Puzzling X-rays from the new colliding wind binary WR 65 (WC9d)

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ABSTRACT
We report the discovery of variability in the X-ray emission from the Wolf-Rayet type star WR 65. Using archival Chandra data spanning over 5 yr we detect changes of the X-ray flux by a factor of 3 accompanied by changes in the X-ray spectra. We believe that this X-ray emission originates from wind-wind collision in a massive binary system. The observed changes can be explained by the variations in the emission measure of the hot plasma, and by the different absorption column along the binary orbit. The X-ray spectra of WR 65 display prominent emission features at wavelengths corresponding to the lines of strongly ionized Fe, Ca, Ar, S, Si, and Mg. WR 65 is a carbon rich WC9d star that is a persistent dust maker. This is the first investigation of any X-ray spectrum for a star of this spectral type. There are indications that the dust and the complex geometry of the colliding wind region are pivotal in explaining the X-ray properties of WR 65.

Key words: stars:early-type – stars:Wolf-Rayet – stars: individual:WR 65 – X-ray:stars

1 INTRODUCTION
More than 54% of all Wolf-Rayet (WR) stars are in binary systems that consist of a WR and an OB-type star [Wallace 2007]. The collision between two stellar winds in these systems produces characteristic signatures in different wavelength bands that can include non-thermal radio emission [Eichler & Usov 1993], copious and variable X-rays [Stevens, Blondin & Pollock 1992], and dust emission in the infrared (IR) [Williams, van der Hucht & The 1987].

Subject of this Letter is the WC9d star WR 65. Williams, van der Hucht & The (1987) reported the presence of warm dust in this object. They discussed that in early-type WC stars an increase in the wind density provided by e.g. shock compression in colliding winds in binary systems may be sufficient to result in grain formation. Zubko (1998) found no need to invoke binarity to explain the presence of dust in late WC stars. He fitted the observed IR spectrum of WR 65 assuming a single star with mass-loss in the form of dust with $\dot{M}_d = 5.4 \times 10^{-10} M_\odot \text{yr}^{-1}$ and surrounded by a dust shell with an inner radius of 520 $R_\odot$. 

In a previous paper [Oskinova et al. 2003] we demonstrated that single WC type stars are X-ray quiet and proposed that all X-ray active WC stars must be in binary systems. X-ray emission from WR 65 was detected and tentatively explained as a result of wind-wind collision. In this paper we report on the X-ray light curve of WR 65 and changes in its X-ray spectra that unambiguously confirm its status as a colliding-wind binary (CWB).

Table 1. Coordinates of WR 65 from different sources

| Ref          | Band | RA J2000 | DEC J2000 |
|--------------|------|----------|-----------|
| Simbad       | opt  | 15h 13m 41s68 | -59d 11m 43s3 |
| Chapman et al. (1999) | radio | 15h 13m 41s49 | -59d 11m 43s8 |
| Chandra HRC-I | X-ray | 15h 13m 41s76 | -59d 11m 44s1 |
| Catalog USNO-B1.0 | opt  | 15h 13m 41s73 | -59d 11m 43s4 |

Figure 1. Archival Spitzer image (8 $\mu$m). WR 65 is the bright object at the bottom, close to the detector edge. The coordinates are galactic.

2 WR 65 AND ITS X-RAY LIGHT-CURVE
The coordinates of WR 65 from different sources are compiled in Table I. The coordinates from Simbad and the USNO-B1.0 catalog agree well with the source location in the Chandra HRC-I image. Except for WR 65 there are no other known objects at this position. WR 65 is a probable member of the cluster Pismis 20, which contains one more WR star, WR 67, and has a distance of $d = 3272 \pm 303$ pc [Turner 1994].

We fit the optical spectrum of WR 65 and its available photometry using the Potsdam Wolf-Rayet (PoWR) stellar atmosphere models [Hamann & Graefen 2003]. The deduced stellar parameters are listed in Table 2.
Therefore we paid special attention to the background subtracted on the peripheral region of the PWN mentioned above. DeLaney et al. (2006) find that it is constant over at least twelve years. We defined background regions as annuli around a stellar point source. Conveniently, the X-ray emission from the PWN is well studied in archival Chandra ACIS-I images of WR 65. The star is 7.5' or 1.4 pc. Given the strong mass-loss rate of WR 65 and its strong UV field, it is plausible that the nebula is physically associated with this star.

In the X-ray sky, WR 65 is located in a very interesting neighborhood (see Fig. 2). The star is 7.4 away from the supernova remnant (SNR) G320.4-1.2 and 4 away from the X-ray bright “Cir Pulsar” and its associated pulsar wind nebula (PWN). The SNR and the Cir pulsar are at the distance $d = 5.2 \pm 1.4$ kpc (Gaensler et al. 2002). This region of the sky is often observed, and serendipitous X-ray observations of WR 65 are in archives.

The most homogeneous data set found in archives is from Chandra ACIS-I observations conducted from year 2000 to 2005. In 2005 WR 65 was also observed on one occasion by Chandra HRC-I and twice by XMM-Newton. The WR 65 X-ray light curve gives strong evidence that the star is a colliding wind binary (CWB). Unfortunately, the light-curve is too sparse to search for the period. Given the time interval between the two recorded maxima, one may conclude that the period is not longer than about five years.

### 3 WR 65: X-RAY SPECTRAL VARIABILITY

Five of the Chandra observations of WR 65 yielded enough counts for a crude X-ray spectral analysis. The background-subtracted spectra obtained at different epochs are displayed in Fig. 3. The spectral energy distribution is harder than for single WR stars (Ignace, Oskinova & Brown 2003). The unresolved emission features coincide with the location of lines of Fe, Ca, Ar, S, Si, and Mg (cf. Figs. 4, 5) in collisionally ionized X-ray spectra. Interestingly, the iron lines at $\lambda 6.7$ keV (1.8 Å) are weaker at some epochs compared to others (e.g. they seem to disappear completely on 2005 February 07). If real, this may reflect the change of the temperature in the hot plasma.

The X-ray spectrum of WR 65 in high states displays strong emission features in the 2-4 Å range (see top panel in Fig. 4). Weak lines of Ca xx (λ 3.2 Å), Ca xx (λ 3.0 Å), and Ar xvii (λ 3.7 Å) are sometimes observed in the X-ray spectra of CWBs, e.g. the WC8 binary $\gamma$ Vel (Schild et al. 2004), the WN6 binary WR 25 (Raassen, van der Hucht & Mewe 2003), and the LBV binary $\eta$ Car (Hamaguchi et al. 2007). It seems plausible to assume that the unresolved Ca and Ar lines contribute to the emission “bump” at 2-4 Å in the WR 65 spectrum. However, the strength of this emission complex in WR 65 is much higher than observed in any other CWB. We rule out its origin from the background PWN emission, because there are no emission features at 2-4 Å in the spectra extracted from an annulus region around WR 65. In colliding wind binaries consisting of an OB star and a WC star, the latter has a significantly denser, C, O-enriched wind that is basically opaque for X-rays (Oskinova et al. 2003). When in the course of the orbital motion the wind collision region (WCR) is at superior conjunction relative to the WC star (with respect to the observer), the X-rays generated in the WCR suffer strong absorption. Despite many still unclear details, this general picture is observationally confirmed by the X-ray spectral analysis of the WC+O type binaries WR 140 and $\gamma$ Vel. In these systems the strongest photo-attenuation is seen in low X-ray states, while the lowest photo-

### Table 2. Stellar parameters of WR 65 (from Hamann et al., in prep.)

| $E_B$ | $\log L_{bol}/L_\odot$ | $v_w$ | $M_\odot$ | $L_{bol}/L_\odot$ |
|-------|----------------|-------|------------|----------------|
| 2.4   | 5.8 - 6.4      | $\geq 2000$ | $10^{-6}$ - $10^{-1}$ |

(a) depending on the adopted reddening law
(b) assuming a clumping contrast $D = 10$

Figure 2. Archival Chandra ACIS-I image (0.2-12.0 keV) of WR 65. The observation is from 18 Oct. 2005. The bright object in the upper-left corner of the image is the pulsar PSR B1509-58. WR 65 is projected onto the outskirts of the pulsar wind emission. The coordinates are equatorial (J2000). North up, east left.

Figure 3. X-ray (0.4-10.0 keV) light-curve of WR 65. The red dots show Chandra ACIS-I count-rates. The blue dots show count-rates converted to ACIS-I rates from Chandra HRC-I and XMM-Newton MOS (upper limit).
to the hard component, $N_{\text{H},2}$, exceeds the interstellar column density by a factor of more than two, but it is lower than the column density to the hard component, $N_{\text{H},1}$. This indicates that the hotter plasma is more deeply embedded.

From the spectrum obtained at 2005/10/18 the model flux is $F_X(0.6-9.0\,\text{keV}) = 1.2 \times 10^{-15}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$, which corresponds to $L_X = 1.1 \times 10^{32}\,\text{erg}\,\text{s}^{-1}$, or in terms of stellar bolometric luminosity to log $L_X/L_{\text{bol}} = -7.2...-7.8$. The flux of the soft spectral component, $F_X(0.6-2.0\,\text{keV}) = 8.3 \times 10^{-16}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}$, corresponds to $L_X(0.6-2.0\,\text{keV}) = 1.0 \times 10^{30}\,\text{erg}\,\text{s}^{-1}$ which is similar to the X-ray luminosity of a single O dwarf (Oskinov 2003).

Spectra observed at other epochs were also fitted with the 2T2N1h-model. For illustration, the spectrum obtained in the low state and its corresponding best-fit model are shown in Fig.7. Figure 8 shows the model parameters depending on the time of observation. Within the error bars, the temperatures $kT_1$ and $kT_2$, and the absorption column to the source for the soft component, $N_{\text{H},1}$, are similar at all observed epochs, and therefore are not plotted in Fig.8. In contrast, the column density to the hard component, $N_{\text{H},2}$, changes at different epochs (panel A of Fig.8). Variations in the EM of the hard and soft components are shown in panels B and C of Fig.8. The EM of the soft component changes strongly, reflecting the X-ray light curve variations, while the changes in the EM of the hard component are less pronounced.

**Figure 5.** Chandra ACIS-I spectra of WR 65 in high (red) and low (blue) states (obtained on 2000/08/14 and 2004/12/28 respectively). Wavelengths of strong spectral lines are indicated.

**Figure 4.** Chandra ACIS-I background subtracted spectra of WR 65 at different epochs. The date of the observation and the exposure time are given in each panel.

...the spectrum of WR 65 with highest signal-to-noise and its best-fit model are shown in Fig.5. The temperatures inferred from spectral fitting are $kT_1 = 1.0 \pm 0.2\,\text{keV}$ and $kT_2 = 13.4 \pm 7.3\,\text{keV}$. Such temperatures can be expected from the collision of metal enriched winds in wide binaries. The temperature is highest at the point of head-on collision, and is decreasing along the shock cone (Stevens, Blondin & Pollock 1992).

The interstellar absorption column density towards the Cir pulsar, $N_{\text{H},\text{int}} = 1 \times 10^{22}\,\text{cm}^{-2}$, is well constrained and is consistent with the color excess inferred from our fitting of the WR 65 spectral energy distribution. The neutral hydrogen column densities are $N_{\text{H},1} = (2.3 \pm 0.3) \times 10^{21}\,\text{cm}^{-2}$ for the soft component and $N_{\text{H},2} = (12.2 \pm 4.1) \times 10^{22}\,\text{cm}^{-2}$ for the hard component. The column density to the soft component, $N_{\text{H},1}$, is well constrained and consistent with the interstellar column density to the hard component, $N_{\text{H},2}$. This indicates that the hotter plasma is more deeply embedded.
4 Discussion

The main findings from the analysis of WR 65 X-ray spectra obtained at different epochs are: (i) the spectra display emission features at the wavelengths of the lines of strongly ionized Fe, Ca, Ar, Si, and Mg; (ii) the star shows strong spectral X-ray variability; (iii) the spectra can be fitted with a two-temperature model, consisting of a soft component with $0.3 < kT_1 < 1.5$ keV and a hard component with $2 < kT_2 < 20$ keV; (iv) the absorption for the hard component is strong and variable, while the absorption for the soft component is less severe and nearly constant; (v) the changes in the EM are due to the wind of the WC star immediately after periastron passage. Quite different from the short-duration rise of column density observed in WR 140 and η Car, the column density in WR 65 is persistently very high, $N_{H2} \sim 10^{23}$ cm$^{-2}$, sharply decreasing only at the maximum X-ray light.

The temporary variations of column density in WR 65 are similar to those measured in the WC8+O binary $γ^2$ Vel (Rauw et al. 2000). Its hard X-ray emission increases by a factor of ~4 when column density decreases by factor of ~2 during the passage of weak-wind inner side of the shock cone across the line of sight (Willis, Schild & Stevens 1995; Rauw et al. 2000; Schild et al. 2004).

In WR 65 the soft X-ray emission is present at all observed epochs. Its variation can be explained by changing emission measure, while the absorption is nearly constant and comparably low. A soft spectral component in the low state is observed in WR 140 and η Car. The origin of soft X-rays in these stars is attributed either to individual stellar winds or to a circumstellar nebula. Accordingly, in these objects the absorbing column to the soft component is similar to the interstellar absorbing column. In contrast, we find for WR 65 that $N_{H}\text{soft} < N_{H1,1} < N_{H1,2}$ and the EM of the soft component changes with the X-ray light-curve. Thus it is

![Figure 6. ACIS-I spectrum of WR 65 obtained on 2005/10/18 and the best fit spectral model -- $tbabs(N_{H1}) \times apec(kT_1) + tbabs(N_{H2}) \times apec(kT_2)$. The xspec spectral fitting package was used. For the model parameters see text.](image)

![Figure 7. Same as in Fig. 6 for the spectrum obtained on 2004/12/28.](image)

![Figure 8. Upper panel same as in Fig. 6. Panel A: variations of absorption column density of the hard component obtained from spectral fits. Panel B: normalization factor that characterizes the emission measure of the hard component. Panel C: normalization factor of the soft component.](image)
unlikely that the intrinsic wind emission of a companion is solely responsible for the soft X-rays from WR 65. WR 65 is a persistent dust maker (van der Hucht 2001). Monnier et al. (2002) notice that binary stars that are persistent dust makers have nearly circular orbits. We can assume that the same holds for WR 65. There is a growing number of WC9d binary stars that constitute the “pinwheel” class of objects (Tuthill et al. 2008; Marchenko & Moffat 2007). In these binary systems the dust is formed in the wind collision region and is distributed along a wide (compared to the orbital separation) Archimedean spiral. The peak of dust production occurs at some distance downstream from the colliding wind stagnation point.

So far there is no direct evidence that WR 65 is a pinwheel. However, the topology and structure of circumstellar matter in a pinwheel could help to explain X-ray spectral variability in WR 65. Wilms, Allen & McCray (2000) presented a model for the absorption of X-rays that includes a treatment of dust grains. Their work confirmed that large-grain absorption for soft X-rays (< 2 keV) is reduced due to the self-blanketing of grains. Interestingly, from the point of view of radiative transfer this is identical to the reduction of opacity for the X-rays in clumped stellar winds (Feldmeier, Oskinova & Hamann 2003). Winds of WC stars are extremely rich in C and O and could have enhanced abundance of Mg and Ne. C and O are dominant absorbers for the softer X-rays (< 1 keV), while Mg and Ne strongly contribute to the absorption of harder X-rays (> 1 keV). In the dusty shell around a WC9d star, C would be depleted from the gaseous phase and form grains, reducing the opacity for the softer X-rays. This may help to explain the large differences between the column densities that we determine from soft and hard X-rays.

Recently, Lemaster, Stone & Gardiner (2007) presented 3-D hydrodynamical simulations of colliding winds. Scaling the results of their simulation to the parameters of WR 65, soft X-ray emission could originate from a large volume extending above the orbital plane. This emission would show little variation with orbital phase and suffer comparably mild absorption in the outer regions of the WC star wind, similarly to what is observed in WR 65. On the other hand, a high postshock temperature of $kT \approx 10$ keV is predicted for a confined region near the point where the winds collide head-on. Densities up to $\rho \approx 10^{14}$ g cm$^{-3}$ can be expected in the dusty spiral arms. Assuming the wind opacity for hard X-rays as $\kappa \approx 5$ cm$^2$ g$^{-1}$ (Antokhin, Owocki & Brown 2004), a spiral arm width of $10^4$ cm would explain the observed high absorption. This width is consistent with the observed width of the dusty spiral arms in WR 104 (Tuthill et al. 2008). The lowest absorbing column can be expected at the phase when the line of sight crosses only the outer low density part of the spiral arms. It is possible that the Chandra observations of WR 65 at high state have caught this orbital phase.

To conclude, our first brief study of the variable X-ray emission from WR 65 indicates that it is a colliding wind system, where the dust and complex geometry of its colliding wind region are pivotal in explaining its X-ray properties. At present, WR 65 is the only known WC9d star where X-ray emission is detected. Future observations are needed to constrain the orbital parameters of WR 65 and allow for detailed modeling.

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