A RICH POPULATION OF X-RAY–EMITTING WOLF-RAYET STARS IN THE GALACTIC STARBURST CLUSTER WESTERLUND 1

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ABSTRACT

Recent optical and infrared studies have revealed that the heavily reddened starburst cluster Westerlund 1 (Wd 1) contains at least 22 Wolf-Rayet (W-R) stars, constituting the richest W-R population of any Galactic cluster. We present results of a sensitive Chandra X-ray observation of Wd 1 that detected 12 of the 22 known W-R stars and the mysterious emission-line star W9. The fraction of detected WN stars is nearly identical to that of WC stars. The WN stars WR-A and WR-B, as well as W9, are exceptionally luminous in X-rays and have similar hard, heavily absorbed X-ray spectra with strong Si xiii and S xv emission lines. The luminous high-temperature X-ray emission of these three stars is characteristic of colliding-wind binary systems, but their binary status remains to be determined. Spectral fits of the X-ray–bright sources WR-A and W9 with isothermal plane-parallel shock models require high absorption column densities, log N_H = 22.56 (cm^{-2}), and yield characteristic shock temperatures kT_s ≈ 3 keV (T_s ≈ 35 MK).

Subject headings: open clusters and associations: individual (Westerlund 1) — stars: formation — stars: Wolf-Rayet — X-rays: stars

1. INTRODUCTION

The heavily reddened cluster Westerlund 1 (Wd 1; Westerlund 1961, 1987) in Ara has recently been recognized as a rare example of a starburst cluster in our own Galaxy. The cluster is massive, compact, and young, with age estimates of ∼3–5 Myr (Brandner et al. 2005, hereafter B05; Clark et al. 2005, hereafter C05). Wd 1 contains a remarkable collection of massive post–main-sequence stars, including early- and late-type supergiants, a luminous blue variable candidate, and the largest known population of Wolf-Rayet (W-R) stars of any Galactic cluster (C05; Negueruela & Clark 2005, hereafter NC05; Clark & Negueruela 2002). A recent VLT study has also revealed a faint population of low-mass pre–main-sequence stars and gives a photometric distance d = 4.0 ± 0.3 kpc (B05), but spectroscopic studies allow a larger range of distances (C05). The extinction is A_v ≈ 9.5–13.6 mag (B05; C05).

Ongoing studies have so far identified 22 W-R stars in Wd 1, and the census is likely incomplete. W-R stars are highly evolved evolutionary descendants of massive O-type stars that are in advanced nuclear burning stages and undergoing extreme mass loss from high-velocity winds, rapidly approaching the end of their lives as supernovae. At least one supernova has already occurred in Wd 1, as evidenced by the discovery of a new X-ray pulsar (Fig. 1; Skinner et al. 2005; Muno et al. 2006).

There is at present no comprehensive theory of X-ray emission from W-R stars. Previous observations have focused mainly on X-ray–bright W-R+OB binaries such as γ Vel and WR 140 (Skinner et al. 2001; Zhekov & Skinner 2000), whose hard emission (kT ≥ 2 keV) is thought to originate primarily in colliding-wind shocks. Much less is known about the X-ray emission of single W-R stars, but by analogy with O-type stars, they are expected to emit soft X-rays (kT < 1 keV) from instability-driven shocks formed in their supersonic winds (Gayley & Owocki 1995). Despite these expectations, X-ray emission from single W-R stars has proved difficult to detect. Recent sensitive observations have shown that single carbon-rich WC stars are exceedingly faint in X-rays, or perhaps even X-ray–quiet, for reasons that are not yet fully understood (Skinner et al. 2006, hereafter S06). Additional X-ray observations are needed to quantify X-ray emission properties across the full range of WC and WN spectral subtypes.

The presence of a rich, equidistant, coeval population of W-R stars in Wd 1 makes it an opportune target for X-ray observations, which are capable of penetrating the high extinction. We present the results of a sensitive Chandra X-ray observation of Wd 1, focusing here on the W-R population. This observation has yielded 12 new W-R X-ray detections and provides valuable new information on the X-ray properties of this unique sample of Galactic W-R stars that can be used to test shock emission models and guide new theoretical development.

2. CHANDRA OBSERVATIONS

Chandra observed Wd 1 on 2005 May 22–23 and June 18–19 with exposure live times of 18,808 s and 38,473 s, respectively. The observations were obtained with the ACIS-S imaging array in timed faint-event mode using a 3.2 s frame time. The pointing positions were (J2000.0) R.A. = 16°47′08″060, decl. = −45°50′27″4 in 2005 May and R.A. = 16°47′07″78, decl. = −45°51′00″9 in 2005 June.
Wolf-Rayet Star X-Ray Sources in Westerlund 1

| No. | R.A. (J2000) | Decl. (J2000) | Counts | Rate (counts s⁻¹) | (E) (keV) | P (ergs s⁻¹) | log L₅₀ | Identification | WR ID |
|-----|-------------|--------------|--------|------------------|-----------|--------------|---------|---------------|-------|
| 1   | 16 46 59.91 | -45 55 25.6 | 11 ± 4 | 5.85 × 10⁻⁴     | 2.84      | 0.46         | 32.06   | 2M 164659.90–455255 | N (WC) |
| 2   | 16 47 03.04 | -45 50 43.4 | 9 ± 3² | 4.82 × 10⁻⁴     | 2.22      | 0.57         | 31.98   | 2M 164703.15–455043 | K (WC) |
| 3   | 16 47 04.06 | -45 51 25.1 | 13 ± 4 | 6.93 × 10⁻⁴     | 3.99      | 0.003        | 32.14   | NT 164704.00–455125 | G (WN) |
| 4   | 16 47 04.14 | -45 50 31.4 | 33 ± 9 | 8.68 × 10⁻³     | 2.63      | 0.63         | 33.77   | 2M 164704.15–455031 | W9   |
| 5   | 16 47 04.19 | -45 51 07.2 | 67 ± 9 | 1.74 × 10⁻³     | 2.82      | 0.85         | 32.54   | NT 164704.23–455107 | L (WN) |
| 6   | 16 47 05.21 | -45 52 25.1 | 77 ± 9 | 2.01 × 10⁻³     | 3.16      | 0.49         | 32.60   | NT 164705.23–455225 | F (WC) |
| 7   | 16 47 05.37 | -45 51 04.9 | 185 ± 14| 4.81 × 10⁻³     | 2.49      | 0.15         | 33.57   | NT 164705.35–455104 | B (WN) |
| 8   | 16 47 05.99 | -45 52 08.3 | 6 ± 3² | 1.56 × 10⁻⁴     | 1.90      | 0.61         | 31.49   | GS 164705.99–455208 | E (WC) |
| 9   | 16 47 06.01 | -45 50 23.1 | 27 ± 6 | 7.01 × 10⁻⁴     | 2.96      | 0.82         | 32.14   | 2M 164706.01–455023 | R (WN) |
| 10  | 16 47 06.26 | -45 51 26.8 | 16 ± 5 | 4.05 × 10⁻⁴     | 5.02      | 0.49         | 31.90   | NT 164706.30–455126 | D (WN) |
| 11  | 16 47 07.62 | -45 49 22.3 | 17 ± 4 | 4.29 × 10⁻⁴     | 3.92      | 0.70         | 31.93   | 2M 164707.61–454922 | 3 (WN) |
| 12  | 16 47 07.65 | -45 52 36.0 | 40 ± 7 | 1.03 × 10⁻³     | 2.30      | 0.43         | 32.31   | 2M 164707.64–455235 | O (WN) |
| 13  | 16 47 08.35 | -45 50 45.5 | 500 ± 23| 1.30 × 10⁻²     | 2.68      | 0.92         | 33.92   | NT 164708.34–455045 | A (WN) |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Data are from the 38,473 s exposure on 2005 June 18–19 unless otherwise noted. All quantities are computed using events in the 0.3–7 keV energy range. Chandra positions are from full-resolution (0.492 pixel) ACIS-S images. X-ray counts inside 3σ source detection regions are background-subtracted. (E) is the mean photon energy and P is the probability that the count rate was constant based on the K-S statistic. Unabsorbed X-ray luminosities L₅₀(0.3–7 keV) are from PIMMS simulations using a one-temperature Raymond-Smith thermal plasma model with κT = 1 keV, N₅₀ = 3 × 10¹⁷ cm⁻², and d = 4 kpc unless otherwise noted, and they have typical uncertainties ±0.4 dex. Candidate identifications lie within 1′ of the X-ray position and are from the Hubble Space Telescope Guide Star Catalog (GS) ver. 2.2, the Two Micron All Sky Survey (2M) database, and archival New Technology Telescope (NT) images (J, H, and K bands). W-R star identifications are from Table 2 of NC05 unless otherwise noted. Exposure live times are 18,808 s for observation 1 (2005 May 22–23) and 38,473 s for observation 2 (2005 June 18–19).

* Tabulated data are from events collected in the first (18.8 ks) observation.
* Faint source, classified as a possible detection.
* Source was detected in both observations. Tabulated data are from events collected in the second (38.5 ks) observation.
* Log L₅₀ is from spectral fit.
* W9 is listed as source 9 in Table 1 of C05, who classify it as sgB[e].
* Low-level variability may be present in source 7 (WR-B) during the second observation, but a K-S test gives P = 0.86 for the first observation. The mean count rates in both observations were the same to within the uncertainties.
* Source 3 in Groh et al. (2006).

Data reduction was based on level 2 event files generated by the Chandra X-Ray Center. Source detection was accomplished using the CIAO¹ tool wavdetect applied to full-resolution images (0.492 pixel size) that were energy-filtered to include only events in the 0.3–7 keV energy range to reduce background. The 3σ elliptical source regions generated by wavdetect were used to extract an event list for each source. The source event lists were used for further timing and spectral analysis. The probability of constant count rate P was computed for each source using the nonparametric Kolmogorov-Smirnov (K-S) statistic (Skinner et al. 2003 and references therein). Spectra and associated instrument response files for brighter sources were extracted from updated level 2 event files using recent CIAO version 3.3 tools that incorporate the latest gain and effective area calibrations (CALDB ver. 3.2). Spectra were analyzed using XSPEC version 12.2.0.

### 3. WOLF-RAYET STARS

#### 3.1. Wolf-Rayet Star X-Ray Detections

Chandra detected 12 of the 22 known W-R stars in Wd 1, including 11 of the 19 W-R stars in the list of NC05 and one of the three W-R stars (all of WN subtype) identified by Groh et al. (2006). Their positions are shown in Figure 1, and X-ray properties are summarized in Table 1. The detection rate was similar for WN and WC stars. Specifically, eight of 15 (53%) of the known WN stars were detected, and four of seven (57%) WC stars. However, the WC9 star WR-E is considered to be a marginal detection.

Three W-R detections show signs of variability, but two of these are faint sources with few counts on which to base a variability analysis. Both WR-K (source 2) and WR-G (source 3) were faintly detected in the first observation but not in the deeper second observation. WR-G had a low probability of constant count rate P = 0.003 in the first observation and a noticeably high mean photon energy. WR-B (source 7) is a suspected WN8+OB binary (NC05) and had P = 0.15 in the second observation. A low-amplitude rise and fall can be seen in its X-ray light curve, but no variability was seen in WR-B during the first observation.

Table 1 gives the X-ray luminosities of W-R stars in Wd 1, and the L₅₀ distribution is shown in Figure 2. The median X-ray luminosity of the detected WN stars, log L₅₀ = 32.23 (ergs s⁻¹), is only slightly larger than the median log L₅₀ = 32.02 for WC stars. The stars WR-A (source 13) and WR-B (source 7), both of which have uncertain WN spectral types (C05), have very high L₅₀ and are very likely binaries. At the other extreme, 45% of the W-R stars in Wd 1 were undetected, and the shape of the L₅₀ distribution at low luminosities is not well determined.

#### 3.2. Wolf-Rayet Star Nondetections

Chandra did not detect 10 of the 22 known W-R stars in Wd 1 down to the detection limit log L₅₀(0.3–7 keV) ≈ 31.3 (ergs s⁻¹), which assumes a 6 count threshold in 57.3 ks and an underlying thermal spectrum with κT = 1 keV and N₅₀ = 3 × 10¹⁷ cm⁻². Higher X-ray absorption in the metal-rich winds of WC stars would decrease the chance of their X-ray

¹ Further information on the Chandra Interactive Analysis of Observations (CIAO) software can be found at http://asc.harvard.edu/ciao.
Fig. 1.—Chandra ACIS-S image (0.3–7 keV) of the central region of Wd 1 obtained on 2005 June 18–19 (38.5 ks). The image has a logarithmic stretch and is rebinned by a factor of 2 to a pixel size of 0.1023. The plus sign marks the Chandra aim point. Circles enclose X-ray–detected W-R stars (Table 1). Source 1 (WR-N) lies to the south and is not shown. Triangles mark positions of undetected W-R stars. Squares enclose the bright X-ray sources W9 (sgB[e]), W30 (OB), and a newly discovered X-ray pulsar. Coordinates are J2000.

detection but does not explain why the fraction of undetected WN stars is just as high as that of WC stars. If the nondetections are predominantly single stars that emit only softer X-rays at $kT < 1$ keV, as occurs for many O-type stars, their emission would be preferentially absorbed and they could escape detection.

Although $N_H$ and X-ray temperature clearly affect X-ray detectability, convincing evidence is now emerging for very large differences in $L_X$ in W-R stars with similar spectral types. In the Wd 1 sample, the WC9 star WR-F (source 6) was clearly detected as a moderately bright X-ray source ($log L_X = 32.60$ [ergs s$^{-1}$]) but the WC9 stars WR-M and WR-H were undetected, with count-rate limits that are at least 10 times smaller. Furthermore, we note that a previous 20 ks Chandra observation failed to detect the single WC8 star WR 135 in Cygnus with a conservative upper limit $log L_X(0.5–7$ keV) $\leq 29.82$ (ergs s$^{-1}$), which gives a remarkably low ratio $log (L_X/L_{bol}) \leq -9.1$ (S06). Assuming $d = 1.74$ kpc and low extinction $A_V = 1.26$ mag (van der Hucht 2001), it is difficult to attribute the WR 135 nondetection entirely to absorption. Despite their similar WC8–WC9 spectral types, WR-F and WR 135 differ in $L_X$ by at least a factor of $\approx 600$. There are no indications of binarity in WR 135, and other attempts to detect apparently single WC stars have yielded negative results (S06). Thus, single WC stars emit X-rays at very low levels (if at all), and the elevated X-ray emission of WC stars such as WR-F in Wd 1 is very likely the result of extraneous factors such as binarity.

3.3. Wolf-Rayet Star X-Ray Spectra

The Chandra spectra of the brightest W-R detections reveal similar properties. They are heavily absorbed below $\approx 1$ keV and have significant emission above $kT \approx 2$ keV. The spectrum of the brightest W-R detection, WR-A (Fig. 3), shows low-energy absorption as well as strong Si xii (1.86 keV) and S xv (2.46 keV) emission lines. These lines emit maximum power at $log T_{max}$ of 7.0 (K) and 7.2 (K), respectively. The spectrum of WR-B is similar and shows prominent Si xii and S xv lines, as does W9 (Fig. 3).

The presence of hotter plasma is not anticipated from models of radiative shocks distributed in the winds of single stars. The harder spectra detected here are clearly of a different origin, and colliding-wind shocks in binary systems are a plausible explanation. To investigate this, we have fitted the spectrum of WR-A with the plane-parallel one-temperature shock model vpshock (Borkowski et al. 2001) in XSPEC version 12.2, using the most recent APED atomic database (“neivers 2.0” in XSPEC).
The \( v_{\text{pshock}} \) model gives very good fits for WR-A, with shock temperatures \( kT_e = 3.5 \) (2.5–4.8; 90% confidence) keV, \( N_H = 3.6 \times 10^{21} \) cm\(^{-2} \), and reduced \( \chi^2 = 1.0–1.1 \). The above \( N_H \) equates to \( A_v = 16.2 \) (14.0–18.9) mag, or \( E(B-V) = 5.45 \) (4.70–6.36) using Gorenstein (1975). Two-temperature optically thin thermal plasma models give similar \( N_H \) values. By comparison, previous studies of the OB supergiant in Wd 1 yield median values \( A_v = 13.6 \) mag, or \( E(B-V) = 4.35 \) (C05). This suggests that the extinction across Wd 1 is quite inhomogeneous or that excess absorbing material such as cold gas is present toward WR-A that has escaped optical detection. The \( v_{\text{pshock}} \) fits give an upper limit on the ionization timescale \( \log \tau \lesssim 11.2 \) (s cm\(^{-1} \)), where \( \tau = n_e t_s \) with \( n_e \) the postshock electron density and \( t_s \) the shock age. Such a low value of \( \tau \) implies that nonequilibrium ionization effects in the shocked plasma may be important.

4. THE UNUSUAL EMISSION-LINE STAR W9

The enigmatic emission-line star W9 lacks any recognizable photospheric features in its R-band spectrum and shows a very broad H\alpha line (C05). It was classified as a B[e] supergiant by C05, but its nature is uncertain and they note that it could contain a W-R component, so we discuss it here. Chandra detected a strong X-ray source (source 4 in Table 1) at an offset of 0.3 from the position of W9 given by C05. Two radio sources lying \( \approx15^\circ \) to the east of W9, identified as Ara A (N) and Ara A (S) by Clark et al. (1998), were located near the Chandra aim point but not detected.

The X-ray properties of W9 are very similar to the X-ray–bright WN star WR-A. They have nearly identical mean photon energies (Table 1), \( L_X \) (Fig. 2), and spectra (Fig. 3). There is little doubt that their X-ray emission is due to the same process, and we suspect that both W9 and WR-A are colliding-wind binaries. Spectral fits of W9 with the \( v_{\text{pshock}} \) model give values for \( N_H, kT_e \), and \( \tau \) that are within 30% of those quoted above for WR-A, and the best-fit W9 column density is \( N_H = 3.6 \) (2.6–4.9; 90% confidence) \times 10^{22} \), or \( A_v = 16.4 \) (11.8–22.3) mag cm\(^{-2} \). Thus, as for WR-A, the X-ray absorption may exceed that expected from previous \( A_v \) estimates.

5. CONCLUSIONS

There are good reasons to believe that most of the W-R X-ray detections in Wd 1 are binaries. This conclusion is more secure for WC stars than for WN stars, since there have been no previous X-ray detections of single WC stars, even at better sensitivities than obtained here. Large differences in \( L_X \) between W-R stars of similar spectral type can be naturally explained if the luminous X-ray sources are colliding-wind binaries. Furthermore, Chandra preferentially detects harder X-ray sources in Wd 1 because of the high extinction. Plane-parallel shock models give good fits of the brightest X-ray detections and require shock temperatures \( kT_e \lesssim 2 \) keV. Such temperatures are higher than predicted for radiative shocks distributed in the winds of single stars but are consistent with colliding-wind emission in binary systems. Even so, more definitive proof of binarity is needed from optical/IR follow-up work. And, interesting questions remain in the X-ray regime. What is the origin of the excess absorption that is inferred from X-ray spectral fits of WR-A and W9? How does the W-R X-ray luminosity function behave at low \( L_X \)—are the undetected W-R stars faint sources below our detection limit, or are they X-ray–quiet?

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