X-rays from colliding stellar winds: the case of close Wolf–Rayet+O binary systems

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ABSTRACT
We have analysed the X-ray emission from a sample of close Wolf–Rayet+O (WR+O) binaries using data from the public Chandra and XMM–Newton archives. Global spectral fits show that two-temperature plasma is needed to match the X-ray emission from these objects, because the hot component (\(kT > 2\) keV) is an important ingredient of the spectral models. In close WR+O binaries, X-rays likely originate in colliding stellar wind (CSW) shocks, driven by the massive winds of the binary components. The CSW shocks in these objects are expected to be radiative because of the high density of the plasma in the interaction region. In contrast, our analysis shows that, in our sample of close WR+O binaries, the CSW shocks are adiabatic. This is possible only if the mass-loss rates of the stellar components in the binary are at least one order of magnitude smaller than the values currently accepted. The most likely explanation for the X-ray properties of close WR+O binaries is that their winds are two-component flows. The more massive component (dense clumps) has a role in the optical/ultraviolet emission from these objects, while the smooth rarefied component is a key factor in the X-ray emission from these objects.

Key words: shock waves – stars: Wolf–Rayet – X-rays: binaries – X-rays: stars.

1 INTRODUCTION
As first proposed by Prilutskii & Usov (1976) and Cherepashchuk (1976), regarding the origin of X-rays in massive Wolf–Rayet+O (WR+O) binaries, it is currently assumed that they arise in colliding stellar wind (CSW) shocks, which result from the interaction of the massive winds of the stars in the binary. The high wind velocities and high mass-loss rates of WR and O stars suggest that the CSW region is a luminous X-ray source. Thus, WR+O binaries are expected to be brighter (more luminous) in X-rays than single WR stars. In fact, this was found to be true in the early surveys of WR stars (Pollock 1987).

It is interesting to note that wide WR+O binaries are among the brightest WR objects in X-rays, and their grating spectra found with modern observatories (e.g. Chandra, XMM–Newton) show numerous lines of various ionic species that indicate thermal emission (Skinner et al. 2001; Raassen et al. 2003; Schild et al. 2004; Pollock et al. 2005; Zhekov & Park 2010b). Analyses of these data have confirmed that X-rays from CSW shocks are the most probable physical explanation for the X-ray emission from wide WR+O binaries (although, in some cases, what is observed might be more complex; Zhekov & Park 2010a,b).

However, from those early X-ray surveys (Pollock 1987), it can be seen that close WR+O binaries are not as luminous in X-rays as wide WR+O binaries. This is an important observation because the stellar wind parameters (which, in general, determine the X-ray emission from CSWs) are practically within the same range for both types of binary system.

As a possible resolution to this problem, Cherepashchuk (1990) proposed that most of the mass flux in the stellar wind of a WR star is in the form of dense clouds. These clouds freely penetrate the CSW region formed by the continuous component of the winds, and they do not contribute to the X-ray emission from the binary. Thus, in a close WR+O binary, only a small part of the stellar-wind gas (the continuous component) plays a role in the X-ray emission from the system. However, in a wide WR+O binary, the CSW region forms far from the stars, where the dense clouds have already expanded and ‘dissolved’ in the continuous component of the wind. Thus, the entire mass flux of the stellar wind contributes to the X-ray emission from the binary.

Because modern X-ray observatories (e.g. Chandra, XMM–Newton) provide us with data of much higher quality (in both sensitivity and spatial resolution) compared to data from previous X-ray missions, we have decided to explore the case of CSWs in close
2 SAMPLE OF CSW BINARYs

In the sample of close CSW binaries, we have included those objects of known WR+O binaries (van der Hucht 2001, see tables 18 and 19) with an orbital period smaller than 20–22 d. We have checked the archives of the modern X-ray observatories (e.g. Chandra and XMM–Newton) for available data on the sample thus defined. Some objects with X-ray detection are not included in our study and we mention, in particular, the following objects: WR 48 (because it is a suggested triple stellar system and its X-ray emission is quite complex; see Sugawara, Tsuboi & Maeda 2008); WR 43a (because it is in the core of NGC 3603, and thus the object cannot be resolved); WR 101k (because it is in the centre of the Galaxy and it is unresolved, as it is 1.8 arcsec from Sgr A; SIMBAD).

Table 1 presents the list of close CSW binaries considered in this work, and it summarizes some of their properties.

3 X-RAY DATA

Because the objects studied are not very bright in X-rays, we have made use of the available data from the Advanced Camera for Imaging Spectroscopy (ACIS-S) onboard Chandra and of the data from the European Photon Imaging Camera (EPIC; pn and MOS detectors) onboard XMM–Newton.

For the analysis of the ACIS-S data, we extracted the X-ray spectra following procedures in the Science Threads for Imaging Spectroscopy of the ciao1 4.3 data analysis software. The response functions and ancillary response functions for all spectra were generated using the Chandra calibration data base CALDB v4.4.2.

In order to extract the X-ray spectra from the EPIC (pn, MOS) data, we made use of the XMM–Newton SAS2 10.0.0 data analysis software. The SAS pipeline processing scripts emproc and epproc were executed in order to incorporate the most recent calibration files. The data were then filtered for high X-ray background, following the instructions in the SAS documentation (e.g. adopting typical threshold rates for high-energy background in pn and MOS: 0.4 and 0.2 cts s⁻¹, respectively). The SAS procedures rmfgen and arfgen were adopted in order to generate the corresponding response matrix files and ancillary response files for each spectrum. For each data set, the MOS spectra in this analysis are the sum of the spectra from the two MOS detectors.

Table 2 presents the basic information about the X-ray data of the objects in our sample of close CSW binaries. Here, we also give some details on the individual objects.

WR 46. There is one pointed observation of this object with XMM–Newton. The EPIC data are of good quality (no long background flares), and thus all the spectra (pn and combined MOS) were included in this analysis. This is the object with the shortest binary period in our sample (see Table 1), and thus the EPIC spectra are average (integrated) over the binary period (also, see Appendix A for a discussion of the variability issue).

WR 47. There are three pointed observations of this star in the XMM–Newton archive, only two of which (see Table 2) have been used in this study because the third showed considerable high-energy X-ray background rates. Both pn and MOS spectra have been included in the current analysis.

WR 139. There are six pointed observations of WR 139 carried out with XMM–Newton. Here, we have used the pn spectra of three of these that have good photon statistics. The basic reason for the lower

Table 1. Properties of the close WR+O binaries. The object name, spectral type, interstellar extinction, distance, orbital period and wind velocity are from the Eighth Catalogue of galactic Wolf–Rayet stars (van der Hucht 2001; \( A_V = 1.11A_I \)) with the following exceptions. (i) The wind velocity for WR 47 is the mean value for WN 6 stars from Eenens & Williams (1994) and that for WR 148 is from Nishimaki et al. (2008). (ii) The orbital period for WR 46 is from Marchenko et al. (2000) and that for WR 145 is from Muntean et al. (2009). (iii) The distance to WR 145 is that to Cyg OB2. The mass-loss rates are the mean values for each object, as found in the literature, with no clumping taken into account. The individual data were scaled correspondingly if derived at values for the distance to the object and/or its stellar wind velocity different from those adopted here. The references given are as follows: 1, Abbott et al. (1986); 2, Crowther, Smith & Hillier (1995); 3, Hamann & Koesterke (1998); 4, Hirv et al. (2006); 5, Kurosawa, Hillier & Pittard (2002); 6, Lamontagne et al. (1996) 7, Moffat et al. (1990); 8, Nishimaki et al. (2008); 9, Nugis, Crowther & Willis (1998); 10, Nugis & Lamers (2000); 11, Prinja, Barlow & Howarth (1990); 12, St-Louis et al. (1988); 13, St-Louis et al. (1993).

| Name   | Spectral type | \( A_V \) (mag) | Distance (kpc) | Period (d) | \( V_{\infty} \) (km s⁻¹) | \( M \) (M⊙ yr⁻¹) | References used for \( M \) |
|--------|---------------|----------------|----------------|------------|-----------------|----------------|----------------------------|
| WR 46  | WN3+OB        | 1.05           | 4.07           | 0.329      | 2450            | 9.94e-06       | 2, 3                      |
| WR 47  | WN6+O5        | 3.96           | 3.80           | 6.24       | 1660            | 2.30e-05       | 6, 7, 10, 12              |
| WR 139 | WN5+O         | 2.83           | 1.90           | 4.21       | 1600            | 1.70e-05       | 1, 4, 5, 8, 10, 11, 12, 13|
| WR 141 | WN5+O5        | 4.10           | 1.26           | 21.7       | 1550            | 2.48e-05       | 1, 8, 10                  |
| WR 145 | WN7/WCE+?     | –              | 1.70           | 22.55      | 1390            | 3.68e-05       | 1, 10                     |
| WR 148 | WN8+B3        | 2.58           | 8.28           | 4.32       | 1500            | 3.95e-05       | 8, 9, 12                  |
| WR 79  | WC7+O5-8      | 1.54           | 1.99           | 8.89       | 2270            | 5.59e-05       | 1, 6, 10, 11, 12          |

1 Chandra Interactive Analysis of Observations; http://cxc.harvard.edu/ciao/ 2 Science Analysis Software; http://xmm.esac.esa.int/sas/
There are two data sets in the Chandra 1.6–1.7 archive (binary phase 0.0) is the time of the maximum X-ray observations. The binary phase for each observation was calculated using the value for $T_0$ from Pourbaix et al. (2004) – the 9th Catalogue of Spectroscopic Binary Orbits – except for WR 46 (see notes to Table 1). The orbital ‘phase’ for WR 145 is assuming value 0.0 for the observation ID 0165360101 since no value for $T_0$ is available in the literature. The moment $T_0$ (binary phase 0.0) is the time of the maximum value for the radial velocity of the WR component in the binary system. The values for the orbital period in Pourbaix et al. (2004) are identical to those in Table 1, except for the values of WR 46 and WR 145. For these, we used more recent sources, as given in the notes to Table 1. The last column gives the references where the corresponding X-ray data have been already discussed in some detail: 1, Bhatt et al. (2010); 2, Fauchez, De Becker & Nazé (2011); 3, Gosset et al. (2011a); 4, Hénault-Brunet et al. (2011); 5, Nazé (2009). Unfortunately, because of the high X-ray background rate, only WR 141A was successfully fitted using a systematic approach to modelling these spectra can be to use a hydrodynamic CSW model. However, the quality of the current data (undispersed CCD spectra with not very good photon statistics for most of the spectra) is not a good basis for carrying out such a modelling in detail. This is the reason why we have decided to use conventional, discrete-temperature plasma, models for the global fits to the X-ray spectra of the objects in our sample. Thus, we adopted the optically thin plasma model apec in a recent version (11.3.2) of the XSPEC analysis package (Arnaud 1996). Because the shocked WR gas dominates the X-ray emission from CSWs in WR+O binaries (the mass loss of a WR star is about an order of magnitude higher than that of an O star), in the global spectral fits we kept the abundances of the chemical elements fixed to the values typical for WN and WC stars, respectively (van der Hucht, Cassinelli & Williams 1986). To derive the X-ray absorption towards each object, we used the Morrison & McCammon (1983) cross-sections (model wabs in XSPEC). It is also worth noting that we found X-ray absorption higher than that expected from the optical/ultraviolet (UV) observations. Because the interaction region in close CSW binaries should be located near the massive stars, it is realistic to attribute this extra X-ray absorption to the massive stellar winds of these objects. For the sake of simplicity, we have assumed that the extra absorption is a result of the stellar wind of the WR star in the system, because it is considerably more massive than that of its companion.

Thus, the models for our final global spectral fits consisted of a number of absorption and emission components. An absorption component is a result of the interstellar matter towards the studied object (model wabs in XSPEC). The value of the neutral hydrogen column density was kept fixed to the value based on the optical/UV observations (e.g. $A_v$ in Table 1) using the Gorenstein (1975) conversion ($N_H = 2.22 \times 10^{21} A_v$ cm$^{-2}$). In advance of our discussion of the derived results, we note that our conclusions from this study do not change if we use a more recent conversion ($N_H = 1.6-1.7 \times 10^{21} A_v$ cm$^{-2}$; Vuong et al. 2003; Getman et al. 2005). Emission components are represented with individual ‘wind’ absorption for each plasma component. The emission and ‘wind’ absorption components have the same abundances. We recall that in the framework of the CSW scenario, the discrete-temperature models represent qualitatively the temperature stratification of the interaction region (see section 5.2 in Zhekov 2007). We note that there are no objects in our sample of close CSW binaries that have elliptical orbits. This means that the amount of hot gas in the interaction region remains the same over an orbital period. So, for each object that had multiphase observations, we adopted the same model normalization for the corresponding plasma component. This is equivalent to a non-variable emission measure with the orbital phase (i.e. there is no variation in the intrinsic X-ray emission). Thus, we attribute a possible X-ray variability to the variable X-ray absorption with the orbital phase.

The X-ray spectrum of WR 141A was successfully fitted using a one-temperature model. We found that two-temperature models gave adequate global fits for the X-ray emission from all other WN and WC stars in the sample except for WR 46, for which we needed a three-temperature model. We note that the two-temperature model gave a statistically acceptable result, but it was not able to match all the spectral details in the spectrum (e.g. it produced almost no
emission for the Si XIII line complex at \( \sim 1.85 \text{ keV} \) and variable silicon abundances could not fix this problem. It is our understanding that a more complex model was needed in this case because of the good photon statistics of the WR 46 spectra (the best quality data in our sample). Also, we had no data on the interstellar absorption towards WR 145, so we fitted for the X-ray absorption in the global spectral fits for this object.

Fig. 1 and Table 3 present the results from the global fits to the X-ray spectra of our sample of close WR+O binaries. We see that the quality of the fits is acceptable, but we note that in many of the cases studied the formal quality of the fit \( (\chi^2/dof) \) is good probably because of the low photon statistics. Nevertheless, we note that the fits firmly establish that a considerable amount of hot-temperature plasma \( (kT > 2 \text{ keV}) \) is present in the objects studied. The ‘canonical’ WN and WC abundances adopted here (van der Hucht et al. 1986) seem to be an adequate approximation to the actual abundances in the objects studied. However, in this respect, it is worth mentioning a by-product from these fits. As seen from Fig. 1, the S XV line complex at \( \sim 2.45 \text{ keV} \) is not well matched by the current model. Our attempts to solve this problem – by adding an additional temperature component – were not successful. The only way to match the S XV ‘bump’ in the spectra was to adopt a variable sulphur abundance. Interestingly, the values for the S abundance derived from all fits are not widely spread but ‘cluster’ around a factor of 3 increase with respect to that in the ‘canonical’ WN and WC abundances. More specifically, the average sulphur abundance from all data sets is \( 2.97 \pm 0.33 \) (where the error is the error of the mean and not the variance). We note that the sulphur value in the van der Hucht et al. (1986) WN and WC abundances is based on the cosmic mass fraction (see the footnote to their table 1). Thus, we obtain an indication from the current analysis that the sulphur abundance in the ‘canonical’ WN and WC sets of abundances might need be increased by a factor of 3.

In the next section, we discuss the global fit results in the framework of the CSW scenario.

5 DISCUSSION

Although our sample of close WR+O binaries is limited, the adopted uniform way of analysing the X-ray emission from the objects studied provides useful information to check the global consistency of the CSW scenario in such objects. We note that our spectral analysis has adopted simplified models – those of discrete-temperature optically thin plasma (Section 4). This means that the X-ray emitting plasma is in collisional ionization equilibrium (CIE), that is, the non-equilibrium ionization (NEI) effects do not affect its emission. Also, the electron and ion temperatures are equal. We can use the corresponding characteristic plasma time-scales to check the validity of these assumptions in the case of close WR+O binaries.

For this purpose, two dimensionless parameters have been introduced: \( \Gamma_{\text{eq}} = \tau \tau_{\text{eq}} \) (Zhekov & Skinner 2000) and \( \Gamma_{\text{NEI}} = \tau \tau_{\text{NEI}} \) (Zhekov 2007). Here, \( \tau \) is the time-scale of the gas dynamics, \( \tau_{\text{eq}} \) is the electron–ion temperature equalization time and \( \tau_{\text{NEI}} \) is the representative NEI time-scale. We recall that the electron and ion temperatures are different if \( \Gamma_{\text{eq}} \leq 1 \), but their difference can be neglected if \( \Gamma_{\text{eq}} \gg 1 \). Similarly, the NEI effects must be taken into account if \( \Gamma_{\text{NEI}} \leq 1 \), but they can be neglected if \( \Gamma_{\text{NEI}} \gg 1 \).

For a total mass of the WR+O systems of 30–40 \( \text{M}_\odot \), we can use the Kepler third law, which is \( a = 2.928 \times 10^{13} \frac{P_{\text{orb}}^{3/2}}{(M/M_\odot)^{1/3}} \text{ cm} \) (where \( M \) is the total mass and \( P_{\text{orb}} \) is the orbital period in days; see Table 1), to estimate the typical length-scale for the gas-dynamic problem (e.g. the binary separation). Then, the stellar wind parameters from Table 1 \( (M, V_{\infty}) \), along with equation (1) in Zhekov \\& Skinner (2000) and equation (1) in Zhekov (2007), show the following. First, the plasma in the CSW shock in the close WR+O binaries considered here has equal electron and ion temperatures \( (\Gamma_{\text{eq}} \gg 1) \). Secondly, the NEI effects are not important in these objects \( (\Gamma_{\text{NEI}} \gg 1) \). All this makes us confident that the adopted spectral models in this study are adequate for the physical conditions of the X-ray emitting plasma in close WR+O binaries.

However, when fitting the total (‘integrated’) X-ray emission from temperature-stratified plasmas (e.g. present in the interaction region in CSW binaries) with discrete-temperature models, we can expect the derived plasma temperatures not to be higher than the maximum temperature in the X-ray emitting region. We note that for a strong shock (with adiabatic index \( \gamma = 5/3 \)) in helium-dominated plasma (mean molecular weight per particle \( \mu = 4/3 \)) the post-shock temperature is \( kT = 2.608 \times (V_{\infty}/1000 \text{ km s}^{-1})^2 \text{ keV} \). Here, \( V_{\infty} \) is the shock velocity, and the maximum shock velocity is equal to the stellar wind velocity \( (V_{\infty} = V_{\infty}) \) in the framework of the CSW model. We see from Tables 1 and 3 that the deduced plasma temperatures in our sample of close WR+O binaries are qualitatively consistent with the adopted physical scenario. Namely, all are lower than the maximum possible plasma temperature in the interaction region of these CSW objects.

Also, in the CSW scenario, the hotter plasma is located near the line connecting the two stellar components in the binary system (i.e. in the denser part of the stellar winds). Thus, we can expect the higher-temperature component of the discrete-temperature models to suffer higher ‘wind’ absorption. As seen from Table 3, in general, this is found in the spectral fits to the X-ray emission from the close WR+O binaries in our sample (although there are some exceptions but these are likely to be the result of poor photon statistics).

Thus, it seems conclusive that the X-ray emission from the close WR+O binaries considered in this study is qualitatively consistent with the physical scenario where X-rays arise in hot temperature-stratified plasmas behind CSW shocks. However, an interesting issue, the total X-ray energetics (luminosity) of CSWs in close binaries, is also worth discussing, as this is directly related to whether the CSW shocks are radiative, adiabatic, etc.

We can use the dimensionless parameter \( \chi = \tau_{\text{cool}}/\tau \), introduced by Stevens, Blondin \\& Pollock (1992), to estimate the importance of radiative losses behind the CSW shocks in the WR+O binaries of our sample. We recall that \( \tau_{\text{cool}} \) and \( \tau \) are the characteristic cooling times of the shocked plasma and the time-scale of the gas dynamics, respectively. Then, from the data in Table 1 and equation (8) in Stevens et al. (1992), we see that the radiative cooling should have an important effect on the physics of CSWs in the close WR+O binaries studied here \( (\chi < 1) \). This means that only numerical hydrodynamic modelling of the interaction region must be used to compare the theoretical predictions with observations. However, we can perform a qualitative check on the X-ray energetics, as mentioned above, by considering two extremes: (i) highly radiative CSW shocks and (ii) adiabatic CSW shocks.

In the case of radiative shocks, we have an upper limit on the available energy (luminosity) that can be converted into X-ray emission: no more energy is emitted than the energy flux crossing the shock front per unit area. For the maximum X-ray luminosity, we have \( L_x = (1/2) \int \rho V_{\text{wind}}^2 dS \), where \( \rho \) is the density of the wind in front of the shock, \( V_{\text{wind}} \) is the wind velocity component perpendicular to the shock front and \( S \) is the shock surface. In the case of CSWs, the integration is over the entire CSW ‘cone’. Although its shape varies from one object to another, we can expect a
Figure 1. The background-subtracted spectra overlaid with the best-fitting model. Each panel shows the name of the object and the binary phase in parentheses (see Tables 2 and 3). The spectra are re-binned to have a minimum of 10–20 counts per bin. In the panels with two different spectra in the same data set, the upper and lower (in red) curves are for the pn and MOS spectra, respectively.
Table 3. Global spectral model results. Fit results from the two-temperature optically thin plasma model with individual wind absorption for each component. A three-temperature plasma model was used only in the case of WR 46 – the parameters of the third component are given in the second line for this object. The uncertainties are 1σ errors from the fit.

| Name   | Phasec | $\chi^2$/dof | $N_{\text{H}, \text{ISM}}$ | $N_{\text{He}, 1}$ | $N_{\text{He}, 2}$ | $kT_1$ | $kT_2$ | $EM_1$ | $EM_2$ | $F_X$ |
|--------|--------|--------------|-----------------|-----------------|-----------------|--------|--------|--------|--------|--------|
| WR 46  | 0.55   | 231/255      | 2.10            | 0.00$^{+0.34}_{-0.01} $ | 0.15$^{+0.01}_{-0.01} $ | 5.55$^{+1.31}_{-0.27} $ | 0.35$^{+0.09}_{-0.09} $ | 0.57$^{+0.02}_{-0.02} $ | 3.75$^{+0.83}_{-0.65} $ | 4.44$^{+0.78}_{-0.10} $ | 3.43$^{+1.07}_{-0.28} $ | 3.28$^{+0.52}_{-0.61} $ | 1.20 (3.00) |
| WR 47  | 0.62   | 244/295      | 7.92            | 0.53$^{+0.08}_{-0.16} $ | 0.59$^{+0.03}_{-0.03} $ | 12.3$^{+1.3}_{-1.2} $ | 0.00$^{+0.21}_{-0.00} $ | 4.02$^{+0.34}_{-0.33} $ | 8.05$^{+0.34}_{-0.38} $ | 2.27 (8.02) |
| WR 139 | 0.47   | 362/335      | 5.86            | 0.23$^{+0.04}_{-0.03} $ | 0.58$^{+0.04}_{-0.03} $ | 3.66$^{+0.60}_{-0.35} $ | 6.11$^{+0.63}_{-0.58} $ | 3.08$^{+0.13}_{-0.17} $ | 17.8$^{+0.71}_{-0.62} $ | 9.40 (27.3) |
| WR 141 | 0.02   | 35/39        | 8.20            | 4.40$^{+0.53}_{-0.59} $ | 3.40$^{+0.43}_{-0.30} $ | 6.82$^{+0.75}_{-0.68} $ | ...    |        |        |        | 8.49 (19.1) |
| WR 145 | 0.33   | 180/278      | 35.4$^{+3.5}_{-2.2} $ | 0.00            | 0.99$^{+0.14}_{-0.12} $ | 16.5$^{+3.5}_{-4.5} $ | 0.00       | 4.75$^{+1.46}_{-1.00} $ | 4.90$^{+1.27}_{-1.02} $ | 6.32 (39.7) |
|        |        |              |                 | 47.5$^{+8.9}_{-6.9} $ | 0.00            |        |        |        |        | 4.80 (39.7) |
|        |        |              |                 | 57.5$^{+8.4}_{-6.9} $ | 0.00            |        |        |        |        | 4.59 (39.7) |
|        |        |              |                 | 47.5$^{+7.5}_{-5.9} $ | 0.00            |        |        |        |        | 5.10 (39.7) |
| WR 148 | 0.99   | 54/101       | 5.16            | 1.98$^{+0.73}_{-0.70} $ | 0.40$^{+0.18}_{-0.11} $ | 44.5$^{+12.3}_{-26.5} $ | 1.69$^{+1.83}_{-1.66} $ | 1.03$^{+1.11}_{-0.33} $ | 9.73$^{+12.1}_{-7.64} $ | 0.255 (4.14) |
|        |        |              |                 | 1.05$^{+0.49}_{-0.50} $ |        |        |        |        | 10.1$^{+5.24}_{-6.43} $ | 9.24 (4.14) |
| WR 79  | 0.72   | 40/49        | 3.08            | 0.09$^{+0.01}_{-0.01} $ | 1.27$^{+0.48}_{-0.20} $ | 0.09$^{+0.02}_{-0.01} $ | 3.92$^{+1.26}_{-0.64} $ | 2.38$^{+0.98}_{-0.78} $ | 2.92$^{+4.09}_{-1.35} $ | 1.80 (33.6) |
|        |        |              |                 | 0.09$^{+0.02}_{-0.02} $ |        |        |        |        | 4.21$^{+1.40}_{-0.78} $ | 1.70 (33.6) |

* The binary phase for each observation from Table 2.
* The interstellar absorption column density in units of $10^{21}$ cm$^{-2}$.
* The helium-dominated wind absorption column density in units of $10^{21}$ cm$^{-2}$.
* The plasma temperature is in keV.
* The emission measure ($EM = \int n_e n_H dV$) in units of $10^{-4}$ cm$^{-3}$ at the distance for each object from Table 1.
* The observed flux (0.5–10 keV) followed in parentheses by the unabsorbed value. The units are $10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

The X-ray luminosity has no correlation with the wind luminosity but that it clearly correlates with the CSW parameter. We see that the X-ray luminosity has no correlation with the wind luminosity but that it clearly correlates with the CSW parameter. Interestingly, the derived proportionality between log $L_X$ and log $C_{\text{CSW}}$ is 1.05 ± 0.09 (the error is a 1σ error from the fit). Thus, $L_X \propto C_{\text{CSW}}^{1.05}$. All of this is surprising because it means that the CSW shocks in close WR+O binaries are more likely to be adiabatic rather than strongly radiative. We note again that our sample of studied objects is limited, but nevertheless the results in Fig. 2 are very interesting and we discuss these in some detail.

It is worth noting another result from Fig. 2, which favours the case of adiabatic CSWs in the close WR+O binaries in our sample, that is, the low efficiency of converting the wind luminosity into X-rays.
X-ray emission: $L_X/L_{\text{wind}} \sim 10^{-4}$–$10^{-5}$. Of course, this ratio cannot be very close to unity because the CSW shock cone occupies only part of the `sky' of the WR star (the shocked WR wind dominates the X-ray emission from the interaction region). However, it seems unlikely that such a low value of $L_X/L_{\text{wind}}$ can be explained only by geometrical effects, and some other explanation is needed. Moreover, by its very definition, the term `radiative shocks' means that the high percentage of the energy influx is radiated away (mostly in X-rays for fast shocks), while the opposite is valid for `adiabatic shocks'. Fig. 3 shows the result from our numerical integration for the maximum possible X-ray luminosity, $L_X = (1/2) \int \rho V^2_{\text{wind}} \, ds$, in the case of highly radiative CSW shocks. In such a case, the interaction region collapses and its shape coincides with that of the contact discontinuity between the shocked WR and O star winds. We have adopted the Canto, Raga & Wilkin (1996) solution for the shape of the CSW `cone'. We see that the theoretical $L_X/L_{\text{wind}}$ values are considerably higher than those observed. Thus, with respect to the wind luminosity of the more massive star in the binary, the relatively low values for the X-ray luminosity do support the conclusion that the CSWs in our sample of close WR+O binaries are adiabatic.

However, adiabatic CSW shocks are possible in this case only if the mass-loss rate of the stellar winds in the binaries is considerably smaller (e.g. at least by an order of magnitude) than the values listed in Table 1. (We note that, in such a case, the actual values of the CSW parameter will be smaller and the plot in the right panel of Fig. 2 will be shifted to the left on the x-axis. A detailed analysis is needed in this case; see discussion below.) In other words, our analysis of the X-ray emission from close WR+O binaries indicates considerable clumping in the winds of these massive stars. It seems plausible to propose that the stellar wind of a massive WR (O) star is likely to be a two-component flow: a rarefied continuous component with low mass-loss rate and a `discrete' component consisting of numerous dense clumps. The first component forms the CSW interaction region and thus plays a role for the X-ray emission from close WR+O binaries. The second component dominates their optical/UV spectra. We note that in the last two decades observational evidence has been gathered of the physical scenario of clumpy stellar winds in the hot massive stars, and this has become a standard ingredient in the analysis of the optical, UV and infrared spectra of these objects (see Puls, Vink & Najarro 2008 for a recent review). Here, from an analysis of the X-ray spectra of close WR+O binaries, we find additional evidence that the stellar wind in massive stars is clumpy (highly inhomogeneous) on a length-scale at least of the order of the binary separation (approximately the size of the CSW region). It is worth noting, though, that we need more detailed knowledge, both observational and theoretical, in order to build a coherent physical scenario of clumpy stellar winds in massive stars. For example, we need to answer the following questions. What is the origin of the clumps? What is the distribution of clumps by their size? What is the clump evolution with the distance from the star? Do the homogeneous components of the wind and the clumps share the same bulk velocity, and thus what is the efficiency of the radiative force that drives both of these? Do both components of the stellar wind reach terminal wind velocity in front of the interaction region? Does radiative braking play an important role for this complex wind structure?

An interesting issue in this respect concerns the fate of the dense clumps when interacting with the CSW region of the rarefied homogeneous components of the stellar winds in close WR+O binaries. Cherepashchuk (1990) proposed a qualitative scenario where the dense clumps pass freely through the interaction region and some of them are decelerated in the O-star photosphere, where their X-rays are transformed into optical emission. However, Pittard (2007) carried out hydrodynamical simulations of a CSW binary with clumpy winds that showed efficient destruction of clumps while they are interacting with the CSW shocks. As a result, the average density in the interaction region increases and this is similar to the case of smooth winds with higher mass-loss rates. We have to keep in mind that these simulations were suitable for wide CSW binaries, and specifically for the stellar wind and binary parameters of WR 140 (see Pittard 2007 for details), and the reality might be different in close CSW binaries. Namely, the clumps are likely to be smaller closer to the base of the stellar wind, they might have much larger density contrast with respect to the smooth component, etc. Also, if the clumps are destroyed in the CSW region in close WR+O binaries, then these objects would have been much more luminous in X-rays than deduced from observations. Thus, it seems plausible to assume that the dense clumps of the stellar winds `survive' while crossing the CSW region in close WR+O binaries. It is difficult to describe what the possible observational evidence could be from the interaction of these dense clumps with the CSW region, because it depends on such `hard-to-guess' details as mentioned at the end of the previous paragraph.
Thus, we believe that future X-ray observations with much better photon statistics might be very helpful in this respect. The results from such observations must be considered in conjunction with those from the optical/UV spectral domain in order to build a self-consistent physical scenario of the stellar winds in massive stars. Such a global analysis might reveal that the smooth component has very little or no contribution to the optical/UV emission of a massive star, and X-ray observations could be the only tool to reveal its presence and physical properties. The analysis should also take into account the fact that massive O stars are X-ray sources themselves (for a recent review, see Güdel & Nazé 2009). We note only that their emission is ‘soft’ with plasma temperatures below 1 keV (e.g. Wojdowski & Schulz 2005; Zhekov & Pallà 2007; see also sections 4.1.3 and 4.3 in the review paper of Güdel & Nazé 2009), in contrast to what is found in close WR+O binaries (e.g. Table 3). However, there might still be many uncertainties surrounding the issue of the intrinsic contribution of the WR star to the total X-ray emission from the binary.

The pointed observations of modern X-ray observatories (Chandra, XMM–Newton) of a few, presumably single, WC stars have resulted only in non-detections (Oskinova et al. 2003; Skinner et al. 2006). Could it be that all single WC stars are X-ray quiet? In such a case, there will be no contribution from a WC star to the total X-ray emission from a WR+O binary system.

In contrast to this, the analysis by Skinner et al. (2010) of the X-ray spectra of a small sample of presumably single WN stars has shown that these objects emit X-rays that arise from an admixture of cool ($kT < 1$ keV) and hot ($kT > 2$ keV) plasma. The presence of hot plasma ($kT > 2$ keV) makes them similar to the CSW binaries studied here and distinct from the single O stars. So, could it be that these WN stars are not single stars but binaries? However, there are some differences in the X-ray characteristics between the single WN stars and the close WR+O binaries in our sample. The latter are more X-ray luminous with a minimum value of $\log L_X \approx 32.5$ erg s$^{-1}$ (Fig. 2) while most of the X-ray-detected, presumably single, WN stars have luminosities below this value (see fig. 10 of Skinner et al. 2010). Also, there is an indication that the $L_X \propto L_{\text{wind}}$ relation holds for single WN stars, while this is not the case for close WR+O binaries (compare fig. 10 of Skinner et al. 2010 with the left panel in Fig. 2). Because the X-ray production mechanism in single WN stars has not been identified yet, one possibility is that those detected in X-rays are in fact WR binaries with a normal (non-degenerate) companion (see the discussion in section 4.4 of Skinner et al. 2010), which might also explain their $L_X \propto L_{\text{wind}}$ trend (see section 7.2 in Zhekov & Park 2010b). Also, we emphasize that more X-ray data with good quality are needed, and a global analysis, such as that mentioned above, will help us to better understand the physical scenario for the stellar winds of hot massive stars.

Finally, the object with the shortest period in our sample, WR 46, deserves a few more comments. This object has a very complex variability pattern in the optical, UV and perhaps X-rays (e.g. Marchenko et al. 2000; Gosset et al. 2011a; Hénault-Brunet et al. 2011; see also Appendix A). Gosset et al. (2011a) proposed that its hard X-ray emission might arise in CSW shocks. Hénault-Brunet et al. (2011) argued that non-radial pulsations were the most likely scenario to explain its characteristics, and they even drew an analogy between WR 46 and ζ Pup (a massive, presumably single, O star) in this respect. Based on the results presented here (e.g. high plasma temperatures) and because the X-ray variability pattern is not well established (see Appendix A), we believe that the physical scenario of CSWs in a short-period WR+O binary is a more likely explanation for the X-ray properties of WR 46.

\section{6 Conclusions}

Using data from the Chandra and XMM–Newton public archives, we have analysed the X-ray emission from a small sample of close WR+O binaries. In such objects, X-rays are likely to originate in the CSW shocks driven by the massive winds of the binary components. The main results and conclusions from our analysis are as follows.

(i) Global spectral fits show that the two-temperature plasma is needed to match the X-ray emission from these objects because the hot component ($kT > 2$ keV) is an important ingredient of the spectral models.

(ii) In general, CSW shocks in close binaries are expected to be radiative because of the high density of the plasma in the interaction region, and the X-ray emission is dominated by that of the shocked WR wind. Thus, a correlation between the X-ray luminosity from these objects and the mechanical luminosity of the WR wind should exist: $L_X \propto L_{\text{wind}}$. Interestingly, we do not find such a correlation for the objects studied here.

(iii) Our analysis shows that a correlation between the X-ray luminosity and the so-called CSW parameter (see Section 5) does hold. This means that CSWs in close WR+O binaries must be adiabatic. This is possible only if the mass-loss rates of the hot stars in these objects are at least one order of magnitude smaller than the values currently accepted.

(iv) The most likely explanation for the X-ray properties of close WR+O binaries could be that their winds are two-component flows. The more massive component (dense clumps) plays a role in the optical/UV emission from these objects. However, the smooth rarefied component is a key factor for their X-ray emission. We believe that global analysis (modelling) of optical, UV and X-ray emission from close WR+O binaries will help us to build a self-consistent physical picture of the stellar winds and the close circumstellar environment in these objects.

(v) To further check the results presented here, a similar analysis should be applied to close O+O binaries because these are evolutionary progenitors of the WR+O binaries. The work of De Becker et al. (2004) is an example of the relevance of such a proposition. Their study of the X-ray emission from HD 159176 (an O+O system with a 3.367-d period) has shown that the CSW model overestimates the observed X-ray luminosity for the standard wind parameters.

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APPENDIX A: DETAILS OF THE X-RAY DATA FOR WR 46 AND WR 79

WR 46

One of the most interesting characteristics of WR 46 is its variability established in the optical/UV (e.g. Marchenko et al. 2000, and references therein). Because XMM–Newton is capable of providing optical/UV data simultaneously with X-ray data, the corresponding WR 46 observations allow us to search for X-ray variability that might correlate with what is found in the optical/UV. Gosset et al. (2011a) and Hénault-Brunet et al. (2011) have reported that such a correlation does exist. (We note that Gosset et al. 2011a have suggested that the X-ray variability is restricted only to the 0.2–0.5 keV energy range.)

Adopting a recent version of the sas software (Section 3), we have extracted background-subtracted X-ray LCs from the reprocessed EPIC data. We have also built UV LCs in the two filters (UVM2, UVM2) from the reprocessed data of the Optical Monitor used in these observations. For consistency with the UV data, the X-ray LCs are binned in 2000-s time intervals. Fig. A1 presents the corresponding X-ray and UV LCs of WR 46. We see that the variability pattern in WR 46 is complex. Namely, the expected 0.329-d period is evident only in the UV filter UVM2. This is not the case for the other UV filter (UVM2), although these data are taken one after the other (see the left panel in the top row of Fig. A1). Such behaviour is strange (or interesting) because the throughput curves for these filters overlap considerably (see fig. 88, section 3.5.5.1 in the XMM–Newton Users Handbook3). Similarly, the X-ray variability (if any) does not seem to be ‘identical’ in different types of EPIC detector: pn and MOS.

To quantify the variability pattern in WR 46, we performed the following exercise, which indicates whether the corresponding emission is variable. First, we fitted each LC with a constant (adopting $\chi^2$ fitting). Secondly, excluding the two ‘extreme’ values (i.e. the maximum and minimum values) in each LC, we fitted the LC with a constant again. The result as a formal goodness-of-fit is as follows. For the complete LC, the goodness-of-fit for a constant emission is 0.0002 (UVM2), 0.0 (UVM2), 0.49 (X-ray, pn) and 0.99 (X-ray, MOS). When the two extreme values are excluded, the goodness-of-fit is 0.24 (UVM2), 0.0 (UVM2), 0.87 (X-ray, pn) and 1.0 (X-ray, MOS). We note that the exclusion of one or two data points from a sequence of measurements is not expected to change the global trend in a variability pattern of a physical quantity. Thus, we feel it is safe to conclude that only the UV emission of WR 46 in the UVM2 filter of the optical monitor onboard XMM–Newton shows a clear sign of not being constant. We believe that more X-ray and UV data, taken simultaneously, are needed to firmly establish whether the X-ray emission from WR 46 is variable and, if it is, then on what time-scale and on what luminosity scale, and whether it correlates with the variability detected in other spectral domains (e.g. optical, UV).

WR 79

The XMM–Newton observations of WR 79 were analysed by Gosset et al. (2011b). However, because of the superb spatial resolution of Chandra, the ACIS-S images of WR 79 reveal that there are two nearby sources within 6 arcsec from WR 79 (Fig. A2). We denote

3 See Documents & Manuals at http://xmm.esac.esa.int/.
**Figure A1.** *XMM–Newton* LCs of WR 46. Top row: LCs as a function of observing time in two UV filters of the Optical Monitor (UVM2; UVW2) and in the (0.2–10 keV) energy range with the EPIC detectors (pn; MOS denotes the total emission from the two MOS detectors). Middle and bottom rows: LCs folded with the orbital period. The values for period and zero-phase time are from Marchenko et al. (2000). Note that for graphical convenience the data points are plotted twice: the data for phase values (1.0–2.0) are the same as those for phase values (0.0–1.0). Circles mark the maximum and minimum values in each LC. The X-ray LCs are background-subtracted.

**Figure A2.** WR 79 images: the *Chandra* ACIS-S images for the two observations used in this study with Obs. ID 5372 (Obs 1) and 6291 (Obs 2), and an *XMM–Newton* MOS1 image (Obs. ID 0109490401). All images are centred at the optical position of WR 79 (SIMBAD) marked by a circle with crosshairs. Two X-ray sources are seen a close distance from WR 79, marked by a circle and denoted S1 and S2. A square marks the optical position of CCDM J16543−4149D (a binary system; SIMBAD). The large (green) circle has a diameter of 15 arcsec.
Figure A3. The background-subtracted spectra of the X-ray sources from Fig. A2. The WR 79 spectra extracted from the Chandra ACIS-S data are shown in the first two panels of the upper row because those from the large extraction region with a diameter of 15 arcsec (the large green circle in Fig. A2) are drawn in red, while the spectra only of WR 79 itself are given in black (these are used in the current study; see Fig. 1). For comparison, the archive XMM–Newton MOS1 spectrum of WR 79 is shown in the right-hand panel of the upper row. The X-ray spectra of sources S1 and S2 (Fig. A2) are shown in the lower row. No spectrum of S1 from Obs 2 is presented because there are only two counts in it. All the spectra are re-binned to have a minimum 10 cts per bin.

these as S1 (the northern source) and S2 (the southern source). The S1 coordinates are \( \alpha_{2000} = 16^h54^m19^{s}41 \) and \( \delta_{2000} = -41^\circ49'08''15' \), and WR 79 is the only object in SIMBAD within 5 arcsec from S1 (a radial distance of 4.7 arcsec). Thus, source S1 is unidentified as yet. The S2 coordinates are \( \alpha_{2000} = 16^h54^m19^{s}44 \) and \( \delta_{2000} = -41^\circ49'16''71' \) (a radial distance of 5.9 arcsec to WR 79), and the binary system CCDM J16543–4149D is the only object in SIMBAD within 2 arcsec from S2 (a radial distance of 1.9 arcsec). Thus, source S2 is unidentified as yet.

It is important to note that it is possible to extract a ‘net’ X-ray spectrum of WR 79 from the Chandra data, while only a total spectrum for all three sources, WR 79, S1 and S2, can be obtained from the XMM–Newton data (Figs A2 and A3). We see from Fig. A2 that S1 is definitely a variable source. Fig. A3 illustrates that the X-ray emission from S1 and S2 might alter the X-ray emission from WR 79 appreciably when the latter is observed with an X-ray telescope that does not have very high spatial resolution. We note that the total number of counts from sources S1 and S2 amounts to 37–47 per cent of that from WR 79 as directly measured in the ACIS-S data of the two Chandra observations. Also, the X-ray emission of S1 and S2 is much softer compared to that of WR 79. If the total spectrum of these three sources is assigned to WR 79 alone, then from an analysis of such a ‘combined’ spectrum we can draw conclusions about the X-ray characteristics (e.g. plasma temperature, X-ray absorptions, variability), which will not be correct. From all this, we can safely conclude that, for the moment, Chandra observations are the only observations that can provide us with valuable information on the X-ray emission from the WR + O binary WR 79.

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