Feldmeier A., Puls J., Pauldrach A. W. A., 1996, MPE Rep., 263, 9
Lemen J. R., Mewe R., Schrijver C. J., Fludra A., 1989, ApJ, 341, 474
Leutenegger M. A., Paerels F. B. S., Kahn S. M., Cohen D. H., 2005, ApJ, 628, 986
Lucy L. B., 1982, ApJ, 255, 286
Lucy L. B., White R. L., 1980, ApJ, 241, 300
Luo D., McCray R., MacLow M.-M., 1990, ApJ, 362, 267
Miller N. A., Cassinelli J. P., Waldron W. L., MacFarlane J. J., Cohen D. H., 2002, ApJ, 577, 951
Morrison R., McCammon D., 1983, ApJ, 270, 119
Myasnikov A. V., Zhekov S. A., 1993, MNRAS, 260, 221
Myasnikov A. V., Zhekov S. A., Belov N. A., 1998, MNRAS, 298, 1021

Figure 4. Total stellar ‘cloudiness’ versus global line shift for the OB stars of the sample. The error bars (dotted lines) are 1σ errors from the fit (the errors of the total stellar ‘cloudiness’ follow from the 1σ errors for the total emission measure as derived in the fit, and the uncertainties of the distance to the studied object are not taken into account in the error propagation). The objects with good photon statistics (total number of counts in the spectrum higher than 5000) are marked by triangles. Data points within circles are binaries or multiple systems (as identified in SIMBAD). Stars are identified by numbers as in Table 1. The data point for θ¹ Ori C (number 3) is the average of the two observations.
APPENDIX A: THE MODEL

The physical background of the radiative shock model was given in Section 2 along with the basic features of our global model that assumes a distribution of radiative shocks in the stellar wind of massive OB stars. Some technical details about these two models are described in this Appendix.

(i) Shock model. As discussed in Section 2.1, the X-ray spectrum of a parcel of gas downstream from the shock front is given by the emission from an optically-thin plasma in CIE. Thus, the total spectrum of a radiative shock is an integral over a range of plasma temperatures, $T \leq T_{sh}$, in the cooling zone (see equation 5), where $T_{sh}$ is the immediate post-shock temperature for a strong shock. As seen from equation (5), the emission measure in the cooling zone is a power-law function of temperature, $T$, and the spectrum at each value of $T$ is assumed to be that given by the APEC model in XSPEC.

The technical realization is based on the XSPEC subroutine SUMDEM with the Astrophysical Plasma Emission Code (APEC) switch ON. For convenience, the numerical integration is over common logarithms (d$logE$). The X-ray emission from plasma cooler than $300,000$ K is not taken into account.

Thus, our XSPEC model of the X-ray emission from a radiative shock has the following parameters: the post-shock temperature $T_{sh}$, chemical abundances and the normalization factor $\Gamma_{sh}$. As for all optically-thin plasma models in XSPEC, the model normalization is related to the emission measure of the hot plasma, and in this case, $\Gamma_{sh}$ gives the total emission measure (EM) in a radiative shock (for temperatures $T \leq T_{sh}$).

(ii) Global model. Our global model assumes that the X-rays from massive OB stars originate in an ensemble of radiative shocks (Section 2.2). We use Chebyshev polynomials algorithm (Lemen et al. 1989) to describe the smoothed DEM in this ensemble of shocks. Since the basic parameter for shocks is the immediate post-shock temperature, this distribution is computed relative to $T_{sh}$. Thus, the total EM in each shock of the ensemble is derived from the spectral fits. Note that the situation is similar in the XSPEC model C6PVMKL (which is based on Lemen et al. 1989) where the basic vectors are those giving the X-ray emission (spectrum) from optically-thin plasma in CIE. Here, the difference is that at each temperature $T_{sh}$, we have the X-ray spectrum from a radiative shock, as described in Section 2.1 and above. In the technical realization of the global shock model, the total X-ray spectrum is derived by integrating the spectra from radiative shocks over the range of post-shock temperatures. For convenience, this integration is over common logarithms (d$logT_{sh}$).

It should be noted that there is one important qualitative difference between the use of the global shock model and the model with DEM of optically-thin plasma (e.g. C6PVMKL in XSPEC) for interpreting the observed X-ray spectra. In the former case, the EM at a given temperature, $T_{sh}$, in the distribution is the total EM (including plasma with $T \leq T_{sh}$) in a radiative shock with velocity corresponding to this post-shock temperature. In the latter case, the EM is that of an isothermal hot gas at that given temperature in the distribution. If an object is studied whose X-ray emission originates in radiative shocks, as is the case of massive OB stars, and a model like C6PVMKL in XSPEC is adopted, it is not quite correct to assign a shock velocity to each temperature value in the hot gas distribution. This is because the hot plasma in a radiative shock is not isothermal (Section 2.1). Thus, the amount of hot gas at each temperature in the C6PVMKL distribution is the total contribution from all radiative shocks having some plasma at that temperature. This limitation is not present in our global shock model discussed in this work.

Additional advantage of the radiative shock model is that its normalization factor, $\Gamma_{sh}$, which gives the total emission measure in the shock, can be expressed through some of the basic shock parameters (as done in deriving equation 5 using equation 3). In the simplified picture of spherically-symmetric stellar winds, it is justified to assume that the shocks move radially, and their surface can be presented as a fraction, $\delta$, of the ‘local’ sphere: $\delta = \frac{4\pi R^2}{d X}$. Thus, the normalization parameter, $\Gamma_{sh}$ of our XSPEC model can be written as

$$\Gamma_{sh} = \frac{5A(1 + x_e)n_{sh}v_{sh}}{2\Lambda_0} \frac{10^{-14}}{4\pi R^2} \delta$$

(A1)

where $d X$ is the distance to the object in kpc, and all other quantities are defined in Section 2. The quantity $(10^{-14}/4\pi R^2)$ comes from the XSPEC normalization factor of the flux for optically-thin plasma models. Note that $\Gamma_{sh}$ does not depend on the shock radius since in the case under consideration the gas density, $n_{sh}$, goes as $R^{-2}$. Again, the relative number density of hydrogen is assumed $x_H = 0.9$ and $x_e = 1.1$ for a fully ionized plasma. For simplicity, in deriving equation (A1) we replaced the local wind velocity with the terminal speed which means that the effective surface of the shock (presented by $\delta$) has the ‘maximum’ value. We note that the quantity, $\delta$, may have values larger than unity since it represents the total area of the shocks with a particular velocity within the entire ensemble of shocks. Thus, once the value of the flux normalization parameter, $\Gamma_{sh}$, is derived from a spectral fit, it can be further used to gain insight into the physical picture, provided some of the stellar parameters are already known from other studies.

This paper has been typeset from a \TeX\ file prepared by the author.