X-rays from the colliding wind binary WR 146

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ABSTRACT
The X-ray emission from the massive binary WR 146 is analysed in the framework of the colliding stellar wind (CSW) picture. The theoretical CSW model spectra match well the shape of the observed X-ray spectrum of WR 146 but they overestimate considerably the observed X-ray flux (emission measure). This is valid both in the case of complete temperature equalization and in the case of partial electron heating at the shock fronts (different electron and ion temperatures), but, there are indications for a better correspondence between model predictions and observations for the latter. To reconcile the model predictions and observations, the mass-loss rate of WR 146 must be reduced by a factor of 8 - 10 compared to the currently accepted value for this object (the latter already takes clumping into account). No excess X-ray absorption is derived from the CSW modelling.

Key words: shock waves — stars: individual: WR 146 — stars: Wolf-Rayet — X-rays: stars.

1 INTRODUCTION
Massive stars of early spectral types, OB and Wolf-Rayet (WR) stars, possess fast and massive stellar winds (\(V_{\text{wind}} = 1000 - 5000 \text{ km s}^{-1} ; M \sim 10^{-7} - 10^{-5} \text{ M}_\odot \text{ yr}^{-1}\)) that play an important role for their evolution. On the other hand, when a binary harbours two massive stellar components, the interaction of their massive winds gives rise to the phenomenon of colliding stellar winds (CSW), whose observational manifestation allows us to study the physics of strong shocks in some detail. Due to the high velocity of the stellar winds from massive stars, the shocked plasma in the CSW region is heated to high temperatures, thus, it is expected to be a strong source of X-ray emission (e.g., Prilutskii & Usov 1976; Cherepashchuk 1976).

We note that the first systematic X-ray survey of WRs with the Einstein Observatory showed that WR+O binaries are the brightest X-ray sources amongst them (Pollock 1987), but the quality of the X-ray data was not very high. With the launch of the Chandra and XMM-Newton observatories the number of WR+O binaries with good quality X-ray spectra has increased and some of the objects were studied in considerable detail. Thus, in the last two-three decades it became generally accepted that the enhanced X-ray emission from WR+O binaries likely originates from the interaction region of the winds of the massive binary components (see Rauw & Nazé 2016 for a recent review on the progress of studies, both theoretical and observational, of X-ray emission from interacting wind massive binaries of early spectral type).

However, it is our understanding that carrying out detailed comparison between theory and observations is the most reliable way to test the currently accepted physical picture of a given phenomenon. In this respect, the modern tools for analysing and modelling of observational data allow us to perform direct confrontation of our physical ideas (models) with observations, and it is indeed the case in the X-ray astronomy.

This is exactly the goal of the current study of the colliding stellar wind phenomenon, namely, to carry out a direct comparison of the CSW model results and the X-ray observations of the massive Wolf-Rayet binary WR 146. Previous studies based on such an approach provided us with valuable pieces of information on the physical picture of CSW binaries (e.g., Zhekov & Skinner 2000; Zhekov & Park 2010; Zhekov 2015). We believe that the more objects are analysed in such a way the better our understanding of the CSW phenomenon is.

Our paper is organized as follows. We summarize information on WR 146 in Section 2. In Section 3, we review the recent X-ray observations of WR 146. In Section 4, we present results from a direct comparison of the CSW model with the X-ray emission of WR 146. In Section 5, we discuss our results, and we present our conclusions in Section 6.
2 THE WOLF-RAYET STAR WR 146

WR 146 (MR 112) is a massive binary whose components are a carbon-rich (WC) Wolf-Rayet star and an O-type star (van der Hucht 2001). It is a wide colliding wind binary showing non-thermal radio emission (Dougherty et al. 1996). High-resolution radio observations resolved its emission into three different sources: two thermal sources (identified with the WR and O star, respectively) and one non-thermal source (associated with the CSW region in the binary) with an estimated binary separation of 0′′162 ± 0′′008 (Dougherty et al. 2000). Similar result for the binary separation (0′′168 ± 0′′031) was obtained from the optical observations with the Hubble Space Telescope (HST) (Niemela et al. 1998). It is interesting to note that Setia Gunawan et al. (2000) reported 3.38-year periodic variations superimposed on the 1.4-GHz slow rise in the radio emission from WR 146. However, as the authors stated these variations are too short to be the WR+O binary period and might be caused by a third, low-mass, object in the system.

The optical extinction of $A_V = 8.32$ mag was derived from detailed quantitative analysis of optical and infrared emission from WR 146 (Dessart et al. 2000), implying a foreground column density of $N_H = (1.37 - 1.85) \times 10^{22}$ cm$^{-2}$. The range corresponds to the conversion that is used: $N_H = (1.6 - 1.7) \times 10^{21} A_V$ cm$^{-2}$ (Vuong et al. 2003; Getman et al. 2005); and $N_H = 2.22 \times 10^{21} A_V$ cm$^{-2}$ (Gorenstein 1975).

We adopt the stellar wind parameters (velocity and mass loss) of the WR component $V_{WR} = 2700$ km s$^{-1}$ and $M_{WR} = 3.15 \times 10^{-5}$ M$_\odot$ yr$^{-1}$; and of the O-star component $V_O = 1500$ km s$^{-1}$ and $M_O = 6.32 \times 10^{-6}$ M$_\odot$ yr$^{-1}$ that are based on the analysis by Dougherty et al. (2000) and Dessart et al. (2000). From the same analysis, the distance to WR 146 is 1.4 kpc, which results in projected (or minimum) binary separation of 226.8 ± 11.2 au (0′′162 ± 0′′008).

In X-rays, a marginal detection was reported from the Einstein survey of Wolf-Rayet stars, $6.5 \pm 10^{-3}$ cts s$^{-1}$ (Pollock 1987), and also from the ROSAT survey of Wolf-Rayet stars, $3.5 \pm 1.9 \times 10^{-3}$ cts s$^{-1}$ (Pollock et al. 1995). However, both data sets had poor photon statistics ($\leq 30$ source counts). Rauw et al. (2015) reported a clear detection ($\sim 1870$ source counts) of WR 146 in their analysis of X-ray emission from massive stars in the star-forming region Cygnus OB2. A two-temperature plasma (kT = 0.36 and 2.1 keV) could acceptably represent the observed Chandra ACIS-I spectrum of WR 146. By comparing with the Einstein and ROSAT data (mentioned above), the authors also concluded that a long-term (years) variability might be present but the uncertainties in the old data prevent any firm conclusions on the variations of the X-ray flux from this object.

3 OBSERVATIONS AND DATA REDUCTION

We searched the Chandra and XMM-Newton archives for data on WR 146 and found the following Chandra ACIS-I data sets suitable for analysis of the X-ray emission from this object. Namely, one pointed observation (WR 146 located on axis) taken on 2007 March 17 (ObsId: 7426) with effective exposure of 19.7 ks and two observations being part of the Chandra Cygnus OB2 Survey (ObsId: 10967 and 10968; WR 146 located correspondingly at 9.67 and 7.86 off axis) both obtained on 2010 March 2 with the same effective exposure of 28.9 ks. We will further refer to these observations as Obs 1, Obs 2 and Obs 3 (Fig. 1).

Following the Science Threads for Imaging Spectroscopy in the CIAO 4.81 data analysis software, we extracted the WR 146 X-ray spectra from the three data sets (we have initially re-processed the data adopting the CIAO CHANDRA_REPRO script). We note that the near-by source BD+404243 (11′′3 from WR 146) was also detected in Obs 1 (24 source counts). Although it is considerably fainter than WR 146, we excluded its contribution to the X-ray spectra of WR 146 extracted from Obs 2 and Obs 3 (denoted by the red circle in Fig. 1). The WR 146 source counts were 719 (Obs 1), 773 (Obs 2) and 784 (Obs 3). The Chandra calibration database CALDB v.4.7.2 was used to construct the response matrices and the ancillary response files.

We constructed the background-subtracted light curves and found no variability on time scales shorter than the effective exposure of each observation. Namely, using time bins between 100 and 1000 s, the X-ray LCs were statistically similar but with shorter time scales.
consistent with a constant flux: adopting \( \chi^2 \) fitting, the LCs were fitted with a constant and the goodness of fit was \( \geq 0.94 \) (Obs 1), \( \geq 0.95 \) (Obs 2) and \( \geq 0.60 \) (Obs 3). Anticipating the results from our analysis, we note that the observed flux from WR 146 was the same in Obs 1, Obs 2 and Obs 3.

For the spectral analysis in this study, we made use of standard as well as custom models in versions 11.3.2 and 12.9.1 of xspec (Arnaud 1996).

4 CSW MODEL SPECTRA

4.1 CSW model

In this study, we consider CSW picture that results from interaction of two spherically symmetric gas flows (stellar winds) that have reached their terminal velocities in front of the shocks. This is well justified in wide binary systems (as WR 146), where neither radiative braking nor orbital motion (orbital velocities are much less than the wind velocities) is expected to play an important role. In such a case, the interaction region has cylindrical symmetry and two-dimensional (2D) numerical hydrodynamic models are well suited for calculating the physical parameters of the CSW structure.

We recall that the basic input parameters for the CSW hydrodynamic model in WR+o binaries are the mass loss and velocity of the stellar winds of the binary components and the binary separation (Lebedev & Myasnikov 1990; Luo et al. 1990; Stevens et al. 1992; Myasnikov & Zhekov 1993). The former define a dimensionless parameter \( \Lambda = (M_{W_1}v_{WR}/M_{O}v_{O}) \) which determines the shape and the structure of the CSW interaction region (Myasnikov & Zhekov 1993).

Given the wind parameters and the binary separation (Section 2), we see that the shocked plasma in the CSW region of WR 146 will be adiabatic. It follows from the values of either of dimensionless parameters \( \chi \) (Stevens et al. 1992) and \( \Gamma_{ff} \) (Myasnikov & Zhekov 1993): \( \chi = 574.0 \) (\( \chi > 1 \) - adiabatic case), \( \Gamma_{ff} = 0.0002 \) (\( \Gamma_{ff} > 1 \) - cooling is important). In general, partial electron heating might occur behind strong shocks, and the value of the dimensionless parameter \( \Gamma_{eq} = 0.02 \) indicates that this should be taken into account in the case of WR 146 (\( \Gamma_{eq} < 1 \) if the difference of electron and ion temperatures is important; see Zhekov & Skinner 2000). Also, the value of the dimensionless parameter \( \Gamma_{NEI} = 1.55 \) indicates that the nonequilibrium ionization effects (NEI) could play an important role in the CSW region of WR 146 as well (the NEI effects can be neglected if \( \Gamma_{NEI} \geq 1 \); see Zhekov 2007).

We therefore made use of our CSW xspec models that take into account the different ion and electron temperature behind the shocks (Zhekov & Skinner 2000) and the NEI effects in hot plasmas (Zhekov 2007). These models are based on the 2D numerical hydrodynamic model of CSW by Lebedev & Myasnikov (1990) (see also Myasnikov & Zhekov 1993). The latter adopts the ‘shock fitting’ technique, which provides an exact solution to all discontinuity surfaces (the two shocks and the contact discontinuity) of the CSW region. This means that there is no numerical ‘mixing’ of the shocked gases of the stellar winds, which in turn allows the different chemical composition of the WR and O-star wind to be explicitly taken into account in modelling the X-ray emission from the CSW region in WR 146.

We recall that the entire fitting procedure is threefold: (a) given the stellar wind and binary parameters, the hydrodynamic model provides the physical parameters of the CSW region; (b) based on these results, we prepare the input quantities (e.g., distribution of temperature, emission measure, ionization age) for the spectral model in xspec; (c) the CSW xspec model fits the observed X-ray spectrum. Note that in xspec we can fit for the X-ray absorption, chemical abundances and the model normalization parameter. If adjustments of other physical parameters are required, all three steps should be repeated: i.e., our fitting procedure is an iterative process. It is important to keep in mind that the normalization parameter (norm) of the CSW model in xspec is a dimensionless quantity that gives the ratio of observed to theoretical fluxes. Thus, the entire fitting procedure is aimed at getting a value of norm = 1.0, which indicates a perfect match between the observed count rate and that predicted by the model (norm < 1.0 indicates a theoretical flux higher than that required by the observations and the opposite is valid for norm > 1.0). This in turn helps us obtain some constraints on the basic parameters of the CSW picture (e.g., mass-loss rates, binary separation).

Finally, we note that our CSW models were originally developed in the xspec version 11.3.2. The models were now ‘transferred’ into xspec version 12.9.1. We tested the CSW models in both xspec versions using the latest atomic data (as in xspec 12.9.1) and the model results were identical.

4.2 CSW spectral model fits

As an initial step, we fitted each of the spectra separately using standard thin-plasma and shock models in xspec. We found that the observed X-ray flux was the same in all of them: e.g., two-temperature fits provide the following observed fluxes in the (0.5 - 10 keV) energy range 4.10\( \times 10^{-13} \) ergs cm\(^{-2}\) s\(^{-1}\) (Obs 1), 3.87\( \times 10^{-13} \) ergs cm\(^{-2}\) s\(^{-1}\) (Obs 2), 4.04\( \times 10^{-13} \) ergs cm\(^{-2}\) s\(^{-1}\) (Obs 3) as the 1\( \sigma \) confidence range is given in the square brackets. That is there was no long-term variability present. So to take advantage of the available photon statistics, we further fitted these spectra simultaneously by imposing the same CSW model parameters for each individual spectrum.

In all the spectral fits, the chemical abundances of the shocked O-star wind were solar (Anders & Grevesse 1989). For the shocked WR-star wind, we adopted the carbon and oxygen abundances from Dessart et al. (2000): C / He = 0.08; O / He = 0.02 by number; while the other elements had their values typical for the WC stars (van der Hucht et al. 1986). The Ne, Mg and Si abundances of the shocked WR plasma were allowed to vary to improve the quality of the fits.

Our basic CSW model was the one that adopts the nominal values of the wind and binary parameters of WR 146 (see Section 2). The theoretical spectrum matched well the shape of the observed spectra but it overestimated the observed flux considerably which means that the observations require much smaller emission measure in the CSW region than that the nominal WR 146 parameters suggest.

We recall that the emission measure in the CSW region that results from interaction of spherically symmetric stel-
Figure 2. Some parameters from the CSW model fits to the X-ray spectra of WR 146 as function of the partial heating ($\beta = T_e/T$) at the shock fronts. Left-hand panels: the case with reduced mass-loss rate. Right-hand panels: the case with increased binary separation. The horizontal dashed line in the $\chi^2$-plots is at a value of $\chi^2_{min} + 1$, thus, illustrating the formal $1\sigma$-boundaries for the ‘best’-fit $\beta$ case. These boundaries are indicated by two vertical dashed lines on the other plots. The $A_V$ values in the plots are calculated from the values of the X-ray absorption column densities derived in the fits using the Gorenstein conversion (Gorenstein 1975). The horizontal dashed line in the $A_V$-plots corresponds to the value of optical extinction derived from analysis of optical and infrared spectra of WR 146 (Dessart et al. 2000).

Lar winds is proportional to the square of the stellar wind mass loss and is reversely proportional to the binary separation ($EM \propto n^2 V$, $n$ is the number density, $V$ is the volume; $n \propto M/a^2$ and $V \propto a^3$, therefore $EM \propto M^2/a$). We thus iterated through our fitting procedure, that is we repeated all three steps of its numerous times by adopting either reduced mass-loss rates or increased binary separation until the CSW spectral models provided excellent correspondence between theoretical and observed fluxes for each individual case (i.e., having normalization parameter of the xspec model norm $\approx 1$). Similarly, we explored a range of values for the partial heating of the electrons at the shock fronts ($\beta = T_e/T$, $T_e$ is the electron temperature and $T$ is the mean plasma temperature), since both decrease of mass loss and increase of binary separation make the electron-ion temperature equalization run slower downstream from the shock front due to the reduced plasma density (e.g., see eq.1 in Zhekov & Skinner 2000).

Some fit results are summarized in Figure 2, while the ‘best’-fit results are given in Table 1 and Figure 3.

Although all the models are acceptable in formal statistical sense (see both top panels in Fig. 2), we note that the ‘smooth’ $\chi^2$ curve illustrates the similarity of our fitting
procedure and the \texttt{STEPPAR} command in XSPEC\(^2\). Namely, we perform a fit while stepping the value of a parameter ($\beta$, the partial electron heating in this case) in a given range. This allows us to derive the best-fit value (determined by the minimum of the $\chi^2$ statistic, $\chi^2_{\text{min}}$) and the corresponding confidence range for this parameter. For example, the formal 1$\sigma$ errors come in the usual way, namely: $\chi^2 = \chi^2_{\text{min}} + 1$. We see from Fig. 2 that the CSW models with partial electron heating at the shock fronts ($\beta < 1$) provide better fits to the observed X-ray spectra of WR 146. The best fits are with $\beta = 0.26_{-0.09}^{+0.10}$ and $\beta = 0.21_{-0.03}^{+0.03}$ for the model series with reduced mass loss and increased binary separation, respectively (denoted by the dashed lines in the right-hand side panels in Fig. 2). For these best fits, the mass-loss rates are correspondingly reduced by a factor of $7.9_{-0.5}^{+0.5}$ and the binary separation is correspondingly increased by a factor of $320_{-1.8}^{+2.0}$ with respect to their nominal values (see Table 2). We note that the derived uncertainties on the mass-loss rate and binary separation factors are larger than those from individual fits since the latter reflect only the quality of data.

On the other hand, we think that the formal errors on the derived $\beta$-values are not that important while it is in fact important that CSW models with partial electron heating are a better representation of the observed X-ray spectrum of the CSW binary WR 146. Interestingly, similar conclusion is valid for other wide CSW binaries as WR 140 (see Table 3 in Zhekov & Skinner 2000), WR 137 (see Table 2 in Zhekov 2013) and CygOB2 9 (Parkin et al. 2011).

Also, the derived values of the X-ray absorption for the ‘best’-fitting models are consistent with the optical extinction deduced from analysis of the optical and infrared emission of WR 146 (Dessart et al. 2000). Thus, no excess absorption, that might be due to the massive stellar winds, is indicated from analysis of the X-ray emission from this object in the framework of the CSW picture\(^3\).

But, the most interesting result from the direct confrontation of the CSW models and the X-ray spectra of WR 146 is probably that considerably reduced mass-loss rates (by a factor of ~ 8) and/or increased binary separation (by a factor of ~ 30) are required to have a good correspondence between the CSW theory and observations. This result deserves some more discussion, we believe, thus, we will return to it in Section 5. However, we would also like to explore the variability issue a bit more before continuing our discussion.

### 4.3 On the long-term X-ray variability of WR 146

We note that the lack of relatively long-term variability of its X-ray emission (Section 2 and 4.2) is something to expect in the case of CSW wide binaries, unless the object has highly eccentric orbit with not very long binary period (e.g., a few years) as is the case of the prototype CSW binary, the WR+O system WR 140 (Williams et al. 1990; Williams et al. 2005) converisions were adopted (see Section 2). However, these conversions are based on analysis only of nearby dense clouds ($d < 500$ pc) and they deviate from the galactic conversion (Vuong et al. 2003). We thus give preference to the Gorenstein (1975) conversion.

### Table 1. CSW Spectral Model Results

| Parameter                  | ‘Basic’ | ‘$M$’ | ‘$D$’ | ‘$M’ + $r_{ei}$’ | ‘$D’ + $r_{ei}$’ |
|---------------------------|---------|-------|-------|-----------------|-----------------|
| Reduced $M$ by a factor of | 1.0     | 1.0   | 1.0   | 1.0             | 1.0             |
| Increased D by a factor of | 1.0     | 1.0   | 1.0   | 1.0             | 1.0             |
| $\beta = T_{ei}/T$        | 1.0     | 1.0   | 1.0   | 1.0             | 1.0             |
| $\chi^2$/dof              | 85/103  | 79/103| 94/103| 65/103          | 71/103          |
| $N_H$ (10$^{22}$ cm$^{-2}$)| 1.23$^{+0.11}_{-0.08}$ | 1.64$^{+0.10}_{-0.10}$ | 1.59$^{+0.04}_{-0.03}$ | 1.79$^{+0.12}_{-0.08}$ | 1.89$^{+0.08}_{-0.06}$ |
| $N_e$                      | 0.56$^{+0.05}_{-0.03}$ | 0.35$^{+0.05}_{-0.03}$ | $< 0.06$ | 0.32$^{+0.23}_{-0.16}$ | 0.11$^{+0.08}_{-0.06}$ |
| Mg                         | 1.06$^{+0.32}_{-0.24}$ | 0.48$^{+0.11}_{-0.10}$ | 0.17$^{+0.07}_{-0.08}$ | 0.29$^{+0.12}_{-0.10}$ | 0.40$^{+0.07}_{-0.06}$ |
| Si                         | 2.15$^{+0.60}_{-0.53}$ | 0.86$^{+0.24}_{-0.22}$ | 0.11$^{+0.24}_{-0.11}$ | 0.41$^{+0.25}_{-0.23}$ | $< 0.09$ |
| $\chi^2_{\text{norm}}$   | 0.007$^{+0.004}_{-0.004}$ | 1.00$^{+0.05}_{-0.05}$ | 0.90$^{+0.05}_{-0.04}$ | 1.00$^{+0.05}_{-0.05}$ | 1.00$^{+0.04}_{-0.04}$ |
| $F_X$ (10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | 4.14 | 4.16 | 4.25 | 3.69 | 3.62 |

Note – Results from simultaneous fits to the Chandra spectra of WR 146 using model spectra from the CSW hydrodynamic simulations. The model with nominal stellar wind and binary parameters is denoted ‘Basic’. The models with reduced mass-loss rates are denoted with ‘$M$’ and those with increased binary separations are denoted with ‘$D$’. The models denoted with + $r_{ei}$ are their corresponding best-fit versions that take into account the different electron and ion temperatures (parameter $\beta$ gives the partial heating at the shock front). For each model, given is the factor by which the mass-loss rates of the stellar winds were reduced or the binary separation was increased (see Section 4.2 for details). Tabulated quantities are the neutral hydrogen absorption column density ($N_H$), the Ne, Mg, and Si abundances, the normalization parameter ($\text{norm}$) and the absorbed X-ray flux ($F_X$) in the 0.5 - 10 keV range followed in parentheses by the unabsorbed value. The $\text{norm}$ parameter is a dimensionless quantity that gives the ratio of observed to theoretical fluxes. A value of $\text{norm} = 1.0$ indicates a perfect match between the observed count rate and that predicted by the model. The derived abundances are with respect to the typical WR 146 abundances (see text; Section 4.2). Errors on the $\beta$ values from the xspec fits as those of the reduced $M$ and increased $D$ factors have been propagated from the $1\sigma$ values on the $\text{norm}$ parameter. The errors on the $\beta$ parameter for the best-fit case (models B1 and B2) are from the entire fitting procedure (see text for details).

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\(^2\) https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/xanadu/xspec/manual/node87.html

\(^3\) Note that our X-ray analysis may indicate some excess absorption if the Vuong et al. (2003) and Getman et al. (2005) conversions were adopted (see Section 2). However, these conversions are based on analysis only of nearby dense clouds ($d < 500$ pc) and they deviate from the galactic conversion (Vuong et al. 2003). We thus give preference to the Gorenstein (1975) conversion.
Figure 3. The background-subtracted spectra of WR 146 overlaid with the CSW model ‘best’ fits. The case with reduced mass-loss rate is shown in the left-hand panels while that with increased binary separation in the right-hand panels: respectively models (B1) and (B2) from Table 1. The spectra were re-binned to have a minimum of 20 counts per bin.

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2011 and the references therin). Rauw et al. (2015) reported that there is no appreciable sign of variability between the Einstein and Chandra observations of WR 146, but the case of ROSAT observations was not completely settled.

We searched the ROSAT archive and found that WR 146 fell in the ROSAT field of view on 1993 April 29: PSPC data set rp900314n00 (30′6 off axis) with nominal exposure of 19.4 ks. Following the recommendations for the ROSAT Data Processing⁴, we extracted the source and background spectra. The net source counts were 121 ± 20 in an effective exposure of 18.7 ks. Since the data were taken after 1991 Oct 14, we adopted the response matrix spcch_gain2.256.rmf and we used the package FCARF to construct the corresponding ancillary response file.

Although the quality of the spectrum is not high it is much better than that of the data used in the ROSAT survey of WR stars (see the comment on the X-ray counts in Section 2), so, we decided to use this ROSAT spectrum to check the long-term variability of WR 146. Figure 4 shows the ROSAT spectrum overlaid with one of the CSW models (model A2 in Table 1) that matches very well the Chandra spectra of this object. We see a good correspondence between the CSW model and ROSAT observation: \( \chi^2/\text{dof} = 17/25 \); observed count rate of \( 6.5 \times 10^{-3} \) cts s\(^{-1} \) vs. model count rate of \( 6.0 \times 10^{-3} \) cts s\(^{-1} \). Also, if we kept the spectral shape unchanged (i.e. abundances and X-ray absorption fixed) and varied only the normalization parameter of the model, the best-fitting ROSAT flux (‘required’

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⁴ https://heasarc.gsfc.nasa.gov/docs/rofat/rhp_proc_analysis.html
CSW emission measure) was within 4 per cent of its nominal (as of model A2) value. This, in conjunction with the results by Rauw et al. (2015), makes us confident to conclude that there is no indication for a long-term (of approximately two-three decades) variability in the X-ray emission from WR 146. We note that this corresponds well to the CSW wide binary status of this object. Namely, from the Kepler’s third law and assumed reasonable total mass of the binary components of 20-40 solar masses, the projected (minimum) binary separation of 226.8 au (Section 2) suggests a binary period of more than ~ 550 years. Thus, the available X-ray observations (from Einstein-through-ROSAT-to-Chandra) cover less than 5 per cent of that, and no considerable changes of the binary separation and local X-ray absorption (if any, see Section 4.2) are expected over such a small piece of the orbit in a wide binary system.

5 DISCUSSION

WR 146 is a wide CSW binary (Section 2), thus, the goal of this study was to carry out direct comparison between the CSW model spectra and the X-ray observations. It is worth noting that we have attributed the entire X-ray emission from WR 146 to some X-ray production mechanism that may operate in massive binaries: the CSW phenomenon in this case. This is a reasonable assumption, we believe, since the WR star in this system is a carbon-rich object and the WC stars are very faint or X-ray quiet objects: all the pointed observations of presumably single WC stars resulted in non-detections (Oskinova et al. 2003; Skinner et al. 2006). On the other hand, massive OB stars are X-ray sources and we could expect no more than a few \(10^{32}\) ergs s\(^{-1}\) from the O-star companion in WR 146, provided it had a bolometric luminosity even as high as \(10^{39}\) – \(10^{40}\) ergs s\(^{-1}\). Rauw et al. (2015) have shown that the OB stars in CygOB2 (WR 146 being a probable member of this star-forming region) follow the X-ray-to-bolometric luminosity relation \(\log(L_X/L_{bol}) = -7.2 \pm 0.2\). Such a possible contribution is not substantial compared to that from the CSW region in WR 146 (\(L_X > 3.8 \times 10^{35}\) ergs s\(^{-1}\) for an adopted distance of 1.4 kpc, using the unabsorbed fluxes from Table 1) but even if it were, then what about the X-ray emission from the CSWs themselves?

The very basic result from the CSW model analysis is the ‘requirement’ of considerable changes of the stellar mass-loss rates and/or binary separation with respect to their currently accepted values to make the theory and observations converge.

In fact, we considered in some detail two limiting cases that gave very good correspondence between the theoretical and observed flux (emission measure): (a) reduced mass losses; (b) increased binary separation (Section 4.2). However, it is our understanding that case (b) does not seem very realistic since it could suggest a very ‘special’ (in general possible but with low probability) observational circumstances: e.g., the orbital inclination angle of the spatially-resolved binary WR 146 should be very close to 90° (only within 2° of it), for the expected (i.e. actual) binary separation is at least as ~ 30 times as large (Table 1 and Fig. 2) the measured (projected) one.

In general, other combinations of mass-loss rates and orbital separation with values in the range we have considered separately for each of them that give a reduction of the emission measure similar to that used in our analysis (\(EM \propto \dot{M}/a\)) can give acceptable fits to the X-ray spectra of WR 146. However, a reasonable value of the binary separation (say, ~ 2 – 3 times its minimum value) will still require mass-loss rates considerably reduced by a factor of 4 - 5 (or even more) compared to their currently accepted values for this CSW binary. But, is WR 146 unique in this respect?

We recall that one of the basic results of the direct modelling of the X-ray emission from the wide CSW binaries WR 137 and WR 147 in the framework of the CSW picture was along the same lines. Namely, an appreciable reduction of the mass-loss rates was needed to reconcile the model predictions with observations: of about one order of magnitude for WR 137 (Zhekov 2015); and of about a factor of four for WR 147 (Zhekov & Park 2010). Thus, there is already some ‘statistics’ which gives indications for an appreciable mismatch between the stellar wind parameters of Wolf-Rayet stars derived from analysis of their optical/UV and radio emission and their corresponding values that are needed to explain the observed X-ray emission from the same objects.

We have to keep in mind that the stellar wind parameters (e.g., mass-loss rates) of massive stars are in a way model-dependent since they are deduced by adopting some physical picture with related assumptions, approximations etc.

The CSW picture in wide massive binaries is quite simple from a technical point of view: it adopts adiabatic shocks that result from interaction of homogeneous gas flows (stellar winds). On the other hand, winds of massive WR stars are likely not smooth but clumpy and this is adopted in the sophisticated stellar atmosphere models used to derive their stellar wind properties (e.g., Hamann et al. 2006; Sander et al. 2012). In these models, a standard volume filling factor of 0.1 throughout the stellar wind is usually assumed that results in a factor of ~ 3 = 1/\(\sqrt{0.1}\) mass-loss reduction compared to models with homogenous winds. We note that the mass-loss rate of WR 146 adopted in this study (Section 2) is from Dessart et al. (2000): it is based on spectral analysis with stellar atmosphere model with stellar-wind clumping taken into account.

Using thus derived mass-loss rates in a CSW model.
that assumes homogenous gas flows (stellar winds) means that we have explored a physical picture in which the dense clumps expand further out from the massive star itself. Thus, they ‘merge’ with each other and form a homogenous stellar wind well beyond the UV/optical line formation region but before the stellar winds collide in the wide binary system. However, even in such a case the adopted ‘basic’ mass-loss rates of the stellar components in WR 146 produce way too high an X-ray emission from the CSW region compared to what is required by the observations.

Then, could it be that the stellar winds of WR stars are two-component flows: the more massive component (dense clumps) are responsible for the optical/UV emission from these objects and the smooth rarefied component is a basic factor for their X-ray emission that comes from the CSW region in WR binaries?

Although such a physical picture may seem speculative, it could in general explain the discrepancy between the ‘optical/UV’ stellar wind parameters and their ‘X-ray’ values required by the corresponding CSW picture in wide binaries. However, based on numerical hydrodynamic simulations of ‘clumpy’ CSW in wide binaries Pittard (2007) concluded that clumps will dissolve in the CSW region and the X-rays emission will be very similar to that from smooth winds. Thus, introducing a two-component wind might not resolve the mass-loss issue discussed here.

But, a similar mass-loss mismatch has also emerged from analysis of the X-ray emission from wind-blown bubbles (WBB) around WR stars, that is from a different physical picture. Namely, theoretical hydrodynamic WBB models match very well the shape of the observed X-ray spectra but they again ‘require’ an appreciable reduction of the currently accepted mass-loss rates for the central star of the studied WBB: by a factor of $\sim 3-4$ for NGC 6888 (Zhekov & Park 2011); and almost by an order of magnitude for NGC 2359 (Zhekov 2014).

Summarizing this kind of results from modelling the X-ray emission from wide CSW binaries and wind-blown bubbles, we could say that they all seem to point to relatively small mass-loss rates from Wolf-Rayet stars, $M < 10^{-7} M_\odot$ yr$^{-1}$, and such values are in general atypical for these massive stars (e.g., see Crowther 2007 for a review on the physical properties of WR stars).

We thus think that more efforts are needed to build a self-consistent picture of the stellar winds from Wolf-Rayet stars that is based on global modelling of the WR emission in different spectral domains: e.g., radio, optical/UV, X-ray. Such an approach may also help reduce the uncertainties of the distances to WR stars. On the one hand, these uncertainties are not negligible since the distances to WR stars are not well constrained: e.g., as a rule most distances to WRs are ‘photometric’ (van der Hucht 2001). And, on the other hand, these uncertainties directly affect the results on the stellar wind parameters.

Along the same lines, could it be that such a mass-loss reduction is required not only for the WR stars but for other massive stars of early spectral type? For example, Parkin et al. (2014) reported that the mass-loss rates of the binary components in the O+O binary Cyg OB2 9 (Schulte 9) should be reduced by a factor of $\sim 7.5 - 7.7$ compared to their currently accepted values. This result is based on analysis (hydrodynamic modelling) of the X-ray emission in the framework of the CSW picture. We would like to emphasize that the CSW shocks in Cyg OB2 9 are in adiabatic regime, as they are in the case of WR 146 and other CSW binaries with WR components discussed above. This is an important detail since the physics of adiabatic CSWs (thus, their corresponding numerical modelling) is relatively simple from a technical point of view which makes the corresponding numerical results quite reliable.

We note that if future studies do justify the need of a considerable (of about one order of magnitude) reduction of the mass-loss rates in massive stars of early spectral type, this may have an important impact on our understanding of the physics of these objects. Namely, we will have a new and deeper insight of the driving mechanism of their stellar winds and the evolution of these massive stars as well, since the latter considerably depends on how they lose mass during their life time. Also, the evolution of massive stars of early spectral type is an important ingredient for understanding the physics of young stellar clusters and star-forming regions where these stars are born and where they have huge impact on their environment.

However, caution is advised before making such an important turn. We have to see first if such a mass-loss discrepancy emerges in other objects, thoroughly evaluate all these basic findings, and only then proceed with so general conclusions.

We thus think that a good approach for handling this issue is to adopt the global spectral modelling of the observational properties of massive stars (especially of Wolf-Rayet stars) in different spectral domains (e.g., radio, optical/UV, X-ray) as proposed above. This will show whether we could reconcile the results on mass-loss rates from different analyses, that is to see if a solution is possible all these results may converge on. Alternatively, such an approach may reveal some additional caveats in our understanding of the physics of stellar winds in massive stars or of the physics of fast shock, that result from the interaction of the highly supersonic flows (stellar winds) in massive binaries. Could it be that we are missing some key detail of the CSW physics in massive binaries that has a very important impact on the origin of X-rays in these objects? We believe that the global spectral modelling will help us clarify all that.

6 CONCLUSIONS

In this work, we presented an analysis of the X-ray emission from the massive binary WR 146 in the framework of the colliding stellar wind picture. The main results and conclusions from a direct comparison between the results from the numerical hydrodynamic CSW model and the Chandra and ROSAT data on this object are as follows.

(i) We confirm (see also Rauw et al. 2015) that there are no indications of long-term (of approximately two decades) variability in the X-ray emission from WR 146. This is in accord with the CSW picture in wide (in fact, spatially resolved) massive binaries.

(ii) CSW model spectra match well the shape of the observed X-ray spectrum of WR 146. There are indications that models with partial electron heating at the shock fronts (different electron and ion temperatures) with $\beta = T_e/T = 0.2 - 0.3$ ($T_e$ is the electron temperature and $T$ is the mean...
plasma temperature) to be a better representation of the X-ray data than those with complete temperature equalization. Also, the derived X-ray absorption from the spectral fits is consistent with the optical extinction to WR 146.

(iii) On the other hand, CSW models overestimate the observed X-ray flux (emission measure) considerably. To reconcile the model predictions and observations, the mass-loss rate of WR 146 must be reduced by a factor of 8 - 10 compared to the currently accepted value for this object (the latter already takes clumping into account).

(iv) Finally, the considerable mismatch between the mass-loss rates based on X-ray studies and those from analysis in other spectral domains for this and other WR stars makes us believe that we need to build a self-consistent picture of the stellar winds from such massive stars adopting a global spectral modelling of their properties.

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