Winds of Massive Stars: High-resolution X-Ray Spectra of Stars in NGC 3603

David P. Huenemoerder1, Norbert S. Schulz2, and Joy S. Nichols3
1 Massachusetts Institute of Technology 77 Massachusetts Avenue, Cambridge, MA 02139, USA
2 Harvard-Smithsonian Center for Astrophysics 60 Garden Street, Cambridge, MA 02138, USA

Received 2018 May 17; revised 2018 November 21; accepted 2018 November 21; published 2019 January 3

Abstract

The starburst phenomenon is an influential process in the evolution of stellar systems. The formation of massive stars can have a profound effect on their environment through ionizing radiation, kinetic energy of massive winds, and ultimately supernovae explosions. NGC 3603 is a relatively nearby galactic starburst region, close enough that individual stars can be observed in detail. It is well recognized as an important cluster in relation to the similar but more distant R136a association, the much more active Arches cluster, and the distant powerhouses in starburst galaxies.

Mass-loss rates and compositions can be determined through high-resolution spectroscopy. In X-rays, we can characterize emission mechanisms, discriminating between wind-shocks, magnetic confinement, or colliding winds. X-ray emission line strengths and shapes are key diagnostics of wind structure.

Some early Chandra observations of hot stars challenged the canonical wind-shock models (Schulz et al. 2003; Gagné et al. 2005) when some massive stars, such as θ1 Ori C were found to have narrow lines and high temperatures. Gagné et al. (2005) successfully applied a magnetically confined wind model to the θ1 Ori C spectra, and this is now largely accepted as an explanation for narrow lines in hot stars. Other stars, such as ζ Pup, do show wind-broadened profiles (Cassinelli et al. 2001; Kahn et al. 2001; Kramer et al. 2003). The wind-shock models for single stars do not predict the high plasma temperatures seen in some stars. In binary systems, colliding winds can lead to high temperatures because the temperature is proportional to the square of the wind velocity (Luo et al. 1990; Stevens et al. 1992).

NGC 3603 is the closest starburst cluster at a distance of ~7.6 kpc and an age of about 1–3 Myr (Hofmann et al. 1995; Stolte et al. 2006; Melena et al. 2008). Stolte et al. (2006) compared NGC 3603’s central Young Cluster (YC) to other clusters and note that it has a similar core radius to the Orion Nebular Cluster (ONC) of about 0.2 pc, and even a similar stellar number density of about 2 × 104 pc−3, but its mass density of 1 × 105 M⊙ pc−3 is five times that of the ONC; the NGC 3603 YC core mass equals the entire mass of the ONC. The Arches cluster has somewhat higher mass and mass density than NGC 3603 YC; R136 is very similar to NGC 3603 in many ways (Moffat et al. 1994; Stolte et al. 2006). Hence, the NGC 3603 yc represents an important object to study among others because, in the words of Stolte et al. (2006), it “provides a resolved template for extragalactic star-forming regions.”

The stars in the core of NGC 3603 are collectively known as HD 97950 and also WR 43. Moffat et al. (1985) first identified the central unresolved object as multiple WN-type stars. Hofmann et al. (1995) resolved the stellar core of NGC 3603 into 28 stars using speckle interferometry. These stars reside in a central 6 × 6 arcsec2 field (at 7.6 kpc, 6 arcsec corresponds to 0.22 pc). They identified several of the components as late WN or Of stars. Crowther & Dessart (1998) conducted a spectroscopic analysis of the core stars in NGC 3603 and determined their fundamental properties. HD 97950 was resolved into several different components, and three of them, A1, B, and C, have been classified as WN6h+abs types—nitrogen-rich Wolf–Rayet (WR) stars with a substantial abundance of hydrogen; they have not evolved past hydrogen-core burning. Melena et al. (2008) obtained spectra of NGC 3603 stars, determining characteristics for 16 additional objects; they also compared to many of the previous results. The three WN stars’ winds contribute about 65% of the cluster kinetic energy, which is more than that from this clusters’ 20–30 other O-stars combined (Crowther & Dessart 1998).

In the ACIS image data analyzed by Moffat et al. (2002), source C was the brightest in X-rays. HD 97950-C is a WN6h+abs type, with L/L⊙ ∼ 106, M/M⊙ ∼ 62, M ∼ 10−4 M⊙ yr−1, and a terminal wind velocity of 2500 km s−1 (Crowther & Dessart 1998). It is also a single-lined spectroscopic binary (Schnurr et al. 2008) with a period of 8.9 days and a velocity amplitude of 200 km s−1.

The WR stellar class contains some of the most massive and luminous stars. Their dense, high-velocity stellar winds, and ultimate supernova explosion significantly affect the composition and dynamics of the interstellar medium. They are important in galactic feedback and can alter the environment in their host star cluster. There is some evidence that the X-ray production in WR stars is perhaps different from known O-star mechanisms of wind-shocks, which are thought to occur near the stellar photosphere in the wind acceleration zone, or from magnetically confined winds, in which strong magnetic fields...
constrain the winds. High-resolution X-ray spectra of WR 6 (EZ CMa), from XMM-Newton-Newton RGS and from Chandra/HETG spectrometers showed that the X-rays are generated far out in the wind (Oskinova et al. 2012; Huenemoerder et al. 2015). The X-ray emission mechanism is not known. Hence, more high-resolution spectra of very massive stars are required to further study winds in this regime. The central cluster of NGC 3603 provides us with an opportunity to study in detail some of the most massive stars in the Galaxy.

2. Observations and Calibration

Using the Chandra/HETG spectrometer (Canizares et al. 2005), we observed NGC 3603 in 2011 for 47 ks (observation ID 13266). The HETGS spectra cover the range from about 1–30 Å, as dispersed by two types of grating facets, the High Energy Grating (HEG) and the Medium Energy Grating (MEG), with resolving powers ranging from 100 to 1000 and approximately constant full width at half maximum (FWHM) of 12 mÅ for HEG and 23 mÅ for MEG. Our observation was designed as a “snapshot,” just long enough to characterize the strongest emission lines of the brightest members, based on the low-resolution ACIS observations.

The Chandra data were reprocessed with standard Chandra Interactive Analysis of Observations (CIAO) programs (Fruscione et al. 2006) to apply calibration data appropriate to the epoch of observation (primarily CIAO 4.6 and the corresponding calibration database, version 4.5.9, though some recent reprocessing was done with CIAO 4.10 and CALDB 4.7.8). The counts spectra are composed of four orders per source per observation: the ±1 orders for each grating type, the MEG and HEG, which have different efficiencies and resolving powers. The default binning oversamples the instrumental resolution by about a factor of four.

Observation-specific calibration files are required for analysis to convolve a model flux spectrum with the instrumental response to produce model counts. CIAO programs were used to make the effective areas (“Auxiliary Response File,” or ARF) and the spectral redistribution and extraction-aperture efficiency files (“Response Matrix File,” or RMF) for each spectral order for each source (see Davis 2001 for a detailed definition of the response).

To extract spectra of multiple sources, we need to customize source positions and extraction regions to minimize confusion. In Figure 1 we show X-ray images of the field at successively decreasing scales. In the rightmost panel, we overlay positions of the optical components from Drissen et al. (1995). Properties of objects relevant to this study are given in Table 1.

From the marginal histograms, we can see that the X-rays in the core are dominated by components A1, B, and C, and that in this observation, C is fainter than A1. The dispersion direction is roughly diagonal, and the MEG trace of A1+B can be seen faintly in the upper-left panel of Figure 1 extending to the upper right, along with the bright sources MTT 68 at about 1.4 arcmin northwest of the core (Melnick et al. 1989; Roman-Lopes 2013), and MTT 71 at about 1.7 arcmin northeast of the core. The HETG resolution is not affected by off-axis angles below 2°.

We used MARX4 (Davis et al. 2012) to simulate the field and to assess source confusion in detail. While components A1 and B are marginally resolved in zeroth order, they are not in the dispersed spectrum, due to the additional grating astigmatic profile in the cross-dispersion direction. The wavelength offset between A1 and B, projected along the MEG direction, is 1.46 pixels (0.016 Å), or about 800 km s⁻¹ at 6 Å. With the extraction centered on A1, a combination of positive and negative orders would in principle result in B’s contributions being offset by ±800 km s⁻¹ then summed with A1. However, A1 is twice as bright as B, and using a narrow extraction region reduces B’s contribution further, as does including the well separated HEG spectra. Experiments in fitting faked data with offsets showed that line centroids are unaffected (as expected), but the line shapes become a bit flatter. Even with some broadening due to confusion, we will see in Section 3 that the line widths are still much larger than we expect from source confusion.

In Figure 2, we show cross-dispersion profiles as fit to MARX simulations, using the 6–10 Å region of the MEG spectrum of the A1+B extraction. The counts in the A1 extraction region in the MEG arm alone are about 60% of A1. We also analyzed MTT 68, MTT 71, and Sher 47. The latter, however, is aligned with the A1+B MEG spectrum, so its MEG spectrum is not useful. In turn, its MEG counts contaminate the A1+B spectrum, though it is offset enough, by 0.63 Å, that any emission lines will not overlap those of A1+B. It is somewhat fainter—we estimate that Sh 47 could contribute about 12% of the A1+B HEG plus MEG counts spectrum. As a further test of confusion from Sh 47, we can compare the HEG and MEG flux of A1+B, which should differ if Sh 47 contaminates the MEG arm, and we can look for offset spectral features. In Figure 3, we show the HEG and MEG fluxes5 for the A1+B extraction. The fluxes agree, and there are no features at the expected offsets. Hence, we conclude that the limited extraction region widths and order-sorting have mitigated the contributions from Sh 47.

In Figure 4, we show the combined flux spectra for the HEG and MEG first orders of components A1+B, C, MTT 68, and MTT 71. Count rates and fluxes (which are largely model-independent) are given in Table 2.

In this relatively short, single pointing, we cannot totally mitigate source confusion. In the future, we hope to obtain deeper exposures at multiple roll angles, which will allow us to better extract unconfused spectra.

We have examined the background rate by extracting the relatively isolated MTT 68 with standard width spatial masks, which provide 10 times the width of the source region for spectrally adjacent background regions. The rate is less than about 10⁻⁴ cts s⁻¹ Å⁻¹ for standard extraction regions, and is negligible for the grating spectral analysis.

We have not included zeroth orders in our analysis. While the HETG zeroth-order effective area exceeds that of the combined first orders above 2 keV (below 6 Å) by up to a

---

3 Some recent calibration updates have retroactive changes in the effective area of the order of 5% at 12 Å due to revisions in the contamination model. There are no other significant differences in recent (post observation epoch) CIAO versions that affect event processing, spectral extraction, or line characteristics. For these data and our purposes, the effective area revisions are not important, so we have not re-extracted and refit data with the most recent calibrations.

4 http://space.mit.edu/cxc/marx

5 Flux spectra are derived by dividing by the counts expected for a flat spectrum, that is, by the integral over the response. This is an approximation to the flux, but still includes the instrumental broadening. This was done in the ISIS analysis package, and full details are given in the manual (see http://space.mit.edu/cxc/isis/manual.pdf#page.76).
factor of 3 (with a median factor of 1.6), there are uncertainties in the calibration of order 5%–10% between zeroth and first orders. Furthermore, we would require small extraction regions for the close sources, C, B, and A1 and the aperture correction introduces another potentially larger systematic uncertainty. As can be seen from inspection of the counts below 6 Å in

**Figure 1.** Images of the field for decreasing scales. The top left panel is a large-scale view with the cluster core in the lower left and the MEG spectrum running diagonally to the upper right. The lower left is an expanded scale. The left panels are from the HETG observation (observation ID 13266). The right panel shows the deeper ACIS-I data (ObsIDs 12328, 12329), which better shows the event distribution of the HD 97950 core. Known star positions are marked, and marginal histograms along the axes show the X-ray event distributions (y-scales for the upper-panel marginal histograms are arbitrary). Positions of the components are from Drissen et al. (1995). For the y-axis histograms, we have separated events for C from A1-B. In all panels, east is left and north is up.

**Table 1** Properties of Selected NGC 3603 Members

| Star | Spectral Type | Binarity, Period (d) | Mass ($M_\odot$) | $L_{bol}^a$ $(10^6 L_\odot)$ | $v_w$ (km s$^{-1}$) | $\gamma$ (km s$^{-1}$) | $K$ (km s$^{-1}$) | $f_\lambda^b$ (ergs cm$^{-2}$ s$^{-1}$) |
|------|---------------|---------------------|-----------------|--------------------------|----------------|----------------|----------------|-----------------|
| A1  | WN6h + WN6h   | SB2, 3.77          | 116, 89         | 4.0                       | 2700           | 153            | 330, 433       | $5.74 \times 10^{-13}$ |
| A2  | O3 V          | ...                | ...             | 1.2                       | ...            | ...            | ...            | ...             |
| A3  | O3 III (f')   | ...                | ...             | 0.8                       | ...            | ...            | ...            | ...             |
| B   | WN6h          | single             | 89              | 2.9                       | 2700           | 167            | ...            | $2.69 \times 10^{-13}$ |
| C   | WN6h +?       | SB1, 8.9           | 62              | 2.2                       | 2500           | 186            | 200            | $1.08 \times 10^{-12}$ |
| MTT 68 | O2 II*       | vis., 0.38         | 150             | 0.4                       | ...            | ...            | ...            | $1.28 \times 10^{-12}$ |
| MTT 71 | O4 III       | ...                | 80              | 1.5                       | ...            | ...            | ...            | $2.46 \times 10^{-13}$ |
| Sher 47 | O4 IV (f)    | ...                | ...             | 0.5                       | ...            | ...            | ...            | $3.53 \times 10^{-13}$ |

**Notes.** Designations A-B-C refer to the subcomponents of HD 97950. Data sources: Drissen et al. (1995), Crowther & Dessart (1998), van der Hucht (2001), Melena et al. (2008), Schuur et al. (2008), Crowther et al. (2010), Roman-Lopes (2013), Roman-Lopes et al. (2016), and Maíz Apellániz et al. (2016).

* Luminosities for A1, B, and C are from Crowther et al. (2010); others are from Crowther & Dessart (1998) but rescaled to a distance of 7.6 kpc (from their value of 10.1 kpc).

* Flux is the total band (0.5–8.0 keV) from Townsley et al. (2014), with a caveat that these were significantly saturated by CCD event pile-up.
emission can originate from regions of different velocities, temperatures, and overlying continuum absorption optical depths. Winds can also be clumped. These all affect the X-ray energy distribution and line profiles (Owocki & Cohen 2001; Oskinova et al. 2004; Cohen et al. 2014). Instead, our intent is to provide a simple characterization of the emitting plasma appropriate to the quality of the data, and to measure emission line parameters that are independent of global plasma models.

Because of the heavy foreground absorption of about 10$^{22}$ cm$^{-2}$ (Moffat et al. 2002; Romano et al. 2008; Townsley et al. 2014), we are not sensitive to cooler plasma temperatures of a few MK. Since we see emission lines of Si and Mg, we have temperatures near 10 MK, and the continuum present between 2 and 6 Å indicates temperatures in the tens of MK, hence a 27 model should suffice for general characterization of the plasma model. In addition to foreground absorption, there could be intrinsic absorption within the stellar wind itself, hence, we allow the column to be fit.

Since the emission lines are of primary interest, we also fit a global “turbulent” broadening parameter (i.e., constant velocity width), and a Doppler shift. These allow us to characterize the line width and apparent offset of the centroid, which might be due to skewness of the profile (see, for example, Owocki & Cohen 2001).

Finally, we also allowed elemental abundances for Fe, Ar, S, Si, Mg, and Ne to be free. While these parameters are related to the physical abundances, they also compensate for systematic errors in plasma temperatures as per limitations of the adopted two-component model. We modified the Asplund et al. (2009) appropriately for the depleted H fraction of WNH stars given by Crowther & Dessart (1998) in which the H to He number ratio is 6, or by mass fraction, 0.59 H. Only the relative abundances of Mg, Si, and Fe are reasonably constrained, because they have the strongest or most numerous (in the case of Fe) lines.

We fit the 1.7–13 Å region using a Powell minimization method and a Cash (maximum likelihood) statistic. These global fits and residuals are shown in Figure 4. Model parameters are given in Tables 3 and 4. Fluxes of the models, because they characterize the empirical shape of the observed spectrum (and are largely model independent), are given in Table 2. Luminosities, which depend critically on assumed absorption (here all assumed in the foreground), are given in Table 3, using a distance of 7.6 kpc (Melena et al. 2008).

In addition to using Gaussian profiles, we used a simple analytic profile characteristic of asymptotic flow of thick wind (Ignace 2001) as successfully applied to the HETGS spectrum of the WR star, WR 6 (Huenemoerder et al. 2015). This profile has two shape parameters, the terminal velocity ($v_\infty$), and a shape, $q > -1$; $q = 0$ is the nominal wind expansion model, which creates a “shark-fin” shaped profile; $q = -1$ results in a flat-topped profile (as would be emitted by a physically thin expanding shell; and $q > 0$ becomes increasingly steep, rapidly falling from the sharp blue wing at $-v_\infty$ (see Huenemoerder et al. 2015, for example, profiles and the analytic functional form). This line model was not allowed to have a free Doppler shift; line centers were instead frozen at their relatively small line-of-sight velocities.

---

6. The atomic database, AtomDB (www.atomdb.org), is produced by the Astrophysical Plasma Emission Code, or APEC, which is also commonly referred to as the Astrophysical Plasma Emission Database, or APED. These are often used interchangeably when referring to spectral emissivity models derived from APEC.

7. In the usual by-number decimal logarithmic scale in which the hydrogen abundance is 12, the WNH abundances of the elements relevant here are He = 11.22, Ne = 8.02, Mg = 7.69, Si = 7.60, S = 7.21, Ar = 6.49, and Fe = 7.59.
All fitting and modeling was done using the Interactive Spectral Interpretation System (ISIS\textsuperscript{5}; Houck & Denicol\`{o} 2000), which provides interfaces to AtomDB and Xspec models.

In Figure 5 we show the Si XIV to Si XIII region twice, once fit with the AtomDB models using Gaussian profiles, and again as fit with the asymptotic thick wind profiles. The wind-profile is convenient because it clearly delimits the maximum extent of the blue wing, but we cannot claim that it is better than a Gaussian for these stars. Our general qualitative impression is that it seems to better match Si XIV than a Gaussian.

Table 2

| Object | \( r_0 \) | \( r_{\pm 1} \) | \( f_x \) |
|--------|--------|--------|--------|
| A1     | 8.84   | …      | …      |
| B      | 4.72   | 26.0\textsuperscript{*} | 1.31\textsuperscript{*} |
| C      | 6.81   | 9.47   | 0.66   |
| MTT 68 | 15.33  | 22.0   | 1.37   |
| MTT 71 | 4.58   | 9.32   | 0.51   |
| Sher 47\textsuperscript{b} | 7.49   | 3.65   | 0.63   |

Notes. Rates for zeroth order (\( r_0 \)) and \( \pm 1 \)st orders (\( r_{\pm 1} \)) are given in cts ks\textsuperscript{-1}. Flux in the dispersed spectra, \( f_x \), is in \( 10^{-12} \) ergs cm\textsuperscript{-2} s\textsuperscript{-1}, using the model evaluated over 1–40 Å.

\textsuperscript{*} HETGS dispersed spectral rates are for A1+B.

\textsuperscript{b} First orders and flux are from HEG only.

4. X-Ray Light Curves

We extracted light curves from the zeroth order and dispersed spectra for each of the stars studied. Figure 8 shows the count rates. In the zeroth orders, we can isolate stars A1 and B, so we show their zeroth orders individually, along with their sum and the blended count rate in dispersed light.

5. Discussion

X-ray line emission can be a sensitive probe of the structure and energetics of stellar winds from massive stars. The wind temperatures and abundances can be determined from line and continuum emission. Wind radial structure can be determined from He-like triplet ratios, which are strongly affected by UV...
photoexcitation. Wind dynamics can be revealed by X-ray line profiles. It is important that we obtain line profile information on WN stars to understand the wind structure. While the central region of NGC 3603 is crowded, and two of the components (A1 and C) are binary systems, we have demonstrated that useful information can be obtained with the Chandra/HETG. Since our observation was relatively short, we cannot determine the emission line profiles’ shapes in detail, but we can reliably measure centroids and widths. Though there is some unresolvable spatial overlap among some sources, we can still obtain useful mean quantities.

Table 3
Spectral Model Parameters

| Object | N_H | χ_lo | χ_hi | T_lo | T_hi | EM_lo | EM_hi | L_x | log(L_x/L_Bol) |
|--------|-----|------|------|------|------|-------|-------|-----|---------------|
| A1+B   | 1.3 | 0.9  | 1.9  | 8.7  | 6.4  | 9.5   | 36.5  | 27.9| 48.2          |
| C      | 2.6 | 1.9  | 3.0  | 12.1 | 10.7 | 13.4  | 92.1  | 40.5| 100          |
| MTT 68 | 1.5 | 1.2  | 2.1  | 10.8 | 9.0  | 12.6  | 60.7  | 43.5| 100          |
| MTT 71 | 0.8 | 0.8  | 1.5  | 12.6 | 7.3  | 18.6  | 50.2  | 33.0| 100          |
| Sher 47b | 1.0 | ... | ... | 6.9  | 2.8  | 11.1  | 27.6  | 22.1| 35.8          |

Notes. Columns labeled χ_lo, χ_hi are the 90% confidence limits for the preceding parameter. A colon ("::") indicates an uncertain value, as in an error limit which did not converge. The model fit was of the form (AtomDB(1) + AtomDB(2)) # PHABS(1).

a Assumes a distance of 7.6 kpc.
b Only the HEG spectrum was fit, and the value of N_H was assumed.

Table 4
Spectral Model Parameters: Relative Abundances

| Object | Ne | Mg | Si | S | Ar | Fe | χ_lo | χ_hi |
|--------|----|----|----|---|----|----|------|------|
| AB     | 1.7| 0.6| 3.9| 0.9| 0.6| 1.1| 1.1  | 0.7  |
| C      | 6.6| 0.8| 6.6| 0.6| 0.2| 1.3| 1.3  | 0.6  |
| MTT 68 | 0.1| 0.1| 3.8| 1.3| 0.7| 2.2| 2.5  | 1.3  |
| MTT 71 | 0.3| 0.1| 5.0| 1.0| 0.2| 2.6| 2.5  | 0.9  |

Note. Abundances are by number fraction relative to the WNh values of Crowther & Dessart (1998). Columns labeled χ_lo, χ_hi are the 90% confidence limits for the preceding parameter. Only Mg, Si, and Fe are resonably constrained. The others are listed only because they are formal values of the fit. Sh 47 is not included because it had too weak a spectrum to fit abundances, which were assumed to be 1.0.
of HD 97950-C are significantly broadened, characteristic of $v_\infty \sim 1800 \text{ km s}^{-1}$, which is somewhat less than the value determined from UV lines (see Tables 1 and 5). The lines have a significantly blueshifted centroid (see Figure 6), indicating a strong wind signature of absorption on the red wing. The shift is much larger than is expected from any Doppler effect from binary orbital motion.

HD 97950-A1 is a double-lined binary and is spatially confused with HD 97950-B in the HETG spectrum. Fortunately, all the components have the same spectral type of WN6h, so we can obtain mean parameters. HD 97950-A1 dominates, having a somewhat brighter zeroth order (Table 2); the rates of A1 and B are consistent with three identical WN6h stars. These stars have a very high $v_\infty$ of about 3000 km s$^{-1}$ but are consistent with the UV measurements at their 90% confidence levels. The lines, like component C, also have a significantly blueshifted centroid, larger than binary orbital motion could cause. The lines may have the “fin” shape characteristic of the asymptotic flow of an optically thick wind, but this is inconclusive and would require a much longer exposure to quantify. Some of the model profile mismatches apparent in Figure 5 may simply be due to the wrong detailed profile shape. They may be more like the family of wind...
profiles derived by Owoki & Cohen (2001). We attempted parametric fitting (sum of Gaussians) of the Si XIII region shown in Figure 5, but while the fit statistic can be reduced, resulting line ratios are nonphysical (e.g., forbidden-to-intercombination line ratios far above that allowed by standard plasma models). It could be that better spectra will support source-model-independent measurement and confirm such anomalies, but for the present analysis, we prefer the plasma-model-based methods as a first characterization of these spectra.

MTT 68 is a very-early-type star of spectral type O2 If (Roman-Lopes 2013). It has an unshifted but significantly broadened profile, as determined from the Gaussian profile fit (Figure 6). The “fit” profile fit is then forced to have a low q (more flat-topped) to make the line centered on its rest wavelength; this fit serves to characterize the wind velocity from the extent of the blue wing, to about 1700 km s⁻¹, but we prefer a Gaussian (or more weakly skewed) profile. This likely makes the wind different from the WNe stars’ winds.

MTT 71 also has an early spectral type, O4 III. It is fainter than MTT 68, so not as well characterized. We can confirm that its lines are broadened, with vₚ ≈ 2700 km s⁻¹, though with large uncertainty. Whether the lines are shifted or non-Gaussian we cannot reliably determine.

Sher 47 (O4 IV(f)), was prominent in the field and had a visible dispersed spectrum. However, its MEG spectrum was confused with that of HD 97950-A1+B, and thus could not be used. There was not enough line signal in the HEG spectrum to warrant detailed line fits.

We expect winds with embedded shocks to be relatively cool in X-rays (kT ≲ 1 keV). Due to the high line-of-sight absorption, we cannot detect any very cool plasmas because the absorption hides the low temperature, long-wavelength component (above about 12 Å or below about 1 keV). From the presence of strong Si and Mg lines, we know we have plasmas with T ≈ 10 MK. From the presence of S, possibly Fe XXV, and the continuum, we know we have very high temperatures. These stars all have a rather hot plasma component, generally in excess of 50 MK, with comparable or even greater emission measure than the ~10 MK component (Table 3). This high temperature is also obvious via the continuum emission seen in the counts spectra in the 2–4 Å region (Figure 4). For comparison, WR 6 also has a high-temperature component of about 50 MK, but it has a much lower weight relative to the lower temperature plasmas. This is suggestive of colliding winds, though we do not understand the origin of the 50 MK plasma far out in the wind of the single WR 6.

Colliding wind binaries can produce high-temperature plasmas with quite diverse possible X-ray line profiles (Henley et al. 2003), dependent upon the viewing geometry. Emission line skewness depends on the continuum optical depth and path length of the wind collision region. Line emission can also have strong time dependence due to the changing aspect, density, and wind velocity in the collision region throughout the binary orbit.

It is likely that the X-ray emission from the stars we have investigated includes emission from colliding winds. Massive O and WR stars are known to be X-ray sources even as single stars, so colliding winds are an additional source of X-ray emission for these massive stars. Therefore, it is difficult to determine if colliding winds are contributing to the X-ray emission of a source unless the data cover at least one full binary orbit, in which case there may be variability in the light curve modulated by the orbit. Our observation is only about a half day out of the 3.77 days period for A1 and the 8.9 days period of C, so we cannot verify colliding winds in these objects.

We did examine the X-ray light curves (Figure 8), and all appear to be essentially constant. According to one-sample KS-tests, assuming they are constant at their mean count rate and have a variance in accordance with their mean counts, they have a high probability of being constant and normally distributed.

Two WR stars known to have some X-ray emission due to colliding winds (WR 140, Pollock et al. 2005; WR 25, Pollock & Corcoran 2006) show strong variability in their X-ray light curves phased with their highly eccentric binary orbits. These are long-period systems and certainly unlike A1, B, or C in many regards, but they are relevant in showing the dramatic effect of wind collisions on X-ray luminosity and the dependence on binary separation. Some WR stars with shorter periods are WR 46 (P ≈ 0.3 days) and WR 6 (P ≈ 3.8 days). While WR 46 is variable in the UV, it is not convincingly variable in X-rays (Zhekov 2012). WR 6 is variable in X-rays, but erratically, with small amplitudes over a day (~10%), up to a factor of 2 over a long term, but no convincing X-ray periodicity (Ignace et al. 2013). Our derived fluxes differ from those of Townsley et al. (2014) by up to a factor of two (see Tables 1 and 2), but their determinations are uncertain because the Chandra/ACIS imaging-mode data suffered from severe CCD count-rate saturation (“pile-up”; see Townsley et al. 2014, Table 4). It is not conclusive whether our fluxes are indicative of long-term or orbital variability. While it is not unusual for stars like these to be constant in X-rays, longer term observations will be required to better detect and characterize any trends with orbital phase or epoch of observation.

These stars have large X-ray luminosities, in excess of 10³⁴ ergs s⁻¹, which is also high relative to their bolometric luminosities, having Lₓ/Lₜ ≥ 10⁻⁶. This strongly suggests that colliding winds are contributing to the X-ray emission of these stars. Components A1 and C are known to be binaries. The extreme stellar density of the region implies a high likelihood of multiplicity for all of these stars. In general, binary WR stars are more X-ray luminous than single WR stars, with Lₓ/Lₜ > 10⁻⁷ (Stevens et al. 2002). WR binaries have a range of log(Lₓ/Lₜ) of −7.3 to −4.0 (Gagné et al. 2012). Specifically, the two previously mentioned known colliding wind binaries, WR 140 and WR 25, have log(Lₓ/Lₜ) of −4.8 and −5.5, respectively. For comparison, the single WR star, WR 6 (type WN4), has a luminosity 10–20 times lower than the stars studied here and has Lₓ/Lₜ < 10⁻⁶ (Oskinova et al. 2012; Huenemoerder et al. 2015). Table 3 shows the range of −6.0 to −4.8, which is well above the norm for single WR stars. The X-ray luminosities of the NGC 3603 stars also exceed the binary WR stars in the sample studied by Zhekov (2012), where only WR 148 approaches Lₓ ∼ 10³⁴ ergs s⁻¹.

The O-type stars in our sample, MTT 68, MTT 71, and Sher 47 (see Table 1) are also highly luminous for their classes. Single O-stars also have Lₓ/Lₜ ∼ 10⁻⁷ (Nazé et al. 2011). In a review of binary colliding winds, Rauw & Nazé (2016), from a variety of X-ray studies, conclude that X-ray bright colliding...
wind binaries are relatively rare—being in a binary does not necessarily confer high relative X-ray luminosity. Two early O-type stars in the core of NGC 3603, A2 and A3, have not been detected in X-rays though their bolometric luminosities are similar to the detected O-stars; perhaps they are "normal" single systems. Whether the X-ray bright O-type systems in NGC 3603 are binary remains to be determined.

6. Conclusions

The relatively short Chandra/HETG exposure has shown the feasibility of studying this cluster at high X-ray spectral resolution. For the brighter components that are saturated in ACIS imaging observations, we have provided more reliable flux measurements. We have confirmed the high terminal wind velocities in X-rays for HD 97950-A1, B, and C, and we have provided the first empirical estimates of the terminal velocities of MTT 68 and MTT 71 from X-ray line profiles. The high plasma temperatures and the very high values of $L_x/L_{bol}$ strongly suggest a colliding winds origin for their X-rays.

Further studies of NGC 3603 stars in high-resolution X-rays are needed to refine the characteristics of their winds and the origin of their very high X-ray luminosities. Higher signal-to-noise ratios are needed to determine emission line shapes in detail, as these are critical for measurement of the terminal velocity and of the optical depths in their winds. A higher signal is also needed to measure He-like line ratios of Mg XI and Si XIII, because these are sensitive to the UV radiation field and thereby serve as a proxy for distance of formation from the photospheres. Longer term X-ray studies are needed in order to search for variability expected from colliding wind binaries. Two of the systems, A1 and C, are known to be binaries and have relatively short periods, making them amenable to X-ray variability studies. Whether the other stars in this study are binaries remains to be determined and is important for interpretation of their properties.

Support for this work was provided by NASA through the Smithsonian Astrophysical Observatory (SAO) contract SV3-73016 to MIT for Support of the Chandra X-Ray Center (CXC) and Science Instruments. CXC is operated by SAO for and on behalf of NASA under contract NAS8-03060. We thank Prof. Claude Canizares for allocation of observing time for this observation from the HETG Guaranteed Time Observation Program.

Facility: CXC (HETG/ACIS).
Software: MARX (Davis et al. 2012), CIAO (Fruscione et al. 2006), ISIS (Houck & Denicola 2000).

ORCID iDs

David P. Huemoeder @ https://orcid.org/0000-0002-3860-6230
Joy S. Nichols @ https://orcid.org/0000-0003-3298-7455

References

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Canizares, C. R., Davis, J. E., Dewey, D., et al. 2005, PASP, 117, 1144
Cassinelli, J. P., Miller, N. A., Waldron, W. L., MacFarlane, J. J., & Cohen, D. H. 2001, ApJL, 554, L55
Cohen, D. H., Wollman, E. E., Leutenegger, M. A., et al. 2014, MNRAS, 439, 908
Crowther, P. A., & Dessart, L. 1998, MNRAS, 296, 622
Crowther, P. A., Schnurr, O., Hirschi, R., et al. 2010, MNRAS, 408, 731
Davis, J. E. 2001, ApJ, 548, 1010
Davis, J. E., Bautz, M. W., Dewey, D., et al. 2012, Proc. SPIE, 8443, 84431A
Drissen, L., Moffat, A. F. J., Walborn, N. R., & Shara, M. M. 1995, AJ, 110, 2235
Foster, A. R., Ji, L., Smith, R. K., & Brickhouse, N. S. 2012, ApJ, 756, 128
Fruscione, A., McDowell, J. C., Allen, G. E., et al. 2006, Proc. SPIE, 6270, 62701V
Gagné, M., Fehon, G., Savoy, M. R., et al. 2012, in ASP Conf. Ser. 465, 465
Scientific Meeting in Honor of Anthony F. J. Moffat, ed. L. Drissen (San Francisco, CA: ASP), 301
Gagné, M., Oksala, M. E., Cohen, D. H., et al. 2005, ApJ, 628, 986
Henley, D. B., Stevens, I. R., & Pittard, J. M. 2003, MNRAS, 346, 773
Hofmann, K., Seggewiss, W., & Weigelt, G. 1995, A&A, 300, 403
Houck, J. C., & Denicola, L. A. 2000, in ASP Conf. Ser. 216, Astronomical Data Analysis Software and Systems IX, ed. N. Manset, C. Veillet, & D. Crabtree (San Francisco, CA: ASP), 591
Huemoeder, D. P., Gayley, K. G., Hamann, W.-R., et al. 2015, ApJ, 815, 29
Ignace, R. 2001, ApJL, 549, L119
Ignace, R., Gayley, K. G., Hamann, W.-R., et al. 2013, ApJ, 775, 29
Kahn, S. M., Leutenegger, M. A., Cottam, J., et al. 2001, AdA, 365, L312
Kramer, R. H., Cohen, D. H., & Owocki, S. P. 2003, ApJ, 592, 532
Luo, D., McCray, R., & Mac Low, M. 1990, ApJ, 362, 267
Maíz Apellániz, J., Sota, A., Arias, J. I., et al. 2016, ApJS, 224, 4
Melena, N. W., Massey, P., Morrell, N. I., & Zangari, A. M. 2008, AJ, 135, 878
Melnick, J., Tapia, M., & Terlevich, R. 1989, A&A, 213, 89
Moffat, A. F. J., Corcoran, M. F., Stevens, I. R., et al. 2002, ApJ, 573, 191
Moffat, A. F. J., Drissen, L., & Shara, M. M. 1994, ApJ, 436, 183
Moffat, A. F. J., Seggewiss, W., & Shara, M. M. 1985, ApJ, 295, 109
Nazé, Y., Broos, P. S., Oskinova, L., et al. 2011, ApJS, 194, 7
Oskinova, L. M., Feldmeier, A., & Hamann, W.-R. 2004, A&A, 422, 675
Oskinova, L. M., Gayley, K. G., Hamann, W.-R., et al. 2012, ApJL, 747, L25
Owocki, S. P., & Cohen, D. H. 2001, ApJ, 559, 1108
Pollock, A. M. T., & Corcoran, M. F. 2006, A&A, 445, 1093
Pollock, A. M. T., Corcoran, M. F., Stevens, I. R., & Williams, P. M. 2005, ApJ, 629, 482
Rauw, G., & Nazé, Y. 2016, AdSpR, 58, 761
Roman-Lopes, A. 2013, MNRAS, 435, L73
Roman-Lopes, A., Franco, G. A. P., & Sammartim, D. 2016, ApJ, 823, 96
Romano, P., Campana, S., Mignani, R. P., et al. 2008, A&A, 488, 1221
Schnurr, O., Casoli, J., Chené, A., Moffat, A. F. J., & St-Louis, N. 2008, MNRAS, 389, L38
Schulz, N. S., Canizares, C., Huemoeder, D., & Tibbetts, K. 2003, ApJ, 595, 365
Stolte, A., Brandner, W., Brandt, B., & Zinnecker, H. 2006, AJ, 132, 253
Townsley, L. K., Broos, P. S., Garmire, G. P., et al. 2014, ApJS, 213, 1
van der Hucht, K. A. 2001, NewAR, 45, 135
Zhekov, S. A. 2012, MNRAS, 422, 1332