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# A DOZEN COLLIDING-WIND X-RAY BINARIES IN THE STAR CLUSTER R136 IN THE 30 DORADUS REGION

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## ABSTRACT

We analyzed archival *Chandra* X-ray observations of the central portion of the 30 Doradus region in the Large Magellanic Cloud. The image contains 20 X-ray point sources with luminosities between $5 \times 10^{32}$ and $2 \times 10^{35}$ ergs s$^{-1}$ (0.2–3.5 keV). A dozen sources have bright WN Wolf-Rayet or spectral type O stars as optical counterparts. Nine of these are within $\sim$3.4 pc of R136, the central star cluster of NGC 2070. We derive an empirical relation between the X-ray luminosity and the parameters for the stellar wind of the optical counterpart. The relation gives good agreement for known colliding-wind binaries in the Milky Way Galaxy and for the identified X-ray sources in NGC 2070. We conclude that probably all identified X-ray sources in NGC 2070 are colliding-wind binaries and that they are not associated with compact objects. This conclusion contradicts earlier studies where it was argued, using *ROSAT* data, that two earlier discovered X-ray sources are accreting black hole binaries. Five of the 18 brightest stars in R136 are not visible in our X-ray observations. These stars either are single, have low-mass companions, or have very wide orbits. The resulting binary fraction among early-type stars is then unusually high (at least 70%).

*Subject headings:* galaxies: star clusters — Magellanic Clouds — stars: early-type — stars: Wolf-Rayet — X-rays: binaries — X-rays: stars

## 1. INTRODUCTION

30 Doradus (NGC 2070) is an active star-forming region in the Large Magellanic Cloud (LMC). Its most striking feature in the optical is the young and compact star cluster R136 (HD 38268; see Walborn 1973). The cluster was long thought to be a single star with a mass exceeding 3000 $M_\odot$ (Cassinelli, Mathis, & Savage 1981). The discovery that this "single star" fitted a King (1966) model indicated that the object is in fact a cluster of stars (Weigelt & Baier 1985). Later, the *Hubble Space Telescope* (*HST*) provided direct proof for this hypothesis by resolving the cluster into individual stars (Campbell et al. 1992; Massey & Hunter 1998).

The structural parameters of R136—mass (21,000–79,000 $M_\odot$), half-mass radius ($\sim$0.5 pc), and density profile ($W_0 \sim 6$; see, e.g., Campbell et al. 1992; Brandl et al. 1996; Massey & Hunter 1998)—are quite similar to three well-known counterparts in the Milky Way Galaxy: the Arches cluster (Object 17; Nagata et al. 1995), the Quintuplet (AFGL 2004; Nagata et al. 1990; Okuda et al. 1990), and NGC 3603 (Brandl et al. 1999). All younger than $\sim$3 Myr, these clusters are also comparable in age. NGC 3603 is hidden behind a spiral arm but is much easier to observe than the Arches and the Quintuplet, which are located near Galactic coordinates $l = 0\fdg122$, $b = 0\fdg018$ ($\sim$35 pc in projection) of the Galactic center. The extinction in the direction of the Galactic center easily exceeds 20 mag in visual. R136 is conveniently located in the LMC and therefore is quite unique, as it is neither obscured by dust and gas nor perturbed by external tidal fields; the tidal effect of the LMC is negligible (see Portegies Zwart et al. 1999). The large distance of about 50 kpc, however, limits the observability of the cluster. Note that both star clusters Westerlund 1 and 2 (Westerlund 1960, 1961) have rather similar characteristics as the above-mentioned clusters.

In 1991, Wang & Helfand studied the 30 Doradus region with the *Einstein* Imaging Proportional Counter. They found that hot gas surrounds a $\sim$300 pc area around R136. They also found two marginally significant point sources with the *Einstein* High Resolution Imager in the central area of 30 Doradus. A follow-up with the *ROSAT* High Resolution Imager confirmed the presence of two point sources. Wang (1995) analyzed these two sources and used their similarities to Cyg X-1, LMC X-1, and LMC X-3 to conclude that the observed X-ray sources in 30 Doradus also host black holes. Recent *XMM* observations by Dennerl et al. (2001) showed a wealth of X-ray sources in the 30 Doradus region. They pay little attention, however, to the X-ray point sources in R136. In a preliminary study of *Chandra* data of R136, Feigelson (2001; see also L. K. Townsley et al. 2002, in preparation) mentions the presence of a dozen bright X-ray sources with O3 or WN star companions. He argues that the dimmer sources could be colliding-wind binaries but that the brighter sources are probably X-ray binaries with neutron star or black hole primaries. From a practical point of view, however, there are some difficulties associated with claims that there are neutron stars or black holes in R136.

The most massive stars in R136 exceed 120 $M_\odot$. Massey & Hunter (1998) took high-resolution spectra of the brightest 65 stars and concluded that their age is less than 1–2 Myr, where the intermediate-mass stars are slightly older (4–5 Myr; Sirianni et al. 2000). They also argue that the high abundance of stars with spectral type O3 and earlier is a consequence of the young age of the cluster. de Koter, Heap, & Hubeny (1997) analyzed the spectra of the most massive stars in R136 and concluded that the ages of these stars are $\lesssim$1.5 Myr, which is consistent with the results by Massey & Hunter (1998).

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The hydrogen- and helium-burning age of a 120 $M_\odot$ star depends quite sensitively on its metallicity $Z$, being as low as 2.87 Myr for a $Z = 0.001$ (the solar metallicity $Z_\odot = 0.02$) to 4.96 Myr for $Z = 0.04$ (Meynet et al. 1994). Because R136 is only $\sim$2 Myr old, no star in it can have left the main sequence yet. It would therefore be quite remarkable if the star cluster were able to produce black holes before 2 Myr.

We analyze archival *Chandra* data of the central portion of the 30 Doradus region and confirm the detection of the two X-ray point sources previously found by Wang & Helfand (1991). In addition, we find 18 new X-ray sources, of which 13 have WN Wolf-Rayet stars or early type O3f* stars as optical counterparts. One of these X-ray sources is probably a blend of several WN stars in the subcluster R140 (to the north of R136). We argue that the X-rays produced by these systems originate from the colliding winds of the early-type stars. The X-ray luminosities of three of these stars are an order of magnitude higher than the X-ray luminosities of colliding-wind systems in the Milky Way Galaxy.

In § 2, we describe the *Chandra* data and analysis, followed by a description of our findings in § 3. We discuss our results in § 4.

## 2. OBSERVATIONS AND DATA ANALYSIS

The 30 Doradus region was observed with *Chandra* for 21 ks on 2000 September 13 with the Advanced CCD Imaging Spectrometer-Imager (ACIS-I), a $16'.9 \times 16'.9$ array of four front-side–illuminated CCDs (G. P. Garmire, J. A. Nousek, & M. W. Bautz 2002, in preparation). The R136 star cluster was at the telescope's aim point. The data were taken in timed-exposure (TE) mode using the standard integration time of 3.2 s per frame and telemetered to the ground in very faint (VF) mode. See the *Chandra* Proposers' Observatory Guide for details.[4]

We followed the data-preparation threads provided by the *Chandra* team and given on their Web site. We used the *Chandra* Interactive Analysis of Observations (CIAO) software package to perform the reductions, with the most up-to-date (as of 2001 June) calibration files (gain maps, quantum efficiency, quantum efficiency uniformity, effective area) available for this observation. Bad pixels were excluded. Intervals of bad aspect and intervals of background flaring[5] were searched for, but none were found.

To detect sources, we first filtered the unprocessed data to exclude software-flagged cosmic-ray events and then processed the data without including the pixel randomization that is added during standard processing. This custom processing slightly improves the point-spread function (PSF). We then used the CIAO tool *wavdetect*, a wavelet-based source detection program. We found 30 point sources and two extended sources (SNR 0538−69.1 and an unidentified one) in the entire ACIS-I field. Figure 1 shows a $11' \times 11'$ image (*left*) and a blow-up of the central 7″ square (*right*) *Chandra* image with the source names identified. The names of the sources correspond to the 20 sources listed in Table 1.

Radial surface brightness profiles were constructed for the four brightest sources and compared to expected PSF profiles for those chip locations. Only CX 10 (near the star cluster R140) was inconsistent with a point source (3.4 $\sigma$).

The positions listed in Table 1 are the *wavdetect* centroid positions based on the *Chandra* astrometric solution. The uncertainties range from $\sim 0''.1$ for the brighter sources to $\sim 1''$ for the dimmer sources. To perform source identifications, we used Parker's catalog of bright stars in the 30 Doradus region (Parker 1993). These positions are accurate within $0''.4$. Registration of the *Chandra* frame of reference with the Parker frame was accomplished via a uniform shift calculated from a least-squares best fit to the offsets from nearby optical sources of eight X-ray sources (CX 2, CX 4, CX 5, CX 6, CX 7, CX 8, CX 12, and CX 19), six in the central region and two outside the central region. In a similar manner, the Parker frame was registered with the *HST* frame by a uniform shift based on five stars (names from Parker 1993: 1120, 1134, 922, 786, 767) in the central region. The Parker-to-*HST* shift was $0''.07$ in right ascension (R.A.; true arcseconds) and $-1''.32$ in declination (decl.). The total *Chandra*-to-*HST* shift was $1''.35$ in R.A. (true arcseconds) and $0''.66$ in decl. Figure 2 shows the *Chandra* sources (*ellipses*) and Parker stars (*boxes*) overlaid on an *HST* image of the central region. The sizes of the ellipses and boxes indicate the 1 $\sigma$ position errors.

X-ray spectra of the five brightest *Chandra* sources were extracted with the CIAO tool *dmextract*. Spectral fitting (using $\chi^2$ statistics) was done in XSPEC with the data grouped to $\geq$10 counts per bin for CX 1 and CX 8, $\geq$20 counts per bin for CX 2 and CX 10, and $\geq$30 counts per bin for CX 5. Because of the association of nearly all of the X-ray sources with Wolf-Rayet stars, we chose the *mekal* model (Mewe, Gronenschild, & van den Oord 1985) with absorption, which fits better than thermal bremsstrahlung models. A summary of the results is given in Table 1. The spectra of the brightest two sources (CX 2 and CX 5), which are quite representative, are shown in Figure 3. For a better comparison with previous observations, which were mostly done with the *Einstein* observatory, we calculate the luminosities over the same band. Although a source can be detected with only a few counts, $\gtrsim$100 counts are required to fit a spectrum with any confidence. To estimate the luminosity of the dimmer sources, we use a best-fit linear relationship between observed counts and unabsorbed luminosities for four of the brightest five sources. Because the source CX 10 is bright for its count rate and extended, we excluded it when deriving this relation.

We identify source CX 10 with W5 and CX 5 with W7 from Wang (1995). The luminosities for these two sources calculated from our best-fit models are lower than those of Wang by a factor of $\sim$10, but this is somewhat deceptive. Wang used multicolor blackbody disk (MBD) models with absorption and could only fit over the 0.5–2 keV *ROSAT* band. Such models do not fit our broader band (0.3–8 keV) data well. If we restrict our data to the *ROSAT* band, we find that MBD models fit the data, but the column densities required for good fits with these models are much higher than those required for fits with the *mekal* model. When we calculate *intrinsic* source luminosities based on MBD fits to the 0.5–2 keV *Chandra* data, our results are consistent with those of Wang. There is no evidence for variability on the timescale between the two observations 9 yr apart. Also, none of our sources show statistically significant variability during the *Chandra* observation.

[4] See the *Chandra* Web site (http://asc.harvard.edu).

[5] See http://asc.harvard.edu/cal/Links/Acis/acis/Cal_prods/bkgrnd/current for a discussion of background flares.

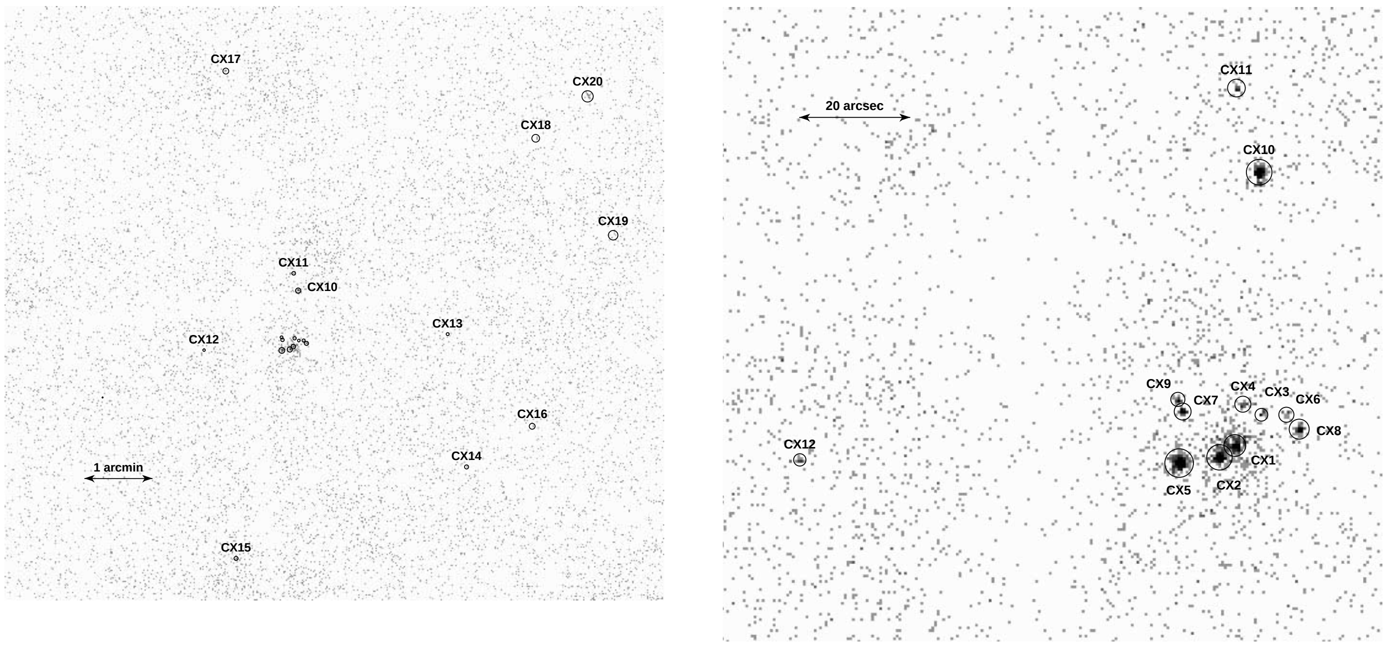


FIG. 1.—X-ray image of the star cluster R136 in the 30 Doradus region. (*left*) 11′ × 11′ view; (*right*) close-up of the cluster. The sources are identified in Table 1.

## 3. RESULTS AND INTERPRETATION

### 3.1. *Optical Counterparts*

We concentrate on the 11 X-ray sources (CX 1–CX 11) that are located within 100″ (∼25 pc in projection at a distance of 51 kpc) from the central star R136a1 of the star cluster R136. For the other eight sources, we have insufficient information to include them in our study. Two of these remaining sources (CX 12 and CX 17) have WN type Wolf-Rayet stars as optical counterparts (see Table 2), CX 14 is an *IRAS* source, and CX 19 has the foreground star MH 2 as counterpart (Fehrenback & Duflot 1970), which is observed in infrared (McGregor & Hyland 1981) and classified as a spectral type M star (Hyland, Thomas, & Robinson

TABLE 1

*Chandra* DETECTIONS OF X-RAY POINT SOURCES NEAR THE STAR CLUSTER R136

| Source | R.A. | Decl. | $r$[a] (arcsec) | Counts[b] | $kT_{mekal}$ (keV) | $n_{\rm H}$ ($10^{21}$ cm$^{-2}$) | $\chi^2$/dof | log $L_{0.2-3.5\,\rm keV}$ (ergs s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| CX 1 .......... | 05 38 42.210 | −69 06 03.85 | 0 | 146 | 1.7 | 2.8 | 14.6/13 | 34.34 |
| CX 2 .......... | 05 38 42.722 | −69 06 06.02 | 3.5 | 390 | 2.1 | 6.3 | 19.7/18 | 34.93 |
| CX 3 .......... | 05 38 41.311 | −69 05 58.30 | 7.3 | 13 | | | | 33.17 |
| CX 4 .......... | 05 38 41.930 | −69 05 56.43 | 7.6 | 16 | | | | 33.31 |
| CX 5 .......... | 05 38 44.077 | −69 06 07.05 | 10.5 | 997 | 3.3 | 4.8 | 33.0/32 | 35.26 |
| CX 6 .......... | 05 38 40.470 | −69 05 58.34 | 10.8 | 9 | | | | 32.86 |
| CX 7 .......... | 05 38 43.962 | −69 05 57.81 | 11.2 | 51 | | | | 33.93 |
| CX 8 .......... | 05 38 40.042 | −69 06 00.94 | 12.0 | 91 | 2.1 | 1.6 | 8.0/6 | 34.00 |
| CX 9 .......... | 05 38 44.130 | −69 05 55.64 | 13.2 | 20 | | | | 33.44 |
| CX 10......... | 05 38 41.391 | −69 05 14.67 | 49.4 | 374 | 1.1 | 7.9 | 11.4/17 | 35.22 |
| CX 11......... | 05 38 42.156 | −69 04 59.46 | 64.4 | 17 | | | | 33.35 |
| CX 12......... | 05 38 56.852 | −69 06 06.48 | 78.4 | 11 | | | | 33.04 |
| CX 13......... | 05 38 16.909 | −69 05 52.57 | 136 | 6 | | | | 32.23 |
| CX 14......... | 05 38 13.755 | −69 07 49.13 | 185 | 7 | | | | 32.55 |
| CX 15......... | 05 38 51.602 | −69 09 09.59 | 192 | 15 | | | | 33.27 |
| CX 16......... | 05 38 02.963 | −69 07 13.28 | 221 | 8 | | | | 32.73 |
| CX 17......... | 05 38 53.226 | −69 02 01.82 | 249 | 13 | | | | 33.17 |
| CX 18......... | 05 38 02.508 | −69 03 00.44 | 281 | 22 | | | | 33.50 |
| CX 19......... | 05 37 49.811 | −69 04 25.14 | 297 | 17 | | | | 33.35 |
| CX 20......... | 05 37 54.057 | −69 02 23.54 | 339 | 94 | | | | 34.22 |

NOTE.—The position of R136 was R.A. $5^{\rm h}38^{\rm m}43^{\rm s}.2$, decl. 69°6′0″ in the year 2000 AD. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. For sources with $\lesssim 90$ counts (including CX 20 because of the lack of an optical counterpart), we estimate the luminosities based on a best-fit linear relation between counts and luminosities for four of the five brightest sources (we excluded CX 10; see § 2).

[a] Distance to the star R136a (CX 1).

[b] Number of counts in 0.3–8.0 keV.

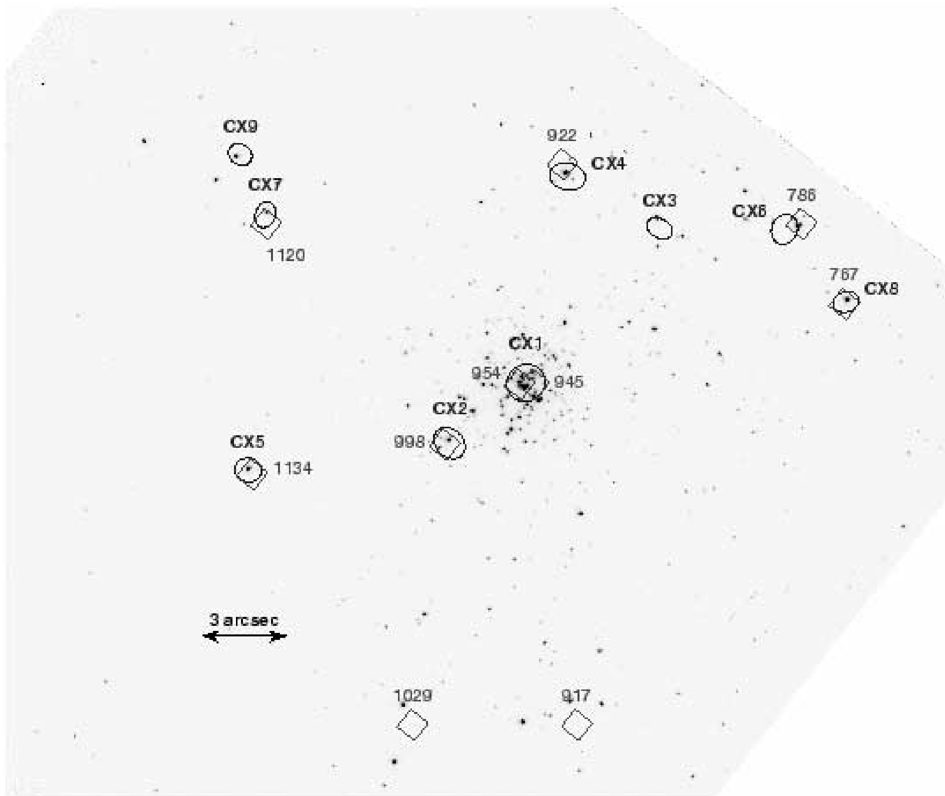


FIG. 2.—*HST* image of R136, the central portion of the 30 Doradus region (Massey & Hunter 1998). The exposure time was 26 s with filter F336W (centered on 3344 Å and with a 381 Å bandpass) using WFPC2. The Wolf-Rayet stars identified by Parker (1993) are indicated by squares, and the ellipses give the locations of the *Chandra* X-ray sources (see Tables 1 and 2). The sizes of the ellipses give the 1 $\sigma$ positional accuracy for the *Chandra* sources.

1978). The remaining five sources (CX 13, CX 15, CX 16, CX 18, and CX 20) are not identified.

All 11 sources (CX 1–CX 11) have a bright optical star within the 1 $\sigma$ error ellipse of the corrected *Chandra* position. Figure 2 gives an *HST* image of R136 (Massey & Hunter 1998). The ellipses indicate the 1 $\sigma$ error at the location of our 11 *Chandra* point sources near R136. Details about these sources are given in Table 1.

Parker (1993) identifies 12 WN-type Wolf-Rayet stars (see Table 2) near the star cluster R136. These are identified in Figure 2 by squares. Five of these (R136a1, a2, a3, a5, and R136b) are embedded deep in the core of the cluster. The source CX 10 has the small cluster R140 as counterpart, which is at about 11.5 pc in projection to the north of R136a. This cluster contains at least two WN stars and one WC star (Moffat et al. 1987). We found CX 10 to be extended, and it may well be a blend of several colliding-wind binaries.

Seven of nine of the remaining sources have WN stars as counterparts, and the other two coincide with spectral type O3f* stars (Crowther & Dessart 1998). Melnick (1978; see also Melnick 1985 and Bosch et al. 1999) lists most of the

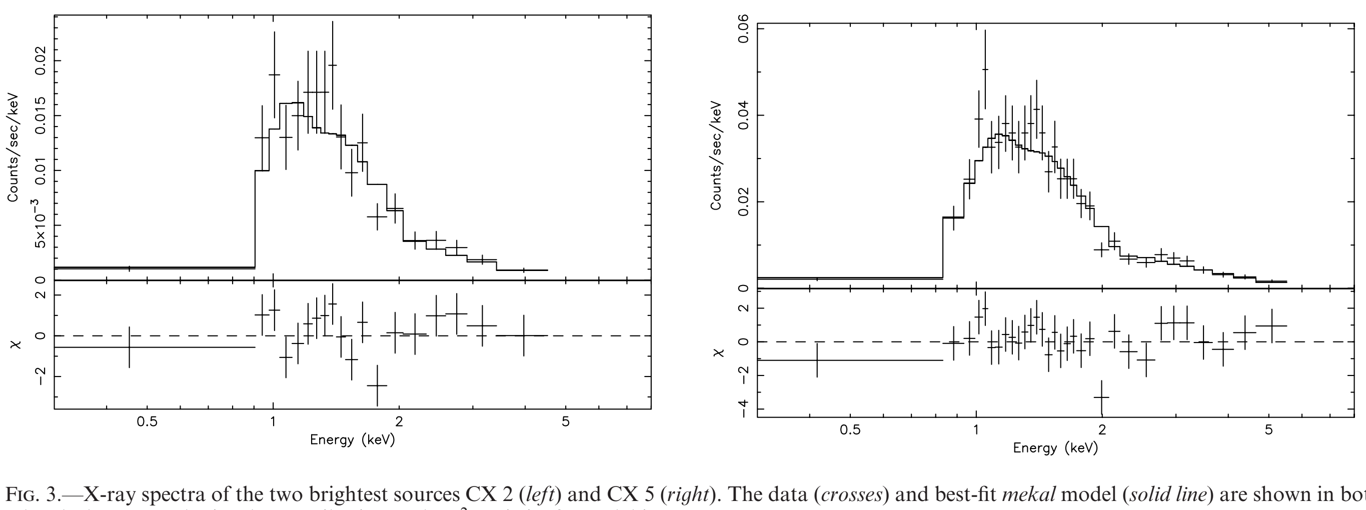


FIG. 3.—X-ray spectra of the two brightest sources CX 2 (*left*) and CX 5 (*right*). The data (*crosses*) and best-fit *mekal* model (*solid line*) are shown in both panels. The lower panels give the contribution to the $\chi^2$ statistics for each bin.

TABLE 2
OPTICAL COUNTERPARTS FOR THE X-RAY SOURCES

| Source (1) | Star (2) | $P$ (3) | Spectral Type (CD) (4) | $\log \dot{m}_{\rm wind}$ ($M_\odot$ yr$^{-1}$) (5) | $\log L_{\rm bol}$ (ergs s$^{-1}$) (6) | Mass ($M_\odot$) (7) | $v_{\rm esc}$ (1000 km s$^{-1}$) (8) | $v_\infty$ (1000 km s$^{-1}$) (9) | Notes (10) |
|---|---|---|---|---|---|---|---|---|---|
| CX 1 .......... | R136a | | 3 WN5 | −4.4? | 40.2 | 111 | 1.93 | 1.08 | WN4.5+OB |
| CX 2 .......... | R136c | 998 | WN5h (+?) | −4.4 | 40.0 | 128 | 2.67 | 1.45 | WN7+OB |
| CX 3 .......... | . . . | 860 | O3V | −5.5 | 30.5 | 77 | 3.70 | | O7Vf |
| CX 4 .......... | Mk 42 | 922 | WN6/O3If | −4.3 | 40.0 | 66.5 | 1.57 | 0.93 | WN+OB |
| CX 5 .......... | Mk 34 | 1134 | WN5h | −4.3 | 40.1 | 179 | 3.14 | 1.66 | WN4.5 (+O?) |
| CX 6 .......... | R134 | 786 | WN6(h) | −4.1 | 40.1 | 179 | 3.14 | 1.66 | WN7 |
| CX 7 .......... | Mk 33Sa | 1120 | O3IIIf*+WC5 | −5.3 | 39.5 | 105 | 2.34 | | WC5+O4 |
| CX 8 .......... | Mk 39 | 767 | WN6/O3If | −4.4 | 40.0 | 66.5 | 1.57 | 0.93 | O4If |
| CX 9 .......... | Mk 33Na | 1140 | O3If*+O6.5V | −5.1 | 39.8 | 105 | 2.37 | | WN4/O4 |
| CX 10......... | R140a | 880 | WN6 | −4.4? | 39.9 | 53.7 | 1.48 | 0.91 | WC5+WN4 |
| CX 11......... | R139 | 952 | O6Iaf/WN | −4.1? | 40.0 | ? | 2.40 | | |
| CX 12......... | R145 | | WN6h | −3.84 | ? | | | | |
| CX 14......... | IRS 2 | | | | | | | | |
| CX 17......... | R144 | | WN6h | −3.65 | ? | | | | |
| CX 19......... | MH 2 | | | | | | | | |

NOTE.—The stellar numbering $P$ (col. [3]) is from Parker 1993. The spectral type and mass-loss rates (cols. [4] and [5]) are taken from Crowther & Dessart (1998, and P. Crowther 2001, private communication). Bolometric luminosities, masses, and escape velocities ($v_{\rm esc}$) for the O stars are from Massey & Hunter using the calculations of Vacca, Garmany, & Shull 1996. Col. (8) ($v_{\rm esc}$) gives, for the Wolf-Rayet stars, the escape velocity from the stellar core ($v_{\rm ce}$) as described in § 3.3. The terminal wind velocities for the O stars are calculated from the effective temperature, as given by Crowther & Dessart. The wind velocities of the Wolf-Rayet stars are calculated assuming the following compositions: for WN5/6 stars, we adopt $Y = 0.983$ and $Z = 0.0172$; for stars with hydrogen enhancement, we use $Y = 0.7324$ and $Z = 0.0176$. Col. (10) contains some notes about the binarity or alternative classification from Melnick (1978, 1985) and from Bosch et al. 1999. Uncertain values are indicated by a question mark, and unknown values are left blank.

Wolf-Rayet stars (and one of the O3f* stars that are associated with our X-ray sources) as binaries with a spectral type O or B companion. The four exceptions P860, Mk 39, R134, and R139 are not known to be binaries. The star Mk 33Na is listed as a binary by Crowther & Dessart (1998) but not by Melnick (1978, 1985). The two stars R144 and R145, which are associated with CX 17 and CX 12, respectively, are little discussed in the literature; both are WN6h stars (Crowther & Smith 1997).

Table 2 lists the X-ray sources and their counterparts.

### 3.2. *The Nature of the X-Ray Sources*

We now study the possibility that the X-rays are produced in the stellar winds in the optical counterparts. Wolf-Rayet stars are known to be bright X-ray sources (Pallavicini et al. 1981), which follow the empirical relation between X-ray and bolometric luminosity of $L_{\rm X}/L_{\rm bol} \simeq 10^{-7\pm1}$. This relation holds for a wide range of stellar spectral types down to late B. White & Long (1986) confirm the existence of this relation for WN- and WC-type Wolf-Rayet stars. An extensive study by Pollock (1987) using the *Einstein* observatory confirms this relation for binaries with a WN or WC Wolf-Rayet star as primary.

The sample of Chlebowski & Garmany (1991) contains early type O stars, which may follow a different relation between $L_{\rm X}$ and $L_{\rm bol}$ than Wolf-Rayet stars. However, the Wolf-Rayet stars listed by White & Long (1986; two WN and four WC stars) and by Pollock (1987; seven WN and four WC stars) follow the same relation as the early type O stars of Chlebowski & Garmany (1991). (To minimize confusion, we decided to show only the stars listed by Chlebowski & Garmany in Fig. 4.)

In Figure 4, we compare the relation between bolometric luminosity $L_{\rm bol}$ and $L_{\rm X}/L_{\rm bol}$ of 11 of our observed X-ray sources with that of the 16 X-ray–bright stars in the sample discussed by Chlebowski & Garmany (1991). To make the comparison, we calculate the 0.5–3.5 keV luminosity from our best-fit models (which were fitted over the entire 0.3–8.0 keV *Chandra* band) since this was the band used by Chlebowski & Garmany (1991), who observed with the *Einstein* observatory (see Table 1). Between the stars in NGC 2070 and the sample of Chlebowski & Garmany (1991), three stars (R140a, Mk 34, and R136c) are considerably brighter than expected from the empirical relation, and the scatter among the stars in NGC 2070 is larger than for the sample

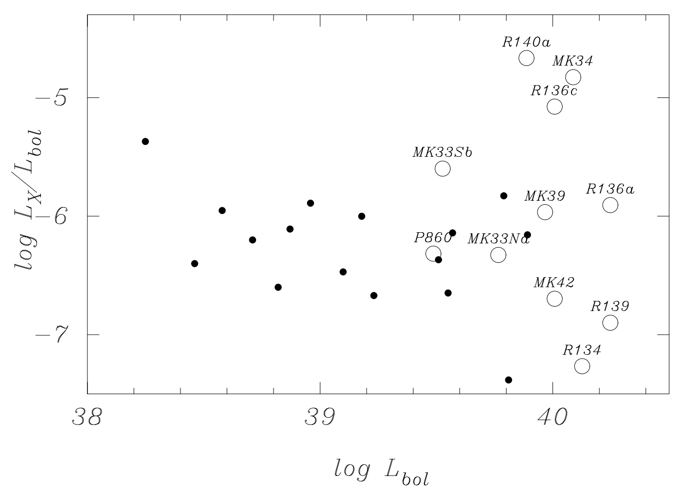


FIG. 4.—Ratio of the X-ray luminosity (0.2–3.5 keV) to the bolometric luminosity ($L_{\rm X}/L_{\rm bol}$) for the X-ray sources from Tables 2 and 3 as a function of the bolometric luminosity (in ergs s$^{-1}$). The known Galactic colliding-wind binaries from Table 3 are indicated with bullets (see Fig. 5 for the error bars). The sources from Table 2 are indicated by circles and identified by the names of their optical counterparts. Note that the two types of sources (Galactic vs. those near NGC 2070) are selected on different criteria, and a direct comparison has to be carried out with care.

of Galactic sources. The unusual brightness of CX 10 may be explained as a blend of several objects in the subcluster R140.

We have no ready explanation for the extreme brightness of the other two stars, but bear in mind that the stars associated with our X-ray sources are unusually bright and massive, ranging from 50 to 150 $M_\odot$ (see Table 2), unlike any stars in the Milky Way Galaxy. It is therefore possible that they do not follow the same relation as the rather "low" mass (15–30 $M_\odot$) stars in the Milky Way Galaxy. Note also that a direct comparison between the Galactic X-ray sources and those near NGC 2070 has to be carried out with care, since both have been selected on different grounds.

### 3.3. *X-Rays from Colliding Stellar Winds*

The typical mass-loss rate for a WN Wolf-Rayet star is between $10^{-5}$ and $10^{-4}$ $M_\odot$ yr$^{-1}$ and somewhat smaller for an Of* star (see Table 2). When the fast mass outflow of one of these stars collides with the mass outflow of a companion star, strong shocks form. For a single star, the shocks will be much weaker because the relative velocity of the shocked material is much smaller for a single star than for one in a binary. The temperature in the shocks can be very high, at which point X-rays are produced (Prilutskii & Usov 1976; Cherepashchuk 1976; Cooke, Fabian, & Pringle 1978). The X-ray emission observed from such systems is generally rather soft ($kT \sim 1$ keV), originating from the outer parts of the wind (Pollock 1987).

We estimate the total X-ray luminosity in the colliding wind in the limit of completely isothermal radiative shocks and assuming that the flow is adiabatic.[6] The total X-ray luminosity is given by the product of the emissivity per unit volume, $n^2\Lambda$, with the volume of the shock-heated wind. Here, $\Lambda \propto T^{-0.6}$ is the emission rate at which the gas cools (see Stevens, Blondin, & Pollock 1992). In the adiabatic limit for a binary star with orbital separation $a \gg r$, the volume of the shock heated gas scales as $a^3$. Here, $r$ is the stellar radius. The density $n \propto \dot{m}_{\rm wind}/(a^2 v_{\rm wind})$. The total luminosity due to the shock is then $L \propto \dot{m}^2_{\rm wind}/(v^2_{\rm wind} a)$. We assume that the postshock temperature equals the temperature on the line connecting the two stars and using $T \propto v^2_{\rm wind}$, and we define (in cgs units)

$$S_{\rm X} = \frac{\dot{m}^2_{\rm wind}}{v^{3.2}_{\rm wind} a} . \tag{1}$$

Here, we assume momentum balance of the two winds on the connecting lines between the two stars; i.e., the two stars are equally windy ("equipetomaniac"). This relation has been tested with detailed calculations by Luo, McCray, & Mac Low (1990) and Stevens et al. (1992).

We now calculate the terminal velocity of the stellar wind of early type O stars and Wolf-Rayet stars. The luminosity $L$ of massive main-sequence stars $L \propto m^3$ and the radius $r \propto m$. With $L \propto r^2 T^4_{\rm eff}$ and the escape velocity from the stellar surface $v^2_{\rm esc} \propto m/r$, we can write $v_{\rm esc} \propto T_{\rm eff}/m^{1/4}$; i.e., the escape velocity of a massive star is proportional to its effective temperature. The terminal velocity in the stellar wind $v_\infty \propto v_{\rm esc}$. However, the velocity of the stellar wind at the moment it collides may be smaller than the escape velocity from the stellar surface but larger then the terminal velocity. We write the velocity at the moment the winds collide as

$$v_{\rm wind} = v_\infty \left(1 - \frac{r}{a}\right) . \tag{2}$$

For simplicity, we assume that the winds collide at distance $a$ from the primary star with radius $r$, which we calculate from the effective temperature and the luminosity.

We calibrate the relation between the terminal velocity and the stellar temperature with the list of O and B stars in Table 3, which results in

$$v_\infty \simeq 130 \frac{T_{\rm eff}}{1000\ {\rm K}} - 2800\ {\rm km\ s^{-1}} . \tag{3}$$

For the O stars in our sample, we can apply the same relation between the wind velocity and the effective temperature of the star. For Wolf-Rayet stars, however, this relation breaks down.[7]

Crowther & Dessart (1998) list mass-loss rates $\dot{m}_{\rm wind}$ and bolometric luminosities $L_{\rm bol}$ for most of the optical counterparts to our X-ray sources but not their terminal velocities. We derive the escape velocity $v_{\rm ce}$ from the core of a Wolf-Rayet star using its luminosity. The terminal velocity then follows from the empirical relation of Nugis & Lamers (2000). The wind velocity is then calculated using equation (2).

The terminal velocity $v_\infty$ is given by (Nugis & Lamers 2000)

$$\log v_\infty/v_{\rm ce} \simeq 0.61 - 0.13 \log \mathscr{L} + 0.3 \log Y . \tag{4}$$

We define the luminosity $\mathscr{L} \equiv L/L_\odot$, mass $\mathscr{M} \equiv m/M_\odot$, and radius $\mathscr{R} \equiv r/R_\odot$ of the core of the Wolf-Rayet star in solar units; $Y$ is the helium mass fraction of the star.

The effective escape velocity from the stellar core is

$$v_{\rm ce} \simeq 438 \sqrt{\frac{\mathscr{M}(1-\Gamma_e)}{\mathscr{R}}}\ {\rm km\ s^{-1}} . \tag{5}$$

Here, $\Gamma_e \simeq 7.66 \times 10^{-5} \sigma_e \mathscr{L}/\mathscr{M}$ corrects the gravity for electron scattering, and the electron scattering coefficient is $\sigma_e \simeq 0.4(X + \frac{1}{2} Y + \frac{1}{4} Z)$ cm$^2$ (see Nugis & Lamers 2000).

The core radius is given by

$$\log \mathscr{R} \simeq -1.845 + 0.338 \log \mathscr{L} . \tag{6}$$

The mass is obtained by iterating the mass-luminosity relation for massive Wolf-Rayet stars (Schaerer & Maeder 1992):

$$\log \mathscr{L} \simeq 2.782 + 2.695 \log \mathscr{M} - 0.461 (\log \mathscr{M})^2 . \tag{7}$$

The $L$-$v_{\rm ce}$ relation derived with this model fits well with the WN4–WN6 stars of Hamann & Koesterke (2000), the cores of planetary nebulae of Kudritzki & Puls (2000), and the sample of 24 Galactic and 14 Magellanic Cloud O stars of Puls et al. (1996).

Figure 5 shows the results of equation (1) with $S_{\rm X}$ along the horizontal axis and the observed X-ray luminosity in the

[6] We refer to the total X-ray luminosity, since our model is too simple to identify any energy dependency.

[7] The radius of a Wolf-Rayet star is ill defined because the wind is optically thick as a result of the large mass-loss rate; the stellar radius depends on the wavelength. The effective temperature of a Wolf-Rayet star is therefore ill defined.

TABLE 3

PARAMETERS FOR KNOWN BLACK HOLE X-RAY BINARIES AND X-RAY SOURCES WITH EARLY-TYPE STARS AS OPTICAL COUNTERPARTS

| Name | Spectral Type | $P_{orb}$ (days) | $T_{eff}$ (1000 K) | $\log L_{bol}$ (ergs s$^{-1}$) | $\log L_X$ (ergs s$^{-1}$) | $N_{counts}$ | $\log \dot{m}_{wind}$ ($M_\odot$ yr$^{-1}$) | $v_\infty$ (km s$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Cyg X-1 ............ | O9.7ab | 5.6 | | | 37.3 | Variable | −7.0 | 1800 |
| LMC X-1 .......... | O7–9II | 4.2 | | | 38.6 | Variable | −7.0 | 2100 |
| LMC X-3 .......... | B3V | 2.3 | | | 38.6 | Variable | −8.0 | 490 |
| HD 1337 ........... | O9III | 3.52 | 34.0 | 39.55 | 32.90 | 32.8 | −6.17 | 2200 |
| HD 12323 ......... | ON9 | 3.07 | 35.9 | 38.25 | 32.88 | 21.1 | −8.37 | 1300 |
| HD 37041 ......... | O9V | 20.79 | 35.9 | 38.46 | 32.06 | 305 | −8.24 | 1700 |
| HD 37468 ......... | O8.5III | 30 | 35.0 | 38.82 | 32.22 | 681 | −8.14 | 1300 |
| HD 57060 ......... | O7Ia | 4.39 | 36.1 | 39.81 | 32.43 | 534 | −5.35 | 1800 |
| HD 75759 ......... | O9Vn | 33.31 | 35.9 | 39.23 | 32.56 | 26.8 | −7.49 | 1600 |
| HD 93206 ......... | O9.7Ib | 6 | 30.6 | 39.57 | 33.43 | 327 | −5.85 | 2500 |
| HD 93205 ......... | O3V | 6.08 | 48.5 | 39.51 | 33.14 | 144 | −6.23 | 3600 |
| HD 93403 ......... | O5III | 15.09 | 42.3 | 39.79 | 33.96 | 667 | −5.82 | 3000 |
| HD 100213........ | O8.5 | 1.39 | 37.0 | 38.58 | 32.63 | 15.1 | −7.65 | 1800 |
| HD 152218........ | O9.5IV | 5.40 | 34.0 | 38.87 | 32.76 | 48.9 | −6.93 | 3000 |
| HD 152590........ | O7.5V | 4.49 | 39.1 | 38.71 | 32.51 | 7.95 | −7.36 | 2300 |
| HD 159176........ | O7V | 3.37 | 40.1 | 38.96 | 33.07 | 859 | −6.72 | 2600 |
| HD 165052........ | O6.5V | 6.14 | 41.2 | 39.18 | 33.18 | 77.5 | −6.62 | 2700 |
| HD 206267........ | O6.5V | 3.71 | 41.2 | 39.10 | 32.63 | 120 | −6.16 | 3100 |
| HD 215835........ | O6V | 2.11 | 42.2 | 39.89 | 33.73 | 22.1 | −5.54 | 3350 |

NOTE.—The first three entries are the black hole X-ray binaries (Gies & Bolton 1982; Liu, van Paradijs, & van den Heuvel 2000). The remaining 16 sources are X-ray–luminous O and B stars observed with *Einstein*. The X-ray data are taken from Chlebowski, Harnden, & Sciortino 1989. Temperature, luminosity, mass-loss rate, and wind velocities are from Chlebowski & Garmany 1991.

Einstein band along the vertical axis. The bullets indicate the locations of the 16 colliding-wind Wolf-Rayet binaries from Chlebowski & Garmany (1991). The orbital separation for these binaries is calculated using Keplers' third law with the mass and orbital period given by Chlebowski & Garmany (1991). When no mass estimate is provided, we assume a total binary mass of $30 \pm 15\ M_\odot$. A fit to this data

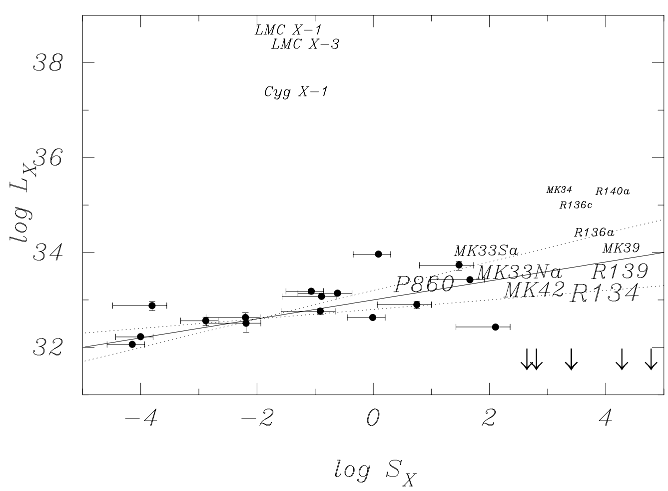


FIG. 5.—X-ray luminosity as a function of $S_X$ (eq. [1]). The bullets give the location of the binaries listed by Chlebowski & Garmany (1991). The *Chandra* X-ray sources from Table 2 are identified by their optical counterpart; the size of their names are proportional to the 1 $\sigma$ errors. The solid line gives a least-squares fit to the bullets, which represent the sources of Table 3. The dotted lines represent the uncertainty interval of the fit. For comparison, we plot the location of three known high-mass X-ray binaries with a black hole (see discussion). The values of $S_X$ (eq. [1]) for the five downward-pointed arrows represent the stars (from left to right) R136b, Mk 37Wb, Mk 35, Mk 30, and Mk 49, which we did not detect in X-rays.

is presented as the solid line in Figure 5, which represents

$$L_X = 10^{33.0 \pm 0.2} S_X^{0.2 \pm 0.1}\ , \qquad (8)$$

where the dotted lines give the uncertainty interval.

The names of the optical counterparts of the X-ray sources from Table 2 are plotted in Figure 5. The value of $S_X$ for these stars is calculated with equation (1) assuming that they are binaries with an orbital separation of 100 $R_\odot$. For the wind velocity in equation (1), we adopt both extremes, the terminal velocity and the escape velocity from the Wolf-Rayet star. The uncertainty thus obtained is proportional to the size of the name tags in Figure 5. Only the orbital period of R140a is known (2.76 days; Moffat et al. 1987). With a total binary mass of about 100 $M_\odot$, this period corresponds to an orbital separation of about 40 $R_\odot$. The accurate orbital separation is not crucial for our crude model as it enters only linearly in equation (1). However, when the orbital separation becomes comparable to the size of the primary (windy) star, the wind velocity $v_{wind}$ may deviate strongly from the terminal wind velocity (via eq. [2]). (Our assumption that binary members are equipetomaniac and equally massive obviously has limited validity.)

## 4. DISCUSSION

We have analyzed archival *Chandra* data of the central portion of the 30 Doradus region including the star clusters R136 and R140.

We confirm the detection of two bright X-ray sources with the stars Mk 34 and R140a as optical counterparts (see Wang & Helfand 1991). The X-ray luminosities of these two sources have not changed noticeably in the 9 yr between observations. The difference in X-ray luminosity between the earlier observation and ours can be attributed to the different spectral fitting.

We identified 20 point sources with an X-ray luminosity ranging from $5 \times 10^{32}$ to $2 \times 10^{35}$ ergs s$^{-1}$. Nine point sources are located within 14″ (3.4 pc) of the center of the star cluster R136; one possibly extended source is associated with the cluster of WN stars R140. Four others have WN stars as counterparts that do not seem to be associated with either of the two clusters.

Wang (1995) analyzed *ROSAT* spectra of our sources CX 5 (his source 7) and CX 10 (his source 5). He concluded that they are probably high-mass X-ray binaries with a black hole as accreting star. His arguments are based on the spectral temperature (0.1–0.2 keV for his source 5 and 0.2–0.4 keV for source 7) and the high luminosity ($\sim 10^{36}$ ergs s$^{-1}$). In addition, he used the measured orbital period of 2.76 days and mass function of 0.12 $M_\odot$ of the star R140a2 (see Moffat et al. 1987) as an argument for the presence of a dark object.

For comparison, we calculated the value of $S_X$ (eq. [1]) for the three known black hole X-ray binaries (see Table 3) and plot these in Figure 5. Their positions in Figure 5 are completely different from the X-ray sources in NGC 2070. Of course, there is an interpretational difficulty here about which state of the black hole binary (see Tanaka & Lewin 1995) should be used for a comparison. In any case, the age of the cluster would make it remarkable if any of the X-ray sources were associated with a black hole or a neutron star. On these grounds, we conclude that none of the X-ray sources in NGC 2070 are associated with compact objects.

We conclude that all sources are consistent with colliding-wind systems. X-rays are produced in the collisions between the winds in close binaries in which these stars reside. We derive an empirical relation for the X-ray luminosity for a colliding-wind binary by substitution of equation (1) in equation (8):

$$L_X = 1.3 \times 10^{34} \left( \frac{\dot{m}_{\rm wind}}{10^{-5}\ M_\odot\ {\rm yr}^{-1}} \right)^{0.4} \times \left( \frac{1000\ {\rm km\ s}^{-1}}{v_{\rm wind}} \right)^{0.65} \left( \frac{R_\odot}{a} \right)^{0.20} {\rm ergs\ s}^{-1} . \quad (9)$$

This relation has a weaker dependence on the velocity and orbital separation compared to Usov's (1992) theoretical expression (his eq. [89]).

About 70% (13/18) of the Wolf-Rayet stars in NGC 2070 are bright in X-rays. The star cluster also contains five spectral type O3f* and WN stars (R136b, Mk 37Wb, Mk 35, Mk 30, and Mk 49), which do not show up in our X-ray image. Using equation (9), one would expect X-ray fluxes at least an order of magnitude above our detection threshold of $5 \times 10^{32}$ ergs s$^{-1}$ (see downward-pointed arrows in Fig. 5). The absence of X-rays for these stars can be explained by the companion mass being much smaller than that of the WN star or by the orbital separation being much larger than the adopted 100 $R_\odot$. Alternatively, these stars are single, in which case they may be much dimmer in X-rays.

The star cluster NGC 3603 has characteristics similar to R136 and therefore may also host a wealth of X-ray sources. As suggested by the referee, we examined the public 50 ks *Chandra* data centered on NGC 3603, but it goes beyond the scope of this paper to fully reduce and analyze these data. The cluster shows a wealth of interesting features including diffuse X-ray emission, exceptionally bright point sources, and a large number of much dimmer point sources (A. F. J. Moffat et al. 2002, in preparation; I. Stevens 2001, private communication). The sources in the cluster center are heavily blended, and it will be a very time consuming task to find optical counterparts.

Other clusters with similar characteristics as R136 are the Arches, the Quintuplet cluster, and Westerlund 1. These clusters also contain a wealth of bright and young early spectral types stars, which, when in binaries, may be bright X-ray point sources with characteristics similar to those discussed in relation to R136.

## 5. CONCLUSIONS

We analyzed a 21 ks archival *Chandra* X-ray observation pointed at the central portion of the 30 Doradus region in the Large Magellanic Cloud. The image contains 18 new X-ray sources, and we confirm the existence of two sources discovered earlier by Wang & Helfand (1991). Nine sources are within $\sim$3.4 pc of the center of the young star cluster R136. The X-ray luminosity (0.2–3.5 keV) of these sources ranges from $5 \times 10^{32}$ (our detection threshold) to $2 \times 10^{35}$ ergs s$^{-1}$. The two known sources have not changed noticeably in X-ray luminosity over the 9 yr between the *Einstein* and our *Chandra* observations.

We conclude that all observed sources, except for five unidentified sources, the *IRAS* source IRS 2, and the foreground infrared source MH 2, have stars as counterparts (10 WN Wolf-Rayet, two Of*, and one O3 V star). We argue that the X-rays in these stars are produced by colliding winds.

We do not agree with Wang (1995) that the two earlier discovered sources (CX 5 and CX 10) host black holes because (1) the stellar environment is too young to produce black holes, (2) the spectra and X-ray luminosities of the sources do not at all agree with other known black hole candidates, and (3) the sources fit well with our simple semianalytic colliding-wind model.

The X-ray luminosities of the other observed sources agree well with our simple colliding-wind model. The model gives the X-ray luminosity as a function of the stellar wind mass loss, its terminal velocity, and the binary separation. The empirical fit, calibrated to 16 known colliding-wind binaries, culminates in equation (9).

This empirical relation can be used to reduce the noise in the relation between the 0.2–3.5 keV X-ray luminosity and the Bolometric luminosity of early-type stars. The luminosity calculated with equation (9) provides a powerful diagnostic for studying colliding-wind X-ray binaries.

If the X-rays are indeed the result of colliding winds in close binaries, possibly all 13 identified sources detected with *Chandra* could be close binaries. In that case, we conclude that the binary fraction among early-type stars in the 30 Doradus region is unusually high; possibly all early-type stars are binaries.

Other star clusters with age, mass, and concentration similar to R136 are likely to contain a similar wealth in bright X-ray sources. In these cases, the emission may also be produced by colliding stellar winds. We then conclude that the star cluster NGC 3603 may contain more than 20 X-ray sources brighter than $10^{33}$ ergs s$^{-1}$, but the majority may be blended in the cluster center. (Preliminary results of an X-ray study with *Chandra* were reported at the AAS December meeting by Corcoran et al. 2000; A. F. J. Moffat et al. 2002, in preparation.)

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