CHANDRA DETECTS THE RARE OXYGEN-TYPE WOLF–RAYET STAR WR 142 AND OB STARS IN BERKELEY 87

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ABSTRACT

We present first results of a Chandra X-ray observation of the rare oxygen-type Wolf–Rayet (WR) star WR 142 (= Sand 5 = St 3) harbored in the young, heavily obscured cluster Berkeley 87. Oxygen-type WO stars are thought to be the most evolved of the WRs and progenitors of supernovae or gamma-ray bursts. As part of an X-ray survey of supposedly single WR stars, we observed WR 142 and the surrounding Berkeley 87 region with Chandra ACIS-I. We detect WR 142 as a faint yet extremely hard X-ray source. Due to weak emission, its nature as a thermal or non-thermal emitter is unclear and thus we discuss several emission mechanisms. Additionally, we report seven detections and eight non-detections by Chandra of massive OB stars in Berkeley 87, two of which are bright yet soft X-ray sources whose spectra provide a dramatic contrast to the hard emission from WR 142.

Key words: open clusters and associations: individual (Berkeley 87) – stars: individual (WR 16, WR 142 = Sand 5 = St 3, BD+36 4032, HD 229059, V439 Cyg) – stars: Wolf–Rayet – X-rays: stars

1. INTRODUCTION

Wolf–Rayet (WR) stars are massive, highly evolved stars nearing the end of their lives as supernovae (SNe) or as collapsing objects emitting gamma-ray bursts (GRBs; e.g., MacFadyen & Woosley 1999; Postnov & Cherepashchuk 2001; Georgy et al. 2009). WR stars undergo rapid mass loss through strong winds, with initial masses of ≥25 M⊙ (Crowther 2007). The classification of WR stars is determined spectroscopically in the optical and is divided among the nitrogen-rich WNs, carbon-rich WCs, and oxygen-rich WOs. For the most part, single WR stars are thought to follow the evolutionary path: O → (LBV/RSG) → WN → WC → WO → SN (or GRB) (Conti et al. 1983; Crowther 2007). The initial mass of the O star determines whether it passes through an intermediate luminous blue variable (LBV) or red supergiant (RSG) phase (Crowther 2007).

Sanduleak (1971) noticed a class of stars that did not have planetary nebulae (PNe) but displayed a WR-like spectrum with strong O vi doublet emission similar to those found in the central stars of PNe named the O vi sequence by Smith & Aller (1969). These stars were suggested to be a separate SO sequence of WR stars (rather than an extension of the WC sequence) by Barlow & Hummer (1982). WO stars are thought to be in the late helium-burning stage, or possibly the carbon-burning stage, where the enhanced oxygen abundance compared to less-evolved WR stars is revealed by mass-loss stripping (Barlow & Hummer 1982). Of the 298 galactic WR stars in the appended Vllth catalog of galactic WR stars (van der Hucht 2001, 2006), only four are of the rare WO spectral type, including the star WR 142, also known as Sand 5 (Sanduleak 1971) and St 3 (Stephenson 1966). Crowther et al. (1998) developed a new classification scheme using primary and secondary oxygen line ratios that confirmed previous classifications of WR 142 as a member of the subclass WO2 (Barlow & Hummer 1982; Kingsburgh et al. 1995).

Despite new discoveries of WR stars in the galactic plane, including a WO type as the exciting star of the PN Th 2-A (Weidmann et al. 2008), little is yet understood about the mechanisms that drive high-energy processes such as X-ray emission in single WR stars, particularly so for the rare WO stars. Although WR stars have much stronger winds and are more evolved chemically, the line-driven instabilities that are thought to give rise to soft X-rays (kT < 1 keV) from shocks in O star winds may also be present in WR winds (Gayley & Owocki 1995). If that is the case, then WR stars may also be capable of producing soft X-rays from radiative wind shocks (Baum et al. 1992).

Few single WR stars had been studied with high sensitivity in X-rays until recently. Thus far, several apparently single WN stars have been observed to emit X-rays (Skinner et al. 2002; Ignace et al. 2003; Oskinova 2005). An ongoing Chandra and XMM-Newton survey has recently detected the apparently single WN stars WR 2, WR 18, WR 79a, and WR 134 with X-ray luminosities log LX ≈ 32.2–32.7 erg s−1 (Skinner et al. 2010b), comparable to some WR+OB binaries like γ Vel (WC8+O7) with log LX = 32.9 erg s−1 (Skinner et al. 2001) or WR 147 (WN8+OB) with log LX = 32.83 erg s−1 (Skinner et al. 2007; see also Section 4.4). Only upper limits of log LX < 29.82–30.97 erg s−1 exist from observations of single WC stars (Oskinova et al. 2003; Skinner et al. 2006). The WC sequence is thus either faint in the X-rays or possibly X-ray quiet. WR 142 just recently became the first WO star to be detected in the X-rays using XMM-Newton (Oskinova et al. 2009).

WR 142 resides in the open cluster Berkeley 87. Table 1 summarizes the general properties of WR 142. Berkeley 87 lies in a heavily obscured region of the Milky Way in Cygnus. Initial cluster age estimates of ∼1–2 Myr (Turner & Forbes 1982, hereafter TF82) have now been revised upward. A study restricted to three of the highest mass cluster stars suggests a slightly older age of ∼3 Myr (Massey et al. 2001). A more recent study (Turner et al. 2010) gives ∼5 Myr. Berkeley 87 is an interesting cluster containing ≈105 cluster members identified by an optical study (TF82), B-supergiants
Table 1: Stellar Properties of WR 142

| Parameter | Value | Notes¹ |
|-----------|-------|--------|
| Spectral type | WO2 | (1)(2) |
| Age (Myr) | ∼3–5 | (3) |
| d (pc) | 1230 ± 40 | (4) |
| V (mag) | 13.4 | (2) |
| Av (mag) | 6.1 | (5) |
| J, H, Kₜ (mag) | 9.54, 8.89, 8.60 | (6) |
| log M/M⊙ | 0.9 ± 0.2 | (7) |
| M (Mₜ yr⁻¹) | 1.7 × 10⁻⁵ | (8) |
| vₚ (km s⁻¹) | 5500 ± 200 | (2) |
| log Lₚ/νc (erg s⁻¹) | 38.2 | (9) |
| log Lₚ/L⊙ | 5.35, 5.65 | (10) |

Note. ¹ References and Notes. (1) Crowther et al. 1998; (2) Kingsburgh et al. 1995; (3) Massey et al. 2001; Polcaro & Norci 1998; Turner et al. 2010; (4) Turner et al. 2006; (5) van der Hucht 2001, using Av = 0.9Aᵥ; (6) 2MASS Point Source Catalog; (7) Smith et al. 1994; (8) unclumped value from Barlow 1991, clumping could reduce M by a factor of ∼2–4 (Crowther 2007); (9) Polcaro et al. 1991, also log Lₚ = (1/2)M⁄₂₂; (10) determined by fitting photometric observations using a range of clamped mass-loss rates; Oskinova et al. 2009.

including HD 229059, an O8.5–9OB star BD+36 4032, a possible LBV Be star V439 Cyg, and the pulsating M3-supergiant BC Cyg. Additionally, OH masers and compact H II regions trace massive star formation 3′–9′ north of WR 142 (Argon et al. 2000; Matthews et al. 1973). At a distance of 1230 ± 40 pc (Turner et al. 2006), the proximity of Berkeley 87 offers ample opportunity to look about the properties of rare objects such as WR 142 as well as the surrounding cluster.

As part of an X-ray survey aimed at determining if single WR stars that are not known to be in binary systems are X-ray emitters (specifically which spectral types), we observed WR 142 with Chandra. We are unaware of any evidence pointing to a companion of WR 142. WR 142 was chosen over other WO stars because of its relatively nearby distance, low AV compared to other WR stars, and interesting surrounding cluster. Its astonishing supersonic wind (vₚ = 5500 km s⁻¹; Kingsburgh et al. 1995) and an unusual optical detection of diffuse emission from the C IV doublet (Polcaro et al. 1991) that is a signature of shocked gas make WR 142 an even more interesting target as one of the few oxygen-type WR stars.

The primary objective of the study presented here is to determine the X-ray properties of WR 142. X-ray emission from WR 142, we used the CIAO wavdetect tool. We ran wavdetect on full-resolution images using events in the 0.3–8 keV range, chosen to reduce background. The wavdetect threshold was set at sigthreshold = 1 × 10⁻⁵. Scale sizes of 1, 2, 4, 8, and 16 were used. The 3σ extraction region determined for WR 142 by wavdetect was an ellipse with an area of ≈11.25 pixels² (Figure 1) and was used for spectral and timing analysis. The CIAO task srextent, which utilized PSF information, was also used to determine the source size of WR 142 and determine if its emission is point-like or extended.

Within the 0.3–8 keV energy range, light curves were extracted using CIAO dmextract and source variability was tested by two different methods. Using unbinned photon arrival times, we applied the Kolmogorov–Smirnov (KS) test (Press et al. 1992). For comparison, the Gregory–Loredo (GL) algorithm (Gregory & Loredo 1992, 1996) was used by applying the CIAO glvary⁶ tool.

CIAO specextract was used to extract source and background spectra. The tool specextract also created response matrix files (RMFs) and auxiliary response files (ARFs). Spectral analysis utilized the HEASOFT Xanadu⁷ software package including XSPEC version 12.5.0. The background region was chosen to be a source-free annulus centered on WR 142 of r = 4 to r = 16 pixels. From this region, we estimate < 1 background count (0.3–8 keV) inside the 3σ elliptical source region for WR 142. The background inside the source region is negligible relative to the number of source counts.

3. RESULTS

3.1. Imaging and Source Identification

WR 142 is detected by Chandra as an X-ray source at J202144.35+372230.7 (Figure 1). Table 2 summarizes some properties of the X-ray emission from WR 142. These coordinates are the source centroid as determined by wavdetect using

⁶ See http://asc.harvard.edu/proposer/POG.
⁷ Further information on Chandra Interactive Analysis of Observations (CIAO) software can be found at http://asc.harvard.edu/ciao.
⁸ http://cxc.harvard.edu/ciao/ahelp/glvary.html
⁹ The Xanadu X-ray analysis software package is developed and maintained by NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC). See http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html for further information.
an energy-filtered image (0.3–8 keV). Without further astrometric calibration, the Chandra ACIS-I absolute position has an accuracy of ≈0′.4 (68% limit).\textsuperscript{10} The X-ray position of WR 142 is in exact agreement with the Two Micron All Sky Survey (2MASS) position of J202144.35+372230.7. Additionally, the Chandra position has offsets from optical counterparts of only 0′.20 from the USNO-B1.0 source at J202144.35+372230.9 and 0′.23 from the Hubble Space Telescope (HST) GSC 2.3.2 source at J202144.36+372230.5. All offsets are well within the positional accuracy of Chandra.

Results from the CIAO tool sremove indicate that WR 142 is not extended. Use of a PSF file specifically tailored for our observation with the WR 142 spectrum and the position of WR 142 on the ACIS-I detector yields a source size of only 0′.52 (0′.41–0′.64, 90% confidence), equivalent to about one ACIS pixel, and a PSF size of 0′.85 (0′.66–1′03, 90% confidence). Thus, the X-ray emission of WR 142 is not extended at the 90% confidence level.

3.2. Spectral Analysis

The X-rays from WR 142 are weak but extremely hard, with a mean photon energy of 4.31 keV (Table 2). Surprisingly, WR 142 does not exhibit any significant emission below 2 keV and there is no evidence of a soft component (Figures 2 and 3). We find only one event below 2 keV, with an energy of 1.89 keV. This is in contrast to a faint soft component at $E \leq 1$ keV in the XMM-Newton EPIC MOS spectrum of WR 142 reported by Oskinova et al. (2009). Assuming that no variability occurred in the WR 142 source spectrum or $N_H$ between the two observations, the most likely explanation for this difference would be the much lower effective area of Chandra ACIS-I at low energies $E \leq 1$ keV.

We tried to fit the spectrum of WR 142 (Figure 3) with several different models: a 1T (one temperature) APEC

Notes. X-ray data using events in the 0.3–8 keV range within a 3σ wavdetect ellipse, which for WR 142 is ≈11.25 pixel\textsuperscript{2}. Tabulated quantities are: J2000.0 X-ray position (R.A., decl.); net counts and net counts error from wavdetect (accumulated in a 70,148 s exposure, rounded to the nearest integer, background-subtracted, and PSF-corrected); 25%, 50%, and 75% photon quartile energies ($E_{25}$, $E_{50}$, and $E_{75}$), mean photon energy ($\langle E \rangle$); probability of constant count rate determined by the KS test and the GL algorithm, where $P_{\text{const}} \leq 0.05$ would indicate likely variability; spectral type as indicated by SIMBAD or otherwise noted; and HST GSC candidate counterpart identification within a 2″ search radius. The offset (in parentheses) is given in arcseconds between the X-ray and counterpart position. Ellipses indicate insufficient counts for reliable measurement.

\textsuperscript{a} Faint B stars not detected: Berkeley 87 Nos. 7 (B), 9 (B0.5 V), 15 (V439 Cyg, B0e B[e]—references in Section 4.3), 16 (B2 V), 18 (B1 V), 31 (B1 V), 34 (B), and 38 (B2 III). Spectral types are from the SIMBAD database.

\textsuperscript{b} Spectral type from Massey et al. (2001).

\textsuperscript{c} Two close HST sources have nearly the same sexagesimal coordinates and are indistinguishable by Chandra.

\textsuperscript{d} Spectral type references in Table 1.

\textsuperscript{10} http://cxc.harvard.edu/cal/ASPECT/celmon/
Figure 2. Histogram showing the observed X-ray event energies for WR 142 in the energy range from 0.3 to 12 keV (wavdetect 3σ ellipse extraction region). The bin size is 1 keV.

optically thin plasma model and a power-law model. The APEC model requires a very high temperature and thus a thermal bremsstrahlung model is similar. Because of low counts, the spectral fit results were somewhat sensitive to binning strategy. Representative spectral fits are shown in Table 3, based on fits of unbinned spectra. Between the different models, there is little variation in the quality of fit using C-statistics (Cash 1979). However, determining whether a particular model is statistically acceptable using C-statistics is not as straightforward as with χ² statistics (Heinrich 2003).

Allowing the abundances to vary from solar displays no significant improvement to the APEC fits, nor does the use of representative WO abundances (Table 3). This is largely because we do not detect any emission lines in the spectrum from elements such as O which are highly non-solar in WO stars. Additionally, all of the O and C lines that lie in the Chandra bandpass are below 1 keV where we do not detect any signal.

The data show a slight preference for a model that includes a Gaussian line for an iron line in the ≈6.4–6.67 keV energy range (Table 3). The counts from WR 142 are not sufficient to distinguish between the possible iron lines. The event energies closest to the possible iron emission, 6.24, 6.40, 6.60, and 6.63 keV, show two events within 0.1 keV of the iron K line complex at 6.67 keV (Fe xxv He-like triplet). If a weak Fe line is present, it is likely to be the 6.67 keV iron K line, which has been detected in other WR stars.

We have also experimented with fits of binned spectra using χ² statistics in order to estimate confidence bounds on important fit parameters (F_X, N_H, kT, Γ_pow). Given the limited number of counts (46), binning at desired levels of >10 counts per bin for fitting with χ² statistics was not feasible. We thus consider spectra binned to a minimum of 6 counts per bin. Results indicate that if the plasma is thermal, as the APEC models assume, then the temperature kT must be very high, with a lower 90% confidence bound of kT > 3.6 keV (Table 3). The Chandra data do not place a useful upper bound on kT.

In determining the X-ray flux, the unbinned spectral fits display fairly consistent results. The fit with the lowest C-statistic shown in Table 3 gives an observed (absorbed) X-ray flux of F_X = 1.8 [0.8–2.5] × 10⁻¹⁴ erg s⁻¹ cm⁻² (0.3–8 keV, 1σ confidence intervals). The error bounds reflect the range of fluxes measured for the different models in Table 3. The best-fit models give X-ray luminosities of log L_X = 30.72–30.82 (erg s⁻¹), which are derived from unabsorbed fluxes (0.3–8 keV) resulting from different unbinned spectral fits in Table 3.

All indications are that the absorption toward WR 142 is high, with N_H around (4–5) × 10²² cm⁻². This is about 3–4 times higher than the absorption estimated from the observed optical extinction of 1.3 × 10²² cm⁻² obtained using A_V ≈ 6.1 (van der Hucht 2001; Gorenstein 1975 conversion). Spectral fits of WR 142 with N_H fixed at the value determined from optical extinction give much larger fit residuals than the fits with larger absorption given in Table 3.

3.3. Timing and Variability Analysis

The source shows no obvious large-scale variations nor flares in its X-ray light curve (Figure 4). As for short-term variability, KS statistics and the GL algorithm give a probability of constant count rate of 0.77 and 0.40, respectively. Thus, neither test implies variability at high confidence levels (>90%) on timescales of hours during the <1 day Chandra observation.
For purposes of comparing the observed X-ray flux by Chandra and the previously published XMM-Newton X-ray flux of $F_X = (4 \pm 2) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ from 0.25 to 12 keV (Oskinova et al. 2009), we measure $F_{X} = (3 \pm 1) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ using an average value of the fluxes from the extended energy range from the three models shown in Table 3. Thus, Chandra and XMM-Newton X-ray fluxes agree to within the uncertainties. Based on the above flux comparison, any variability over the approximate one year interval between the Chandra and XMM-Newton observations was a factor of $\sim 3$ or less.

### 3.4. Summary of WR 142 X-ray Properties

Based on the Chandra data discussed above, the X-ray properties of WR 142 can be summarized as follows: (1) source structure is consistent with a point source at Chandra’s angular resolution; (2) no significant variability is detected over a timescale of $\sim 1$ day; (3) strong X-ray absorption below 2 keV, with an absorption column density ($N_H$) that is a factor of $\sim 3$–4 greater than expected from published optical estimates; (4) no evidence for a soft X-ray component below 2 keV; (5) a spectrum dominated by hard X-rays above 2 keV that can be fit equally well using a very high temperature thermal plasma model or a power-law model; and (6) a relatively low X-ray luminosity $L_X(0.3–8 \text{ keV}) = 30.7–30.8 \text{ erg s}^{-1}$ at $d = 1.23$ kpc, which is $\sim 10$ times less than found for two X-ray bright OB stars in Berkeley 87 (Section 4). We discuss these properties in more detail below.

### 4. OB STARS IN BERKELEY 87

In this section, we comment briefly on OB stars in Berkeley 87 contained in the Chandra FoV. We report Chandra detections of seven OB stars and identify eight undetected B-type stars (Table 2) that are likely cluster members (TF82). Figure 1 shows the relative positions of the X-ray bright stars and the noteworthy non-detection of the LBV candidate V439 Cyg.

#### 4.1. BD+36 4032

This star was classified as O9V by TF82 (Berkeley 87-25) and was the only object explicitly identified as an O-type star in their catalog of 105 likely members of Berkeley 87. The spectral type was later refined to O8.5 III by Massey et al. (2001), who also estimated the mass to be $M_\odot = 39 M_\odot$. BD+36 4032 lies $\sim 3$ northwest of WR 142.

X-ray characteristics are listed in Table 2. The X-ray spectrum is soft (Figure 3) with almost all of the emission emerging below 2 keV, which is dramatically different than the hard emission from WR 142. Reasonably good fits can be obtained using a solar abundance 1T APEC model with a cool plasma component at $kT \approx 0.6$ keV (Table 4). The 1T APEC fit can be improved slightly by adding a second temperature component between 1 and 2 keV, but almost all of the emission measure still resides in the cool component.

The best-fit $N_H$ given in Table 4 equates to $A_V = 5.1$ [4.4–6.5] mag (Gorenstein 1975). This is in good agreement with the optically determined value $A_V = 4.8$ mag using $E(B - V) = 1.60$ and $A_V = 3E(B - V)$ (TF82). Thus, the

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**Table 3**

| Parameter | IT APEC | POWER | POWER + GAUSS |
|-----------|---------|-------|---------------|
| $N_H (10^{22} \text{ cm}^{-2})$ | 5.66 | 4.61 | 4.55 |
| $kT$ (keV) | $\{20\}$ | $\cdots$ | $\cdots$ |
| norm ($10^{-13}$) | 6.36 | $\cdots$ | $\cdots$ |
| $\Gamma_{\text{pow}}$ | $\cdots$ | 1.0 | $\{1.0\}$ |
| $\text{norm}_{\text{pow}}$ ($10^{-6}$) | $\cdots$ | 2.31 | 2.32 |
| $E_{\text{line}}$ (keV) | $\cdots$ | $\cdots$ | [6.67] |
| $\sigma_{\text{line}}$ (keV) | $\cdots$ | $\cdots$ | [0.05] |
| $\text{norm}_{\text{line}}$ ($10^{-6}$) | $\cdots$ | $\cdots$ | 8.68 |
| Abundances$^d$ | WO | $\cdots$ | $\cdots$ |
| C-statistic$^c$ | 215.90 | 215.08 | 214.73 |
| $F_X$ ($10^{-14}$ erg cm$^{-2}$ s$^{-1}$) | 1.65 (3.66) | 1.74 (2.93) | 1.77 (2.96) |
| $F_{X,\text{line}}$ ($10^{-16}$ erg cm$^{-2}$ s$^{-1}$) | $\cdots$ | $\cdots$ | 8.66 (9.28) |
| log $L_X$ (erg s$^{-1}$) | 30.82 | 30.72 | 30.73 |

**Notes.** Based on fits of ACIS spectra using XSPEC v12.5.0. The data were unbinned and not background subtracted (background is negligible). The tabulated parameters are absorption column density ($N_H$), plasma temperature ($kT$), XSPEC normalization (norm), photon power-law index ($\Gamma_{\text{pow}}$), power-law model normalization (norm$_{\text{pow}}$), Gaussian line centroid energy ($E_{\text{line}}$), line width ($\sigma_{\text{line}}$ = FWHM/2.35), and line normalization (norm$_{\text{line}}$). Quantities enclosed in curly braces were held fixed during fitting. WO abundances are from Table 1 of van der Hucht et al. (1986), except the hydrogen and nitrogen abundances are arbitrarily set to the small non-zero value $1 \times 10^{-6}$ of van der Hucht et al. (1986), except the hydrogen and nitrogen abundances. Solar values from Anders & Grevesse (1999) are used for any elements assumed (Turner et al. 2006). a timescale of 1 day; (3) strong X-ray absorption below 2 keV, with an absorption column density ($N_H$) that is a factor of $\sim 3$–4 greater than expected from published optical estimates; (4) no evidence for a soft X-ray component below 2 keV; (5) a spectrum dominated by hard X-rays above 2 keV that can be fit equally well using a very high temperature thermal plasma model or a power-law model; and (6) a relatively low X-ray luminosity $L_X(0.3–8 \text{ keV}) = 30.7–30.8 \text{ erg s}^{-1}$ at $d = 1.23$ kpc, which is $\sim 10$ times less than found for two X-ray bright OB stars in Berkeley 87 (Section 4). We discuss these properties in more detail below.
A second temperature component. The model. No significant fit improvement was obtained by adding triplet (1.84–1.87 keV).

One noticeable difference is that of BD+36 4032 (Figure 3). One noticeable difference is that agrees to within the model uncertainties with that expected from which is likely due to stronger line emission from the Si HD 229059 shows stronger emission in the 1.8–1.9 keV range, assigned a spectral type B2 Iabe but Massey et al. (2001) 2MASS data giving

K source with 2MASS data giving

A kT (keV) 0.56 [0.35–0.69]

norm (10−4) 1.16 [0.69–4.31]

χ²/dof 1.32

F_X (10−13 erg cm−2 s−1) 0.20 (2.91)

log L_X (erg s−1) 31.72

Notes. Based on fits of ACIS spectra binned to a minimum of 10 counts per bin using XSPEC v12.5.0. Square brackets enclose 90% confidence intervals. An ellipsis means the algorithm used to compute 90% confidence limits did not converge. The X-ray flux is the absorbed value, followed in parentheses by the unabsorbed value. A distance of 1.23 kpc is assumed. Solar abundances are from Anders & Grevesse (1989).

excess X-ray absorption detected in WR 142 is not present toward this O star.

4.2. HD 229059
This B supergiant has V = 8.71 mag and was the brightest member of Berkeley 87 listed by TF82 (Berkeley 87-3). They assigned a spectral type B2 Iabe but Massey et al. (2001) classified it as B1 Ia.

The Chandra spectrum of HD 229059 is nearly identical to that of BD+36 4032 (Figure 3). One noticeable difference is that HD 229059 shows stronger emission in the 1.8–1.9 keV range, which is likely due to stronger line emission from the Si Xiii triplet (1.84–1.87 keV).

Spectral fits of HD 229059 give nearly identical results to BD+36 4032. Table 4 summarizes the best-fit 1T APEC model. No significant fit improvement was obtained by adding a second temperature component. The N_H from Table 4 gives A_V = 5.2 [4.5–5.6] mag, in excellent agreement with the optically determined value A_V = 5.1 mag (TF82). Thus, we find no excess X-ray absorption toward HD 229059.

4.3. Berkeley 87-4
This B0.2 III star lies ≈5′1 west of WR 142 and is object number 4 in the list of likely cluster members compiled by TF82. It was included in the study of Massey et al. (2001) who obtained a mass estimate M = 23 M_⊙. Berkeley 87-4 was the third brightest Chandra X-ray detection of the OB stars in Berkeley 87 (Table 2). There are sufficient counts for a crude spectral fit, and a 1T APEC model gives N_H and kT values that are similar to the brighter OB stars BD+36 4032 and HD 229059 but a lower X-ray luminosity (Table 4). The X-ray-derived N_H agrees to within the model uncertainties with that expected from optical reddening (TF82).

4.4. V439 Cyg
This variable star is also known as MWC 1015 and is object number 15 in the list of likely cluster members compiled by TF82. V439 Cyg has anomalous colors and is displaced well to the redward side of the zero-age main-sequence in the cluster color–magnitude diagram (TF82). The star’s spectrum is peculiar and evidently variable, with most recent studies assigning an early B spectral type of B0e (Polcaro & Norci 1998) or B[e] (Massey et al. 2001). V439 Cyg shows some similarities to an LBV (Polcaro & Norci 1998).

V439 Cyg lies ≈3′2 NW of WR 142 and is a bright near-IR source with 2MASS data giving K_s = 7.59 mag and position 2MASS J202133.57+372451.57. There is no X-ray source at or near this position in our Chandra image. A circular region of radius 1′96 (90% encircled energy at E = 2 keV11) centered on the V439 Cyg 2MASS position encloses only one photon in the ACIS-I image (0.3–8 keV range).

To compute an X-ray upper limit, we assume a conservative 4 count ACIS-I detection threshold and an intrinsic thermal stellar spectrum similar to the two OB stars discussed above. Using N_H = 1.0 × 10^{22} cm^{-2} corresponding to E(B − V) = 1.53 (TF82) and a Raymond–Smith solar-abundance thermal plasma model with kT = 0.6 keV, the Chandra PIMMS12 simulator gives an unabsorbed flux upper limit F_X (0.3–8 keV) ≲ 3.9 × 10^{−15} erg cm^{-2} s^{-1}. If V439 Cyg is a cluster member, then d = 1.23 kpc gives log L_X ≤ 29.85 (erg s^{-1}).

Given the unusual nature of V439 Cyg, further consideration of its X-ray non-detection is warranted. In this regard, it is important to note that Chandra detected only the most luminous B stars in the cluster having absolute magnitudes m_V ≤ −2.1 (Section 4.5). Several less-luminous early B stars were undetected (Table 2 notes). This is likely a consequence of the known L_X ∝ L_Bol trend for O and early B-type stars (Berghöfer et al. 1997). The absolute magnitude of V439 Cyg is not well known due to uncertain reddening, but it appears to lie at or near the m_V cutoff for our Chandra detections (Figure 7 of TF82). Thus, V439 Cyg may have insufficient L_Bol to produce an X-ray luminosity above the Chandra detection threshold.

Excess absorption toward V439 Cyg may have also partially contributed to its non-detection. The anomalous colors of V439 Cyg imply excess reddening, and it may be surrounded by a shell of material that was ejected during a previous mass-loss phase (Polcaro & Norci 1998). A gas-rich shell would increase the line-of-sight photoelectric absorption to lower energy X-rays (E < 1 keV).

If V439 Cyg is indeed an LBV (Polcaro & Norci 1998), it could be evolving into the WN phase. For stars of initial masses ~40–75 M_⊙, the evolutionary sequence is (Crowther 2007): O → LBV → WN_H–post. Some putatively single WN7–9 stars (also known as WNL stars) have so far gone undetected in X-rays (Figure 5). But a few recent WNL detections have been reported, including an unambiguous detection of the apparently single WN9ha star WR79a (Skinner et al. 2010b), a possible faint detection of WR 16 (WN8h) in a recent XMM-Newton observation (Figure 5), and a new Chandra detection of the.

11 http://cxc.harvard.edu/cal/Calsoft/psf/eer_on.html
12 For information on Portable Interactive Multi-Mission Simulator (PIMMS), see http://cxc.harvard.edu/iao/ahelp/pimms.html.
WN component of the close WR+OB binary system WR 147 (Zhekov & Park 2010). Although the nature and evolutionary status of V439 Cyg remain somewhat of a mystery, its X-ray non-detection would not be in discord with an evolved star that is approaching the WNL phase, given that a few other WNL stars have also gone undetected in X-rays.

4.5. Other B Stars in Berkeley 87

In addition to the OB stars discussed above, Chandra provides faint X-ray detections of four other B stars in Berkeley 87. These are Berkeley 87 No. 13 (B0.5 III), No. 24 (B1 Ib), No. 26 (B0.5 Iab), and No. 32 (B0.5 III). Their basic properties are summarized in Table 2, but they lack sufficient counts for spectral analysis. We also report non-detections of seven other B stars in Berkeley 87 (Table 2 notes).

The Chandra results show a noticeable trend in that all of the B star detections have high luminosities ($n_{\text{WB}} \lesssim 10^{-2}$; TF82 photometry). Most, but not all, of the undetected B stars are less luminous ($n_{\text{WB}} \gtrsim 2.1$). However, there are a few interesting exceptions. The B1 V star Berkeley 87-31 ($n_{\text{WB}} = -2.7$; TF82) lies nearly on-axis at an offset of 18′.7 from WR 142 but was not detected. However, it does lie near an ACIS-I CCD gap. Two other luminous but undetected B stars, No. 9 (B0.5 V) and No. 38 (B2 III), lie further off-axis (3′9 and 5′0, respectively).

5. DISCUSSION

5.1. Excess X-ray Absorption Toward WR 142

Chandra spectral fits of WR 142 (Table 3) give an absorption column density of $N_{\text{HI}} \approx (4-5) \times 10^{22} \text{ cm}^{-2}$. In contrast, optical studies yield $N_{\text{HI}} \approx 1 \times 10^{22} \text{ cm}^{-2}$ (TF82; Barlow & Hummer 1982; van der Hucht 2001; Gorenstein 1975 conversions) for Berkeley 87 cluster members. Our X-ray analysis of the cluster members BD+36 4032 and HD 229059 (Section 4) also yields $N_{\text{HI}} \approx 1 \times 10^{22} \text{ cm}^{-2}$. Thus, the X-ray spectra clearly show that excess absorption is present toward WR 142 that is not seen toward two other massive cluster members. This could arise either in the dense WO wind or perhaps in cold circumstellar gas.

Excess X-ray absorption seen as a disagreement between absorption based on optical extinction and the X-ray fit $N_{\text{HI}}$ has been seen in other WR stars as well, such as $\gamma^2$ Vel (Skinner et al. 2001) and recently detected WN stars (Skinner et al. 2010b).

Inhomogeneous extinction, although present, does not account for the discrepancy in X-ray and optical $N_{\text{HI}}$ values for WR 142. The spread in extinction values for cluster members is small, from $N_{\text{HI}} = (0.8-1.3) \times 10^{22} \text{ cm}^{-2}$ (TF82; Gorenstein 1975 conversion). Additionally, the smallest foreground extinction is near the south and WR 142 is ≈2.6 southeast of the cluster center (TF82), indicating the excess $N_{\text{HI}}$ is due to local absorption associated with WR 142.

If the excess absorption is due to the wind, we can estimate the radius at which the X-rays emerge using a wind optical depth calculation. From the observed Chandra WR 142 spectrum, the X-rays are entirely absorbed below $\approx 2 \text{ keV}$. Using generic WO abundances (van der Hucht et al. 1986) and assuming the mass-loss parameters in Table 1, the radius of optical depth unity at $E = 2 \text{ keV}$ is $R(\tau = 1, 2 \text{ keV}) \approx 1500 \text{ R}_\odot$. Clumping in the WR winds may reduce the mass-loss rate by a factor of 2–4 (Crowther 2007) and would reduce $R(\tau = 1, 2 \text{ keV})$ by the same factor. $R(\tau = 1)$ is well outside the wind acceleration zone and the wind will already have reached terminal speed, assuming a standard $\beta = 0.5-1.0$ wind velocity law. It should be kept in mind that this is a minimum radius for 2 keV X-rays to escape.

Another possibility regarding excess absorption is the presence of cold circumstellar gas. Nebulosity around WR 142 has been detected (Miller & Chu 1993), though a ring nebula is not present. Polcaro et al. (1997) note excess reddening surrounding WR 142 of at least $N_{\text{HI}} = 2.7 \times 10^{21} \text{ cm}^{-2}$ (Gorenstein 1975 conversion) suggesting dense material, possibly a nebula from the stellar wind. Alternatively, Lozinskaya (1991) detected a distant IR shell (∼23 pc from WR 142) whose dynamical age suggests that it formed before, and therefore independently, of the WR wind. Though it is apparent that some circumstellar material is present, our X-ray spectral fits have not distinguished between wind absorption and absorption by circumstellar gas far from the star. Both the wind and local circumstellar material could contribute to the excess X-ray absorption.

5.2. Is WR 142 a Binary?

There is no evidence from ACIS images (or other observations) that WR 142 is a binary. For an on-axis point source, the Chandra HRMA and ACIS PSF encircle 70% of the source energy for an angular source radius of $\approx 1.2 \text{ arcsec}$ at 2 keV and $\approx 1.3 \text{ arcsec}$ at 6 keV.13 If two X-ray sources are present, their separation must be $<1\text{″}$. The WR 142 X-ray luminosity from this Chandra observation is much less than that of known WR+O binaries, which are generally very luminous in the X-rays. Due to plasma formed in colliding wind shocks, these systems can have luminosities approaching $L_X \approx 10^{35} \text{ erg s}^{-1}$, such as $\gamma^2$ Vel (WC8+O7.5III; Skinner et al. 2001; Schmid et al. 2004). WR 142 is at least 2 orders of magnitude less luminous.

13 http://cxc.harvard.edu/cal/ACIS/Cal_products/pdfs/eer_on.html
However, the possibility of an unseen companion remains. But, a compact companion seems to be unlikely. Theoretical models of the WR winds accreting onto neutron stars predict high luminosity ($\log L_X > 34 \, \text{erg s}^{-1}$; HD 50896 = EZ CMa; Stevens & Willis 1988). Additionally, a neutron star would be required to spin fast enough to throw off most of the accreting material to remain undetected (propeller effect; e.g., Lipunov 1982). If an optically faint lower mass normal stellar companion (rather than a compact object) lies close to WR 142, it could easily escape detection.

Currently, the binary frequency for galactic WR stars is $\sim 40\%$ (van der Hucht 2001). Additional searches for binarity are needed for WR 142. These could include high-resolution infrared imaging or radio interferometry, though they would only be capable of detecting a companion down to separations of a few tenths of an arcsecond. More promising approaches would be to search for periodic photometric or spectroscopic variability that could signal a closer spectroscopic companion. Spectroscopically, an X-ray emitting companion orbiting in the WR wind could reveal itself through phase variability of the WR star ultraviolet lines (Hatchett & McCray 1977).

5.3. Thermal versus Non-thermal Emission

Low counts in the WR 142 ACIS-I spectrum result in nearly identical fits by either thermal APEC models or power-law models. As such, the WR 142 spectrum cannot sufficiently distinguish between a very high temperature thermal plasma and non-thermal processes, e.g., inverse Coulomb scattering due to relativistic electrons accelerated in wind shocks (Chen & White 1991a). In general, other WR stars with higher signal-to-noise spectra show detections of emission lines indicative of thermal emission. While the goodness of fit for spectral models slightly improves with the addition of the Fe K line for WR 142, there are not enough line counts to qualify as a definite line detection. There is no obvious evidence of other thermal emission lines, such as the S line at 2.46 keV. Theoretical models do exist that account for the hard X-ray emission from some early-type stars by non-thermal processes (Chen & White 1991a). However, if WR 142 were a non-thermal X-ray source, it would be the first putatively single WR star in that class. The possibility of non-thermal emission has been previously mentioned for other WR stars such as WR 110 but the evidence for non-thermal emission was not conclusive (Skinner et al. 2002).

5.4. Thermal Emission Mechanisms

Thermal X-ray emission is possible through several processes. Often radiative wind shocks are considered, yet with no emission below 2 keV detected from WR 142, a line-driven flow instability model predicting soft X-rays from radiative wind shocks that is typically assumed for O stars (Gayley & Owocki 1995) cannot explain the hard emission. We discuss wind kinetic energy conversion, colliding wind shocks, magnetically confined wind shocks (MCWSs), and coronal emission as possible thermal emission processes.

5.4.1. Kinetic Energy of the Wind

Due to the extreme mass-loss rate, the kinetic energy in the wind of WR 142 is enough to account for the X-ray luminosity. The kinetic energy of the wind supplies $\log L_{\text{wind}} \approx 38.2 \, \text{erg s}^{-1}$, which is much greater than the X-ray luminosity observed of $\log L_X \approx 31 \, \text{erg s}^{-1})$. The effects of clumping in the wind on the mass-loss rate would not change this conclusion, reducing $\log L_{\text{wind}}$ by 0.6 dex (erg s$^{-1}$) at most. Thus, even if the efficiency for converting the wind kinetic energy into X-rays were small, the wind still could supply the energy.

5.4.2. Colliding Wind Shocks

Because WR 142 has no known companion, a colliding wind shock model does not obviously apply. However, such models could explain the high temperatures of the X-ray emission produced from the high wind speed of WR 142. Assuming $v_{\infty} \approx v_{\infty} = 5500 \, \text{km} \, \text{s}^{-1}$ (Kingsburgh et al. 1995), the maximum X-ray temperature from a colliding wind shock (Equation (1) of Luo et al. 1990) would be $kT_{\text{cm}} \approx 1.95 \, \text{keV}$. If we assume a B0V companion with a radius $R_\ast = 7.4 \, R_\odot$ (Allen 1976), we find that a separation of $\approx 1 \, \text{AU}$ is required to produce the observed Chandra X-ray luminosity through colliding wind shocks (Equation (81) of Usov 1992). If we account for clumped winds, the separation scales as $M/\dot{M}$ and would reduce to 0.7 AU if the mass-loss rate is reduced by a factor of 2. At a distance of 1.23 kpc, a 1 AU separation between WR 142 and its hypothetical companion would produce an angular separation of much less than $1''$ ($\approx 1 \, \text{mas}$) and would not be resolvable by Chandra. However, this separation is smaller than the escape radius for X-rays, which is 375–1500 $R_\odot$ (Section 5.1). A favorable orbital phase and geometry with the wind-blown cavity around the companion along our line of sight would allow for the X-rays to escape (e.g., as occurs in γ² Vel; Schild et al. 2004), especially with clumped winds. To consider shock emission from the fast winds impacting circumstellar material, more information on the CS material’s density, geometry, and distance from WR 142 would be necessary.

5.4.3. Magnetically Confined Wind Shocks

For luminous stars, a surface magnetic field may be able to channel wind flow into shock collisions with sufficient velocity to produce hard X-ray emission. Generally, the magnetic field lines are thought to bend radiatively driven winds toward the magnetic equator, where the hemispheric winds collide. Such magnetically confined wind theories have been used to explain X-ray emission for magnetic Ap–Bp stars (Babel & Montmerle 1997a) and young O-type stars (Babel & Montmerle 1997b; θ¹ Ori C in Gagné et al. 2005). The winds were not radiatively driven in the Ap–Bp model but the resulting shocks are unaffected. We can determine the minimum magnetic field strength necessary to confine the winds in comparison to the wind magnetic confinement parameter using Equation (7) of ud-Doula & Owocki (2002), which is dependent upon the mass-loss rate, $v_{\infty}$, and radius of the star. We approximate the radius of WR 142 to be one solar radius (Abbott et al. 1986). We find that $B \approx \sqrt{\eta_\ast} \, 20$ kG at the stellar surface. Here, $\eta_\ast$ is the wind magnetic confinement parameter and is 1 for marginal confinement, 10 for strong confinement that produces shocks strong enough to produce > 1 keV emission (ud-Doula & Owocki 2002). Wind clumping could reduce the minimum magnetic field strength by
a factor of $\sqrt{2}$ to 2. It remains to be shown that WR stars have such strong magnetic fields.

Additionally, it can be shown that the maximum temperature at the shock front from MCWSs could reach maximum temperatures of tens of keV (Equation (4) of Babel & Montmerle 1997a) for high-velocity ionized metal-rich winds ($\mu \geq 1.33$) such as that of WR 142. The highest temperature is only possible at the shock front and will drop off to lower temperatures for most of the shocked plasma, but still easily could explain the observed hard emission from WR 142. It is important to note though that MCWS theories have not yet been extended to WR stars, where several problems such as larger mass-loss rates have not yet been addressed. Additionally, a magnetic rotator model with modulated winds was invoked to explain the periodic variations of the X-ray emission from $\theta^1$ Orionis C (Babel & Montmerle 1997b) but WR 142 here shows no such periodic X-ray emission or B-field detection so far.

5.4.4. Coronal Emission

As suggested for some OB stars, X-rays could be formed in a thin corona at the base of the wind (e.g., Cassinelli & Olson 1979). However, our calculations suggest that the $kT \approx 3$ keV X-rays emerge from very large radii, roughly $r \gtrsim 1000 R_*$, assuming a spherical homogenous wind. This is too far out to be attributed to a corona. Also, X-ray variability would be expected with coronal emission as magnetic (coronal) emission is usually associated with short-term X-ray variability (e.g., flares). No significant variability or flaring was detected in the Chandra observation.

5.5. Non-thermal Emission Processes

Electrons in the stellar wind accelerated to relativistic energies by the Fermi mechanism and trapped in weak magnetic fields could scatter stellar UV photons to produce X-ray emission and $\gamma$-ray emission (Chen & White 1991a, 1991b), as suggested for WR stars by Pollock (1987). The accelerated electrons undergo adiabatic cooling between shocks and thus can only lose heat through non-thermal processes, such as inverse Compton, non-thermal bremsstrahlung, or synchrotron radio emission (Chen & White 1991a). Such processes may be at work in WR 142: X-ray spectra of WR 142 can be fitted with a power law and Berkeley 87 lies close to an extended region of high-energy $\gamma$-ray emission in Cygnus (Abdo et al. 2007, 2009; Smith et al. 2005), though the primary source of the $\gamma$-ray emission has not yet been proven to be Berkeley 87 itself.

For OB stars, the radiation will produce a power-law electron spectrum where the X-ray flux from inverse Compton emission should scale with energy as $F_X \propto E^{-1/2}$ for electron index $n = 2$ (Chen & White 1991a). Spectral fits in Table 3, when the given photon index $\Gamma_{\text{pow}} = 1$ is converted to an energy index, give $F_X \propto E^\gamma$, though the photon index was poorly constrained. If the photon index is frozen to $\Gamma = 1.5$ so as to produce Chen & White's energy power-law index, the fit is reasonable but exhibits slightly more absorption and higher X-ray flux and luminosity (Table 3 footnotes).

The X-ray emission is predicted to be hard without large-scale variations, and if present, variations only on timescales of hours to days (Chen & White 1991a). However, the Chen & White (1991a) model is tuned to OB stars, such that inverse Compton is the assumed emission mechanism whereas bremsstrahlung may be just as important or even dominate inverse Compton for WR stars. Additionally, other factors, such as the Coulomb effects in the dense WR wind, have not been fully evaluated (Chen & White 1991a). Still, the non-thermal emission process is plausible for some WR stars, especially where non-thermal radio emission is detected (Pollock 1987). WR 142, is as of yet, undetected in the radio. Cappa et al. (2004) determined an upper limit of <0.90 mJy for the 3.6 cm flux density from WR 142. Despite the lack of detection of non-thermal radio emission at 3.6 cm, radio observations at longer wavelengths where non-thermal emission could lead to higher flux densities would be useful. The hard and essentially featureless X-ray spectrum of WR 142 could be non-thermal, but a higher signal-to-noise X-ray spectrum will be needed to distinguish between thermal and non-thermal emission.

6. COMMENTS ON WOLF–RAYET STAR X-RAY EMISSION

The X-ray detection of WR 142 presents a major question: why do we not observe X-rays from the WC subtype when we detect hard emission from a WO star? When plotting $L_{\text{bol}}$ versus $L_X$, WR 142 lies in the region occupied by undetected WC stars (Figure 5). WOs are more evolved than WCs, and WN winds are even more metal-rich and should thus be more efficient absorbers of soft X-rays.

However, WR 142 has a very high terminal wind speed and a very high effective temperature ($T_{\text{eff}}$) compared to WC stars (Crowther 2007). A higher effective temperature would lead to a more fully ionized wind, which lowers the wind opacity ($\kappa$) to X-rays (see Equation (6) of Ignace et al. 2000). The higher wind speed leads to a smaller radius of optical depth unity for X-rays of a given energy where $R(\tau = 1, E) = M/4\pi v_\infty \times \kappa(E)$ (Equation (9) of Ignace et al. 2000). In the case for WR 142, the terminal wind speed is greater and the wind opacity may be smaller than for WC stars, leading to a smaller $R(\tau = 1, E)$. Thus, X-rays may be able to escape from smaller radii closer to the star, which could explain why WR 142 has been detected in the X-rays but why WC stars have (so far) not been detected.

Another possible explanation is that WR 142 is not a single star (see Section 5.2). Some WC stars that are members of binary systems have been known to display hard X-ray emission (e.g., $\gamma^2$ Vel, WC8+O7.5) but the X-ray emission from WR 142 is much less luminous. WR+O binaries display much stronger emission. Perhaps X-ray emission from a binary decreases as a WR star evolves from WN to WC to WO because of changes within the star or its wind. Maybe the luminosity difference lies in the evolution or properties of the unseen companion star. WR 142, if a binary, may not have an O star companion but some other less-massive non-degenerate stellar companion. As discussed in Section 5.4.2, a close companion at the right separation could account for a lower X-ray luminosity using a colliding wind model.

The hard X-ray emission and fast wind from WR 142 may indicate a colliding wind shock that could be explained by an as of yet undetected companion at close separation, such as a BOV star companion at ~1 AU from WR 142 (Section 5.4.2). This close separation would not be resolved by Chandra. If a less massive unseen companion is present, then Chandra may be observing colliding wind shock emission at or near the surface of the companion (Usov 1992) and no intrinsic emission from the stars themselves. Even if the undetected companion star had no wind itself, the overwhelming wind from WR 142 would shock onto the companion’s surface and produce the same effect. For
example, a colliding wind shock onto a less massive companion could occur if the companion were an X-ray faint B or A star and any intrinsic X-ray emission from WR 142, if any exists, were completely absorbed, e.g., by its wind. If this is the case, then we do not detect X-ray emission from WR 142 itself and there is no contradiction with non-detections of single WC stars.

Another thought to consider could involve the very high wind speeds of WR 142. What if the winds give rise to some exotic non-thermal emission processes, such as proposed by Chen & White (1991a), that do not get triggered in WR stars with lower terminal wind speeds or lower $T_{\text{eff}}$? The detection of X-rays from the WO-type WR 142 may even suggest that the absence of X-rays from WC-type stars be considered tentative until sensitive observations of a larger sample of WC stars are obtained.

7. CONCLUSIONS

1. Chandra has detected hard, heavily absorbed X-ray emission from the rare WO-type star WR 142. No soft emission below 2 keV was detected by Chandra.

2. The observed X-ray flux is consistent with the flux from a previous XMM-Newton observation, within the uncertainties, and no significant X-ray variability was detected during the Chandra observation.

3. Due to the faint emission from WR 142, lack of prominent emission lines, and low numbers of counts, statistics are unable to distinguish between thermal and non-thermal X-ray emission mechanisms when fitting the spectrum and both have been considered. If the emission is thermal, very high plasma temperatures are inferred.

4. In addition to WR 142, Chandra detected seven luminous OB stars in Berkeley 87, while eight other B stars were undetected. The hard X-rays and excess absorption of WR 142 contrast with two X-ray bright OB stars in Berkeley 87, which display predominately soft X-ray emission and absorptions consistent with optical values.

5. Though the X-ray emission mechanism in WR 142 is unclear, the hard X-ray spectrum observed by Chandra could be explained by a colliding wind shock onto an as yet unseen companion, though the escape of the X-rays may require a geometry with the companion in front of WR 142. A colliding wind shock interpretation would also resolve an apparent contradiction of non-detections in the X-rays of single WC stars while WR 142 (a WO star) was detected. A key point not to be overlooked is that colliding winds can produce very hot plasma (as observed) even in the absence of magnetic fields.

6. Alternatively, mechanisms that assume stellar magnetic fields such as MCWS or inverse Compton scattering (as formulated by Chen & White 1991a) could play a role in the X-ray emission of WR 142. However, for MCWS, very strong surface fields of tens of kG would be required to effectively confine the powerful WR 142 wind (Section 5.4.3), also noted by Oskinova et al. (2009) in their MCWS interpretation. There is so far no observational evidence of such strong B fields in WR stars, nor do the existing X-ray data show any obvious signatures of impulsive X-ray flares that often accompany magnetic reconnection. If WR 142 has even a weak surface magnetic field, then X-ray production via inverse Compton scattering provides an attractive alternative to the extreme conditions required for magnetic wind confinement. A key question is whether the X-ray spectrum of WR 142 is indeed a power law, as expected for inverse Compton scattering. To answer this question, a higher signal-to-noise X-ray spectrum from a much deeper observation will be required.

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