AN X-RAY SURVEY OF WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS. I.
THE CHANDRA ACIS DATA SET

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ABSTRACT

Wolf-Rayet (WR) stars are evolved massive stars with strong fast stellar winds. WR stars in our Galaxy have shown three possible sources of X-ray emission associated with their winds: shocks in the winds, colliding stellar winds, and wind-blown bubbles; however, quantitative analyses of observations are often hampered by uncertainties in distances and heavy foreground absorption. These problems are mitigated in the Magellanic Clouds (MCs), which are at known distances and have small foreground and internal extinction. We have therefore started a survey of X-ray emission associated with WR stars in the MCs using archival Chandra, ROSAT, and XMM-Newton observations. In the first paper of this series, we report the results for 70 WR stars in the MCs using 192 archival Chandra ACIS observations. X-ray emission is detected from 29 WR stars. We have investigated their X-ray spectral properties, luminosities, and temporal variability. These X-ray sources all have luminosities greater than a few times $10^{32}$ ergs s$^{-1}$, with spectra indicative of highly absorbed emission from a thin plasma at high temperatures typical of colliding winds in WR+OB binary systems. Significant X-ray variability with periods ranging from a few hours up to ~20 days is seen associated with several WR stars. In most of these cases, the X-ray variability can be linked to the orbital motion of the WR star in a binary system, further supporting the colliding wind scenario for the origin of the X-ray emission from these stars.

Subject headings: Magellanic Clouds — stars: Wolf-Rayet — surveys — X-rays: stars

1. INTRODUCTION

Hot, massive stars are so luminous that their radiation can drive fast stellar winds with terminal velocities ($v_{\infty}$) of 1000–3000 km s$^{-1}$ (Prinja et al. 1990). Fast stellar winds have been detected from main-sequence O stars, as well as evolved blue supergiants. The most powerful fast winds belong to Wolf-Rayet (WR) stars, which are evolved massive stars with their H-rich envelopes stripped off. WR stars have typical mass-loss rates ($\dot{M}$) of a few times $10^{-5} M_\odot$ yr$^{-1}$ (de Jager et al. 1988) and stellar wind mechanical luminosities $L_w$ of $10^{37}$–$10^{38}$ ergs s$^{-1}$. The powerful stellar winds of WR stars are associated with three types of shocks that can produce X-ray emission: shocks in the wind itself, colliding winds in a binary system, and shocked wind in a circumstellar bubble.

Shocks in the wind itself are produced by stochastic or radiatively induced instabilities, and the postshock gas reaches X-ray-emitting temperatures (Lucy & White 1980; Gayley & Owocki 1995). Such X-ray emission has been detected, for example, from the WN4 WR star HD 50896 (Willis & Stevens 1996). This is basically the same X-ray emission mechanism for O and early B stars (Berghöfer et al. 1997), but WR winds are heavily enriched in metals (C, N, and O) so that their X-ray emission can be highly absorbed (Pollock 1987). The X-ray emission from shocks in a wind appears as an unresolved point source, and its spectral shape can be described by thermal plasma emission at temperatures of a few times $10^7$ K (Skinner et al. 2002).

In a WR+OB binary system, the WR wind collides with the companion’s fast wind and generates shock-heated plasma at the interaction region. The X-ray emission from such an interaction region has been resolved in the binary system of WR 147 (Pittard et al. 2002). Observations of V444 Cygni (Corcoran et al. 1996) illustrate that the physical conditions and X-ray luminosity of the hot gas at the collision zone vary with the orbital phase of the binary system. X-ray emission from colliding winds typically shows plasma temperatures $>10^7$ K (Corcoran 2003).

The fast WR wind can blow a bubble in the ambient medium, and the bubble interior is filled with shocked stellar wind that emits X-rays (García-Segura et al. 1996b, 1996a). X-ray emission from a WR bubble is distributed and is expected to peak near the inner wall of the bubble shell. Diffuse X-ray emission of hot interior gas has been detected from only two WR bubbles, NGC 6888 and S308 (Bochkarev 1988; Wrigge et al. 1994; Wrigge 1999; Chu et al. 2003a). Their X-ray spectra indicate plasma temperatures of $(1-2) \times 10^6$ K (Chu et al. 2003b).

Systematic X-ray surveys of WR stars using *Einstein* and Röntgensatellit (ROSAT) observations have been limited to our Galaxy (Pollock 1987; Pollock et al. 1995; Wesselowski 1996). The study of the X-ray properties of Galactic WR stars is difficult because the high extinction in the Galactic plane hampers the detection itself, uncertain distances result in poorly determined luminosities, and the unknown existence of binary companions confuses the assessment of the origin of the X-ray emission. The limited spatial resolution and sensitivity of *Einstein* and ROSAT have produced a number of spurious detections, as pointed out by Oskinova et al. (2003).

The *Chandra* and *XMM-Newton* X-ray observatories, with their unprecedented angular resolution and sensitivity, make it possible to study the X-ray emission from WR stars in the nearby Magellanic Clouds (MCs), as illustrated by the recent works on the 30 Doradus region in the Large Magellanic Cloud (LMC) by Portegies Zwart et al. (2002) and Townsley et al. (2006) and on the N66 region in the Small Magellanic Cloud (SMC) by Nazé et al. (2002). The MCs have typical foreground reddening of $E_{B-V} \sim 0.04–0.09$ (Schwering & Israel 1991) and internal reddening of $E_{B-V} \sim 0.06$ (Bessell 1991), much smaller than the reddening in the Galactic plane, thus making it easier to detect the soft X-ray emission from single WR stars and WR bubbles. Furthermore,
WR stars in the MCs are at known distances, 50 kpc for the LMC (Feast 1999) and 60 kpc for the SMC (Cioni et al. 2000), so their X-ray luminosities can be determined without the uncertainties for Galactic WR stars. More importantly, there have been systematic spectroscopic surveys for all WR stars in the MCs to search for binaries (Bartakos et al. 2001; Foellmi et al. 2003a, 2003b; Schnurr et al. 2003), providing an invaluable database to aid the interpretation of X-ray emission from WR stars.

We have started a search for X-ray emission from WR stars in the MCs using Chandra, XMM-Newton, and ROSAT archival observations. In this first paper of a series, we report our Chandra Advanced CCD Imaging Spectrometer (ACIS) archival search for X-ray emission from WR stars in the MCs. At the distance of the MCs, the superb angular resolution of Chandra is especially suited to resolve point X-ray sources from surrounding diffuse emission or nearby point sources, allowing us to make credible associations of X-ray sources with WR stars. Subsequent papers of this series will report our underway analysis of XMM-Newton and ROSAT archival observations of WR stars in the MCs.

2. CHANDRA ACIS OBSERVATIONS OF WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS

The Chandra Archive available by 2004 October was used to search for observations that contained WR stars included in the compilations by Breysacher et al. (1999) for the LMC and by Massey et al. (2003) for the SMC. Only observations made with the ACIS were included in this search because of its sensitivity and spectral resolution. We first selected ACIS observations whose nominal pointings were within 30′ from a WR star and then retrieved the data from the Chandra Archive to check whether the WR star was actually included within the ACIS’s noncircular field of view and to identify the CCD chip that registered the WR star. This search resulted in 192 useful Chandra ACIS observations of 61 WR stars in the LMC and nine WR stars in the SMC. These observations are listed in Tables 1 and 2 for the LMC and SMC, respectively. The table columns are (1) the WR catalog number (Breysacher et al. 1999; Massey et al. 2003), (2) the WR star’s common name, (3) and (4) the equatorial coordinates for J2000.0 as given by Breysacher et al. (1999) for the LMC WR stars and by Massey et al. (2003) for the SMC WR stars, (5) Chandra observation ID, (6) instrument at Chandra’s aim point, (7) identification of the ACIS CCD that registered the WR star, (8) exposure time of the observation, $t_{\text{exp}}$, and (9) usable exposure time, $t_{\text{us}}$, as explained below.

The data reduction and analysis of these observations were performed using the Chandra X-ray Center software CIAO version 3.1 and the HEASARC FTOOLS and XSPEC version 11.0.1 routines (Arnaud 1996). In order to build a homogeneous database and to correct the charge transfer inefficiency (CTI) effects, the level 1 event files of all observations were reprocessed using CIAO tasks to apply the most up-to-date calibration files available in the calibration database CALDB version 2.28. The CTI correction is important for data sets obtained with front-illuminated (FI) CCDs, while data sets obtained with the back-illuminated (BI) CCDs, i.e., ACIS-S1 and S3, show less noticeable CTI effects that have not been corrected. Using CIAO version 3.1 and CALDB version 2.28, the CTI correction can only be applied to FI data sets taken at a focal-plane temperature of $\sim 120$°C. For FI data sets obtained at temperatures of $\sim 110$°C, we used instead the CTI correcor version 1.38 (Townsley et al. 2000), while no correction has been applied to FI data sets at temperatures of $\sim 100$°C. All reprocessed level 1 event lists were subsequently filtered to select events with good ASCC grades and clean status and to reject bad aspect intervals. Known aspect offsets were corrected to improve the absolute astrometry of the data to be better than 1″. Finally, we removed the time intervals when the background count rate was 20% above the quiescent mean value. The remaining intervals of good observation yielded the usable exposure time, $t_{\text{us}}$, listed in column (9) of Tables 1 and 2. Several WR stars have multiple short Chandra observations. For these stars, the reprocessed level 2 event files obtained with the same instrument were merged to improve the signal-to-noise ratio, increasing the sensitivity of the search for X-ray emission from these stars.

3. RESULTS

3.1. Search for X-Ray Emission from Wolf-Rayet Stars in the Magellanic Clouds

To search for X-ray emission from WR stars using the Chandra ACIS observations listed in Tables 1 and 2, we first examined the X-ray and optical images of the WR stars. The X-ray images extracted from the Chandra ACIS observations include all events in the 0.3–7.0 keV energy band and have been constructed with a pixel size from 0.5″ to 1.5″, depending on the signal-to-noise ratio and the density of sources in the field of view. These images are further smoothed using a Gaussian profile with a FWHM of 1–5 pixels. Optical images extracted from the Digitized Sky Survey (DSS) have been used to identify the WR stars in the optical images using the coordinates provided by Breysacher et al. (1999) for the LMC and by Massey et al. (2003) for the SMC. Finally, the X-ray and optical images have been compared to search for a pointlike X-ray source at the location of a WR star or for diffuse emission from a WR star’s circumstellar bubble. This procedure has provided us with a number of pointlike X-ray sources associated with WR stars, but no localized diffuse X-ray emission indicative of a wind-blown bubble is detected around any WR star in the MCs.

In order to perform a quantitative analysis, we define source and background apertures for each WR star, compute the background-subtracted counts within the source aperture, and compare the value to that of the local rms background. Circular source apertures are used, and their radii have been selected to encircle at least 90% of the X-ray flux at $\sim 1.5$ keV. Therefore, the radius of a source aperture increases with the off-axis angle of the WR star. Tailored, smaller source apertures are used when nearby point sources or diffuse emission contaminates the 90% power aperture unevenly (e.g., LMC-WR 103 and SMC-WR 5). The CIAO task dmextract has been used to determine the statistics of the source areas.

5. See http://cxc.harvard.edu/contrib/maxim/bg/index.html.
6. The Digitized Sky Survey (DSS) is based on photographic data obtained using the UK Schmidt Telescope and the Oschin Schmidt Telescope on Palomar Mountain. The UK Schmidt was operated by the Royal Observatory of Edinburgh, with funding from the UK Science and Engineering Research Council, until 1988 June, and thereafter by the Anglo-Australian Observatory. The Palomar Observatory Sky Survey was funded by the National Geographic Society. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The plates were processed into the present compressed digital form with the permission of these institutes. The DSS was produced at the Space Telescope Science Institute under US government grant NAGW-2166.

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| WR No. (1) | WR Name | R.A. (J2000.0) | Decl. (J2000.0) | Obs. ID | Aim Point | CCD | $t_{\text{exp}}$ (ks) | $t_{\text{exp}}$ (ks) |
|-----------|---------|---------------|----------------|---------|-----------|-----|-------------------|-------------------|
| LMC-WR 19 | Brey 16 | 05 09 40.45   | −68 53 24.3    | 125     | ACIS-S    | I2  | 36.7             | 30.4              |
| LMC-WR 20 | Brey 16a| 05 09 53.85   | −68 52 51.6    | 125     | ACIS-S    | I2  | 36.7             | 30.4              |
| LMC-WR 31 | Brey 25 | 05 22 04.34   | −67 59 06.2    | 3356    | ACIS-S    | S3  | 18.7             | 18.6              |
| LMC-WR 49 | Brey 40a| 05 29 33.16   | −70 59 35.2    | 3848    | ACIS-S    | I3  | 33.1             | 33.1              |
| LMC-WR 60 | Brey 49 | 05 33 10.74   | −69 29 00.3    | 122     | ACIS-I    | I2  | 8.6              | 8.4               |
| LMC-WR 61 | Brey 50 | 05 34 19.13   | −69 45 09.8    | 1991    | ACIS-S    | S2  | 59.5             | 59.2              |
| LMC-WR 64 | Brey 53 | 05 34 59.33   | −69 44 05.6    | 1991    | ACIS-S    | I2  | 59.5             | 59.5              |
| LMC-WR 65 | Brey 55 | 05 35 15.22   | −69 05 42.5    | 1083    | ACIS-S    | S0  | 1.7              | 1.6               |
| LMC-WR 67 | Brey 56 | 05 35 42.20   | −69 12 33.9    | 122     | ACIS-S    | S3  | 8.6              | 4.6               |
| LMC-WR 68 | Brey 58 | 05 35 42.21   | −69 11 54.2    | 1044    | ACIS-S    | I3  | 13.8             |                   |
| LMC-WR 69 | TSWR 4 | 05 35 42.21   | −69 11 52.7    | 1044    | ACIS-S    | S3  | 13.8             |                   |
| LMC-WR 70 | Brey 62 | 05 35 43.54   | −69 10 57.2    | 1044    | ACIS-S    | S3  | 17.8             |                   |
| LMC-WR 77 | Brey 65 | 05 35 58.91   | −69 11 47.3    | 1044    | ACIS-S    | I3  | 17.8             |                   |
| LMC-WR 78 | Brey 65b| 05 35 59.11   | −69 11 50.3    | 1044    | ACIS-S    | S3  | 13.8             |                   |
| LMC-WR 79 | Brey 57 | 05 35 59.87   | −69 11 21.4    | 1044    | ACIS-S    | S3  | 13.8             |                   |
| LMC-WR 80 | Brey 65c| 05 35 59.99   | −69 11 30.1    | 1044    | ACIS-S    | S3  | 13.8             |                   |

**TABLE 1**

Chandra ACIS Observations of Wolf-Rayet Stars in the Large Magellanic Cloud
| WR No. (1) | WR Name (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | Obs. ID (5) | Aim Point (6) | CCD (7) | t_{\text{obs}} (ks) (8) | t_{\text{exp}} (ks) (9) |
|-----------|-------------|-------------------|-------------------|-------------|--------------|---------|-----------------|-----------------|
| 1967 ACIS-S | S2 | 98.8 | 91.7 |
| 2832 ACIS-S | S3 | 44.3 | 44.2 |
| 62520 ACIS-I | S4 | 20.8 | 16.6 |
| LMC-WR 82 | Brey 66 | 05 36 33.61 | −69 09 16.8 | 1044 ACIS-S | S4 | 17.8 | 13.8 |
| 1081 ACIS-S | S0 | 0.8 | 0.8 |
| 1082 ACIS-S | S0 | 1.7 | 1.7 |
| 1083 ACIS-S | S1 | 1.7 | 1.6 |
| 1084 ACIS-S | S0 | 1.7 | 1.7 |
| 1085 ACIS-S | S1 | 1.7 | 1.7 |
| 3830 ACIS-S | I3 | 45.3 | 44.3 |
| 62520 ACIS-I | S3 | 21.2 | 15.5 |
| LMC-WR 83 | HD 269858 | 05 36 43.50 | −69 29 45.0 | 119 ACIS-S | S5 | 27.8 | 27.8 |
| 1967 ACIS-S | I2 | 98.8 | 96.3 |
| 2831 ACIS-S | I2 | 49.4 | 49.1 |
| LMC-WR 84 | Brey 68 | 05 36 51.30 | −69 25 55.8 | 119 ACIS-S | S5 | 27.8 | 27.8 |
| 1082 ACIS-S | S2 | 1.7 | 1.7 |
| 1967 ACIS-S | I2 | 98.8 | 96.3 |
| 2831 ACIS-S | I2 | 49.4 | 49.1 |
| LMC-WR 85 | Brey 67 | 05 36 55.02 | −69 11 37.3 | 1084 ACIS-S | S0 | 1.7 | 1.7 |
| 1085 ACIS-S | S1 | 1.7 | 1.7 |
| 1967 ACIS-S | S2 | 98.8 | 91.7 |
| 2831 ACIS-S | S2 | 49.4 | 49.1 |
| LMC-WR 86 | Brey 69 | 05 37 11.51 | −69 07 37.4 | 1044 ACIS-S | S4 | 17.8 | 13.8 |
| 1081 ACIS-S | S0 | 0.8 | 0.8 |
| 1084 ACIS-S | S0 | 1.7 | 1.7 |
| 1085 ACIS-S | S1 | 1.7 | 1.7 |
| 3830 ACIS-S | I2 | 45.3 | 44.3 |
| LMC-WR 87 | Brey 70 | 05 37 29.14 | −69 20 46.7 | 1078 ACIS-S | S1 | 0.7 | 0.7 |
| 1079 ACIS-S | S1 | 0.8 | 0.8 |
| 1080 ACIS-S | S1 | 0.7 | 0.7 |
| 1081 ACIS-S | S1 | 0.8 | 0.8 |
| 1082 ACIS-S | S2 | 1.7 | 1.7 |
| 1083 ACIS-S | S2 | 1.7 | 1.7 |
| 1085 ACIS-S | S2 | 1.7 | 1.7 |
| 3829 ACIS-S | S1 | 49.0 | 46.4 |
| LMC-WR 88 | Brey 70a | 05 37 35.64 | −69 08 39.7 | 1044 ACIS-S | S4 | 17.8 | 13.8 |
| 1081 ACIS-S | S0 | 0.8 | 0.8 |
| 1084 ACIS-S | S0 | 1.7 | 1.7 |
| 1085 ACIS-S | S1 | 1.7 | 1.7 |
| 2783 ACIS-S | I3 | 29.3 | 29.3 |
| 62520 ACIS-I | I3 | 20.6 | 17.6 |
| LMC-WR 89 | Brey 71 | 05 37 40.54 | −69 07 57.2 | 1044 ACIS-S | S4 | 17.8 | 13.8 |
| 1081 ACIS-S | S0 | 0.8 | 0.8 |
| LMC-WR 90 | Brey 74 | 05 37 44.63 | −69 14 25.1 | 1081 ACIS-S | S1 | 0.8 | 0.8 |
| 1084 ACIS-S | S1 | 1.7 | 1.7 |
| 1967 ACIS-S | S1 | 98.8 | 66.4 |
| 2831 ACIS-S | S1 | 49.4 | 49.1 |
| LMC-WR 91 | Brey 73 | 05 37 46.34 | −69 09 09.3 | 1081 ACIS-S | S0 | 0.8 | 0.8 |
| 2783 ACIS-S | S3 | 48.2 | 48.2 |
| 62520 ACIS-I | I3 | 20.6 | 17.6 |
| LMC-WR 92 | Brey 72 | 05 37 49.01 | −69 05 07.8 | 62520 ACIS-I | I3 | 20.6 | 17.6 |
| 1081 ACIS-S | S0 | 0.8 | 0.8 |
| LMC-WR 93 | Brey 74a | 05 37 51.39 | −69 09 46.1 | 2783 ACIS-S | S3 | 48.2 | 48.2 |
| 62520 ACIS-I | I3 | 20.6 | 17.6 |
| LMC-WR 94 | Brey 85 | 05 38 27.66 | −69 29 57.9 | 112 ACIS-S | S1 | 3.0 | 3.0 |
| 1078 ACIS-S | S2 | 0.7 | 0.7 |
| 1079 ACIS-S | S2 | 0.8 | 0.8 |
| 1080 ACIS-S | S2 | 0.7 | 0.7 |
| 1081 ACIS-S | S2 | 0.8 | 0.8 |
and background apertures of each WR star, allowing us to derive its background-subtracted counts and local rms background. For WR stars with multiple observations at very different off-axis angles, the CIAO task dmextract has been applied to each data set individually with appropriate source and background apertures, and the results are weighted by the exposure time and averaged to produce the combined count rate.

Firm, \( \geq 3 \) \( \sigma \) detections of X-ray emission are obtained for 26 WR stars in the LMC and three WR stars in the SMC, and tentative, \( \sim 2 \) \( \sigma \) detections are found for four additional WR stars in the LMC. Tables 3 and 4 list these firm and tentative detections, respectively. The WR star identification is given in columns (1) and (2), the offsets between the X-ray source and the position of the WR star in columns (3) and (4), and the instrument at the telescope aim point and detector used are given in columns (5) and (6), respectively. The Chandra X-ray images and accompanying optical images overlaid with X-ray contours of these 33 WR stars with firm or tentative X-ray detections are displayed in Figure 1. In a large number of WR stars, the spatial coincidence of the X-ray source and the WR star is within 1″, i.e., within the astrometric accuracy of the data, and in most cases the offset is within 2″. There are, however, a few excursions; notably, the X-ray sources associated with Brey 16a, Brey 95a (Table 3), and Brey 74a (Table 4) are \( \sim 2.4″, \sim 4.0″, \) and \( \sim 4.8″ \), respectively, from the nominal positions of these WR stars. Brey 74a is embedded within diffuse X-ray emission, and the tentative detection of X-ray emission from this star may be questioned in view of the large offset. On the other hand, a systematic offset of 1.4″, i.e., with an eastward motion, is found for Brey 16a, Brey 95a (Table 3), and Brey 74a (Table 4) are \( \sim 2.4″, \sim 4.0″, \) and \( \sim 4.8″ \), respectively, from the nominal positions of these WR stars. Brey 74a is embedded within diffuse X-ray emission, and the tentative detection of X-ray emission from this star may be questioned in view of the large offset.

### Table 1—Continued

| WR No. (1) | WR Name (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | Obs. ID (5) | Aim Point (6) | CCD (7) | \( t_{\text{exp}} \) (ks) (8) | \( t_{\text{exp}} \) (ks) (9) |
|------------|-------------|-------------------|------------------|-------------|---------------|--------|-----------------|-----------------|
| LMC-WR 95  | Brey 80     | 05 38 33.69       | −69 04 49.9      | 1082        | ACIS-S        | S3     | 1.7             | 1.7             |
| LMC-WR 96  | Brey 81     | 05 38 36.50       | −69 06 56.8      | 1083        | ACIS-S        | S3     | 1.7             | 1.6             |
| LMC-WR 97  | Mk 51       | 05 38 39.01       | −69 06 49.2      | 1084        | ACIS-S        | S3     | 1.7             | 1.7             |
| LMC-WR 98  | Brey 79     | 05 38 39.26       | −69 06 20.9      | 1085        | ACIS-S        | S3     | 1.7             | 1.7             |
| LMC-WR 99  | Brey 78     | 05 38 40.29       | −69 05 59.5      | 1422        | ACIS-I        | S2     | 4.1             | 4.1             |
| LMC-WR 100 | Brey 75     | 05 38 40.60       | −69 05 57.0      | 1457        | ACIS-S        | S2     | 1.2             | 1.2             |
| LMC-WR 101 | R140a       | 05 38 41.52       | −69 05 13.3      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 102 | R140b       | 05 38 41.54       | −69 05 14.9      | 62520       | ACIS-I        | I2     | 20.6            | 17.6            |
| LMC-WR 104 | Brey 76     | 05 38 41.88       | −69 06 13.7      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 105 | Brey 77     | 05 38 42.12       | −69 05 55.0      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 106 | R36a        | 05 38 42.43       | −69 06 02.2      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 107 | Brey 86     | 05 38 42.41       | −69 04 57.8      | 62520       | ACIS-I        | I2     | 20.6            | 17.6            |
| LMC-WR 111 | R36b        | 05 38 42.78       | −69 06 03.1      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 112 | R36c        | 05 38 42.95       | −69 06 04.2      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 113 | Mk 30       | 05 38 42.99       | −69 05 46.5      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 114 | Mk 35       | 05 38 43.27       | −69 06 14.0      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 115 | Brey 83     | 05 38 44.12       | −69 05 54.9      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 116 | Brey 84     | 05 38 44.27       | −69 06 05.5      | 62520       | ACIS-I        | I3     | 20.6            | 17.6            |
| LMC-WR 117 | Brey 88     | 05 38 47.60       | −69 00 25.0      | 62520       | ACIS-I        | I2     | 20.6            | 17.6            |
| LMC-WR 118 | Brey 89     | 05 38 53.43       | −69 02 00.3      | 62520       | ACIS-I        | I0     | 20.6            | 17.6            |
| LMC-WR 119 | Brey 90     | 05 38 57.14       | −69 06 05.2      | 62520       | ACIS-I        | I1     | 20.7            | 17.6            |
| LMC-WR 120 | Brey 91     | 05 38 58.04       | −69 29 18.6      | 112         | ACIS-S        | S1     | 3.0             | 3.0             |
| LMC-WR 121 | Brey 90a    | 05 39 03.80       | −69 03 46.0      | 62520       | ACIS-I        | I0     | 20.6            | 17.6            |
| LMC-WR 122 | Brey 92     | 05 39 11.38       | −69 02 01.0      | 62520       | ACIS-I        | I0     | 20.6            | 17.6            |
| LMC-WR 124 | Brey 93a    | 05 39 36.21       | −69 39 10.8      | 112         | ACIS-S        | S2     | 3.0             | 3.0             |
| LMC-WR 125 | Brey 94     | 05 39 56.24       | −69 24 24.3      | 119         | ACIS-S        | S3     | 27.8            | 27.7            |
| LMC-WR 126 | Brey 95     | 05 40 07.62       | −69 24 31.1      | 119         | ACIS-S        | S3     | 27.8            | 27.7            |
| LMC-WR 127 | Brey 95a    | 05 40 13.50       | −69 24 02.9      | 119         | ACIS-S        | S3     | 27.8            | 27.7            |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
| WR No. (1) | WR Name (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | Obs. ID (5) | Aim Point (6) | CCD (7) | $t_{\text{exp}}$ (ks) (8) | $t_{\text{obs}}$ (ks) (9) |
|------------|-------------|-------------------|--------------------|-------------|---------------|--------|----------------|----------------|
| SMC-WR 2   | AV 39a      | 00 48 30.81       | $-73\ 15\ 45.1$   | 2945        | ACIS-I        | I3     | 11.6          | 11.6          |
| SMC-WR 3   | AV 60a      | 00 49 59.33       | $-73\ 22\ 13.6$   | 2945        | ACIS-I        | I0     | 11.6          | 11.6          |
| SMC-WR 5   | HD 5980     | 00 59 26.60       | $-72\ 09\ 53.5$   | 444         | ACIS-I        | S2     | 8.4           | 8.2           |
|            |             |                   |                    | 1543        | ACIS-I        | S2     | 7.4           | 6.5           |
|            |             |                   |                    | 1881        | ACIS-I        | I1     | 98.7          | 98.5          |
|            |             |                   |                    | 2862        | ACIS-I        | S2     | 7.6           | 7.5           |
|            |             |                   |                    | 5137        | ACIS-I        | S2     | 8.0           | 8.0           |
| SMC-WR 6   | Sk 108      | 01 03 25.20       | $-72\ 06\ 43.6$   | 48          | ACIS-I        | I2     | 8.6           | 8.4           |
|            |             |                   |                    | 49          | ACIS-I        | I3     | 9.1           | 8.9           |
|            |             |                   |                    | 136         | ACIS-I        | I3     | 9.9           | 9.9           |
|            |             |                   |                    | 140         | ACIS-I        | I3     | 8.2           | 8.2           |
|            |             |                   |                    | 420         | ACIS-I        | I3     | 10.2          | 10.2          |
|            |             |                   |                    | 439         | ACIS-I        | I2     | 6.9           | 6.9           |
|            |             |                   |                    | 440         | ACIS-I        | I2     | 6.9           | 6.9           |
|            |             |                   |                    | 444         | ACIS-I        | I3     | 8.4           | 8.3           |
|            |             |                   |                    | 445         | ACIS-I        | I3     | 7.9           | 7.9           |
|            |             |                   |                    | 1313        | ACIS-I        | I1     | 7.2           | 7.2           |
|            |             |                   |                    | 1314        | ACIS-I        | I1     | 6.9           | 6.8           |
|            |             |                   |                    | 1315        | ACIS-I        | I1     | 6.9           | 6.8           |
|            |             |                   |                    | 1316        | ACIS-I        | I2     | 6.9           | 6.8           |
|            |             |                   |                    | 1317        | ACIS-I        | I3     | 6.9           | 6.8           |
|            |             |                   |                    | 1528        | ACIS-I        | I1     | 6.9           | 6.8           |
|            |             |                   |                    | 1529        | ACIS-I        | I0     | 6.9           | 6.8           |
|            |             |                   |                    | 1534        | ACIS-I        | I3     | 7.4           | 7.4           |
|            |             |                   |                    | 1535        | ACIS-I        | I3     | 7.4           | 7.4           |
|            |             |                   |                    | 1542        | ACIS-I        | I1     | 7.4           | 7.4           |
|            |             |                   |                    | 1543        | ACIS-I        | I3     | 7.4           | 7.4           |
|            |             |                   |                    | 1544        | ACIS-I        | I2     | 7.4           | 7.4           |
|            |             |                   |                    | 1785        | ACIS-I        | I3     | 7.6           | 7.5           |
|            |             |                   |                    | 2835        | ACIS-I        | I1     | 7.8           | 7.8           |
|            |             |                   |                    | 2836        | ACIS-I        | I1     | 7.4           | 7.4           |
|            |             |                   |                    | 2837        | ACIS-I        | I1     | 7.5           | 7.4           |
|            |             |                   |                    | 2839        | ACIS-I        | I3     | 7.5           | 7.4           |
|            |             |                   |                    | 2841        | ACIS-I        | I1     | 7.5           | 7.4           |
|            |             |                   |                    | 2842        | ACIS-I        | I0     | 7.5           | 7.4           |
|            |             |                   |                    | 2858        | ACIS-I        | I3     | 7.6           | 7.5           |
|            |             |                   |                    | 2859        | ACIS-I        | I3     | 7.6           | 7.5           |
|            |             |                   |                    | 2862        | ACIS-I        | I0     | 7.6           | 7.5           |
|            |             |                   |                    | 2863        | ACIS-I        | I3     | 7.6           | 7.5           |
|            |             |                   |                    | 2864        | ACIS-I        | I2     | 7.6           | 7.5           |
|            |             |                   |                    | 3519        | ACIS-S        | S2     | 8.0           | 8.0           |
|            |             |                   |                    | 3520        | ACIS-S        | S2     | 7.6           | 7.3           |
|            |             |                   |                    | 3521        | ACIS-S        | S1     | 7.6           | 0.0           |
|            |             |                   |                    | 3522        | ACIS-S        | S0     | 7.8           | 7.7           |
|            |             |                   |                    | 3524        | ACIS-S        | S3     | 7.6           | 7.6           |
|            |             |                   |                    | 3525        | ACIS-S        | S4     | 7.6           | 6.8           |
|            |             |                   |                    | 3528        | ACIS-I        | I3     | 7.9           | 7.8           |
|            |             |                   |                    | 3532        | ACIS-I        | I1     | 7.7           | 7.6           |
|            |             |                   |                    | 3534        | ACIS-I        | I3     | 7.7           | 7.6           |
|            |             |                   |                    | 3535        | ACIS-I        | I3     | 7.8           | 7.7           |
|            |             |                   |                    | 3536        | ACIS-I        | I2     | 7.6           | 7.6           |
|            |             |                   |                    | 3537        | ACIS-I        | I2     | 7.6           | 7.6           |
|            |             |                   |                    | 3538        | ACIS-I        | I2     | 7.6           | 7.6           |
|            |             |                   |                    | 3539        | ACIS-I        | I2     | 7.6           | 7.6           |
|            |             |                   |                    | 3540        | ACIS-I        | I2     | 7.6           | 7.6           |
|            |             |                   |                    | 3542        | ACIS-I        | I0     | 7.6           | 7.6           |
|            |             |                   |                    | 3544        | ACIS-S        | S3     | 7.9           | 7.5           |
|            |             |                   |                    | 3546        | ACIS-S        | S2     | 7.9           | 7.8           |
|            |             |                   |                    | 3547        | ACIS-S        | S3     | 7.7           | 7.6           |
|            |             |                   |                    | 3548        | ACIS-S        | S4     | 7.7           | 7.6           |
|            |             |                   |                    | 5137        | ACIS-I        | I3     | 8.0           | 8.0           |
|            |             |                   |                    | 5138        | ACIS-I        | I3     | 7.7           | 7.6           |
|            |             |                   |                    | 5139        | ACIS-I        | I2     | 20.4          | 20.3          |
| WR No. (1) | WR Name (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | Obs. ID (5) | Aim Point (6) | CCD (7) | $t_{obs}$ exp (ks) | $t_{exp}$ (ks) |
|------------|-------------|--------------------|---------------------|-------------|--------------|--------|-----------------|--------------|
| 5142       | ACIS-I      | S3                 | 7.7                 | 7.6         |              |        |                 |              |
| 5143       | ACIS-I      | I2                 | 7.4                 | 7.3         |              |        |                 |              |
| 5144       | ACIS-I      | I3                 | 7.1                 | 7.1         |              |        |                 |              |
| 5146       | ACIS-I      | I1                 | 8.1                 | 8.0         |              |        |                 |              |
| 5147       | ACIS-I      | I1                 | 7.9                 | 7.9         |              |        |                 |              |
| 5148       | ACIS-I      | I0                 | 19.3                | 19.3        |              |        |                 |              |
| 5149       | ACIS-I      | I1                 | 7.6                 | 7.5         |              |        |                 |              |
| 5150       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| 5151       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| 5153       | ACIS-I      | I1                 | 7.4                 | 7.4         |              |        |                 |              |
| 5154       | ACIS-I      | I0                 | 7.5                 | 7.4         |              |        |                 |              |
| 5156       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| 5158       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| 5159       | ACIS-I      | I0                 | 7.5                 | 7.4         |              |        |                 |              |
| 5252       | ACIS-S      | S3                 | 7.5                 | 6.9         |              |        |                 |              |

SMC-WR 7 ................................ AV 336a 01 03 35.94 −72 03 21.5

| WR No. (1) | WR Name (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | Obs. ID (5) | Aim Point (6) | CCD (7) | $t_{obs}$ exp (ks) | $t_{exp}$ (ks) |
|------------|-------------|--------------------|---------------------|-------------|--------------|--------|-----------------|--------------|
| 5142       | ACIS-I      | S3                 | 7.7                 | 7.6         |              |        |                 |              |
| 5143       | ACIS-I      | I2                 | 7.4                 | 7.3         |              |        |                 |              |
| 5144       | ACIS-I      | I3                 | 7.1                 | 7.1         |              |        |                 |              |
| 5146       | ACIS-I      | I1                 | 8.1                 | 8.0         |              |        |                 |              |
| 5147       | ACIS-I      | I1                 | 7.9                 | 7.9         |              |        |                 |              |
| 5148       | ACIS-I      | I0                 | 19.3                | 19.3        |              |        |                 |              |
| 5149       | ACIS-I      | I1                 | 7.6                 | 7.5         |              |        |                 |              |
| 5150       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| 5151       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| 5153       | ACIS-I      | I1                 | 7.4                 | 7.4         |              |        |                 |              |
| 5154       | ACIS-I      | I0                 | 7.5                 | 7.4         |              |        |                 |              |
| 5156       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| 5158       | ACIS-I      | I3                 | 7.6                 | 7.5         |              |        |                 |              |
| WR No. (1) | WR Name (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | Obs. ID (5) | Aim Point (6) | CCD (7) | $t_{\text{obs}}$ (ks) (8) | $t_{\text{exp}}$ (ks) (9) |
|------------|-------------|-------------------|-------------------|-------------|--------------|--------|----------------|----------------|
| 2859       | ACIS-I      | I3                | 7.6               | 7.6         | 7.5          |
| 2860       | ACIS-I      | I3                | 7.6               | 7.6         | 7.5          |
| 2862       | ACIS-I      | I0                | 7.6               | 7.6         | 7.5          |
| 2863       | ACIS-I      | I1                | 7.6               | 7.6         | 7.5          |
| 2864       | ACIS-I      | I2                | 7.6               | 7.6         | 7.5          |
| 3519       | ACIS-S      | S2                | 8.0               | 8.0         |              |
| 3520       | ACIS-S      | S3                | 7.6               | 7.6         | 7.3          |
| 3521       | ACIS-S      | S1                | 7.6               | 7.6         | 0.0          |
| 3522       | ACIS-S      | S0                | 7.8               | 7.7         |              |
| 3523       | ACIS-S      | S2                | 7.6               | 7.6         |              |
| 3524       | ACIS-S      | S4                | 7.6               | 7.6         | 6.1          |
| 3527       | ACIS-I      | I3                | 7.9               | 7.9         | 7.8          |
| 3528       | ACIS-I      | I3                | 7.9               | 7.9         | 7.8          |
| 3529       | ACIS-I      | I3                | 7.7               | 7.7         | 7.6          |
| 3530       | ACIS-I      | I3                | 7.7               | 7.7         | 7.6          |
| 3532       | ACIS-I      | I0                | 7.7               | 7.7         | 7.6          |
| 3533       | ACIS-I      | I1                | 7.7               | 7.7         | 7.6          |
| 3534       | ACIS-I      | I2                | 7.7               | 7.7         | 7.6          |
| 3535       | ACIS-I      | I1                | 7.8               | 7.8         | 7.7          |
| 3536       | ACIS-I      | I1                | 7.6               | 7.6         | 7.6          |
| 3537       | ACIS-I      | I0                | 7.6               | 7.6         | 7.6          |
| 3538       | ACIS-I      | I3                | 7.6               | 7.6         | 7.6          |
| 3539       | ACIS-I      | I3                | 7.6               | 7.6         | 7.6          |
| 3540       | ACIS-I      | I3                | 7.6               | 7.6         | 7.6          |
| 3541       | ACIS-I      | I0                | 7.6               | 7.6         | 7.6          |
| 3542       | ACIS-I      | I1                | 7.6               | 7.6         | 7.6          |
| 3543       | ACIS-I      | I2                | 7.6               | 7.6         | 7.6          |
| 3544       | ACIS-S      | S3                | 7.9               | 7.9         | 7.8          |
| 3546       | ACIS-S      | S1                | 7.9               | 7.9         | 7.8          |
| 3547       | ACIS-S      | S2                | 7.7               | 7.7         | 7.6          |
| 3548       | ACIS-S      | S4                | 7.7               | 7.7         | 7.6          |
| 5123       | ACIS-S      | S3                | 20.3              | 20.3        | 11.9         |
| 5124       | ACIS-S      | S3                | 7.9               | 7.9         | 5.4          |
| 5125       | ACIS-S      | S1                | 7.9               | 7.9         | 0.0          |
| 5126       | ACIS-S      | S0                | 7.9               | 7.9         |              |
| 5127       | ACIS-S      | S2                | 7.9               | 7.9         |              |
| 5128       | ACIS-S      | S4                | 7.9               | 7.9         |              |
| 5129       | ACIS-S      | S5                | 7.9               | 7.9         |              |
| 5130       | ACIS-S      | S2                | 19.4              | 19.4        | 19.3         |
| 5131       | ACIS-S      | S3                | 8.0               | 8.0         |              |
| 5132       | ACIS-S      | S1                | 7.5               | 7.5         |              |
| 5133       | ACIS-S      | S0                | 7.5               | 7.5         |              |
| 5134       | ACIS-S      | S2                | 7.5               | 7.5         |              |
| 5135       | ACIS-S      | S4                | 8.1               | 8.0         |              |
| 5136       | ACIS-S      | S5                | 7.9               | 7.9         |              |
| 5137       | ACIS-I      | I3                | 8.0               | 8.0         |              |
| 5138       | ACIS-I      | I3                | 7.7               | 7.7         |              |
| 5139       | ACIS-I      | I2                | 20.4              | 20.4        | 20.3         |
| 5140       | ACIS-I      | I3                | 8.0               | 8.0         |              |
| 5141       | ACIS-I      | I3                | 7.7               | 7.7         |              |
| 5143       | ACIS-I      | I0                | 7.4               | 7.4         |              |
| 5144       | ACIS-I      | I1                | 7.1               | 7.1         |              |
| 5145       | ACIS-I      | I2                | 7.1               | 7.1         |              |
| 5146       | ACIS-I      | I1                | 8.1               | 8.0         |              |
| 5147       | ACIS-I      | I1                | 7.9               | 7.9         |              |
| 5148       | ACIS-I      | I1                | 19.3              | 19.3        |              |
| 5149       | ACIS-I      | I3                | 7.6               | 7.6         |              |
| 5150       | ACIS-I      | I3                | 7.6               | 7.6         |              |
| 5151       | ACIS-I      | I3                | 7.6               | 7.6         |              |
| 5152       | ACIS-I      | I0                | 8.0               | 8.0         |              |
| 5153       | ACIS-I      | I1                | 7.4               | 7.4         |              |
| 5154       | ACIS-I      | I2                | 7.5               | 7.5         |              |
| 5251       | ACIS-S      | S3                | 7.6               | 7.6         |              |
| 5252       | ACIS-S      | S3                | 7.5               | 7.5         | 6.9          |
| WR No.    | WR Name    | R.A. (J2000.0) | Decl. (J2000.0) | Obs. ID | Aim Point | CCD  | $t_{\text{exp}}$ (ks) | $t_{\text{exp}}$ (ks) |
|-----------|------------|----------------|----------------|---------|-----------|------|----------------------|----------------------|
| SMC-WR 9  |            | 00 54 32.17    | −72 44 35.6    | 2946    | ACIS-I    | I1   | 9.3                  | 9.3                  |
| SMC-WR 10 |            | 00 45 28.78    | −73 04 45.2    | 3904    | ACIS-S    | I3   | 74.2                 | 74.2                 |
| SMC-WR 11 |            | 00 52 07.36    | −72 35 37.4    | 2946    | ACIS-I    | I2   | 9.3                  | 9.3                  |
| SMC-WR 12 |            | 01 02 52.07    | −72 06 52.6    | 48      | ACIS-I    | I0   | 8.6                  | 8.4                  |
|           |            |                |                | 49      | ACIS-I    | I1   | 9.1                  | 8.9                  |
|           |            |                |                | 136     | ACIS-I    | I2   | 9.9                  | 9.9                  |
|           |            |                |                | 140     | ACIS-I    | I3   | 8.2                  | 8.2                  |
|           |            |                |                | 420     | ACIS-I    | I3   | 10.2                 | 10.2                 |
|           |            |                |                | 439     | ACIS-I    | I2   | 6.9                  | 6.9                  |
|           |            |                |                | 440     | ACIS-I    | I2   | 6.9                  | 6.9                  |
|           |            |                |                | 444     | ACIS-I    | I3   | 8.4                  | 8.3                  |
|           |            |                |                | 445     | ACIS-I    | I3   | 7.9                  | 7.9                  |
|           |            |                |                | 1231    | ACIS-S    | S4   | 9.6                  | 9.6                  |
|           |            |                |                | 1313    | ACIS-I    | I1   | 7.2                  | 7.2                  |
|           |            |                |                | 1314    | ACIS-I    | I1   | 6.9                  | 6.8                  |
|           |            |                |                | 1315    | ACIS-I    | I1   | 6.9                  | 6.8                  |
|           |            |                |                | 1316    | ACIS-I    | I1   | 6.9                  | 6.8                  |
|           |            |                |                | 1529    | ACIS-I    | I0   | 6.9                  | 6.8                  |
|           |            |                |                | 1536    | ACIS-I    | S3   | 7.4                  | 7.4                  |
|           |            |                |                | 1542    | ACIS-I    | I2   | 7.4                  | 7.4                  |
|           |            |                |                | 1543    | ACIS-I    | I3   | 7.4                  | 7.4                  |
|           |            |                |                | 2833    | ACIS-I    | I1   | 7.8                  | 7.8                  |
|           |            |                |                | 2836    | ACIS-I    | I1   | 7.5                  | 7.4                  |
|           |            |                |                | 2837    | ACIS-I    | I1   | 7.5                  | 7.4                  |
|           |            |                |                | 2838    | ACIS-I    | I1   | 7.5                  | 7.4                  |
|           |            |                |                | 2839    | ACIS-I    | I1   | 7.5                  | 7.4                  |
|           |            |                |                | 2842    | ACIS-I    | I0   | 7.5                  | 7.4                  |
|           |            |                |                | 2858    | ACIS-I    | I3   | 7.6                  | 7.5                  |
|           |            |                |                | 2862    | ACIS-I    | I2   | 7.6                  | 7.5                  |
|           |            |                |                | 2863    | ACIS-I    | I3   | 7.6                  | 7.5                  |
|           |            |                |                | 3519    | ACIS-S    | S2   | 8.0                  | 8.0                  |
|           |            |                |                | 3520    | ACIS-S    | S2   | 7.6                  | 7.3                  |
|           |            |                |                | 3523    | ACIS-S    | S1   | 7.6                  | 7.6                  |
|           |            |                |                | 3524    | ACIS-S    | S3   | 7.6                  | 7.6                  |
|           |            |                |                | 3525    | ACIS-S    | S4   | 6.8                  | 6.8                  |
|           |            |                |                | 3528    | ACIS-I    | I3   | 7.9                  | 7.8                  |
|           |            |                |                | 3532    | ACIS-I    | I1   | 7.7                  | 7.6                  |
|           |            |                |                | 3534    | ACIS-I    | I3   | 7.7                  | 7.6                  |
|           |            |                |                | 3535    | ACIS-I    | I1   | 7.8                  | 7.7                  |
|           |            |                |                | 3536    | ACIS-I    | I0   | 7.6                  | 7.6                  |
|           |            |                |                | 3537    | ACIS-I    | I0   | 7.6                  | 7.6                  |
|           |            |                |                | 3538    | ACIS-I    | I2   | 7.6                  | 7.6                  |
|           |            |                |                | 3539    | ACIS-I    | I2   | 7.6                  | 7.6                  |
|           |            |                |                | 3540    | ACIS-I    | I2   | 7.6                  | 7.6                  |
|           |            |                |                | 3542    | ACIS-I    | I0   | 7.6                  | 7.6                  |
|           |            |                |                | 3544    | ACIS-S    | S3   | 7.9                  | 7.5                  |
|           |            |                |                | 3546    | ACIS-S    | S2   | 7.9                  | 7.8                  |
|           |            |                |                | 3547    | ACIS-S    | S3   | 7.9                  | 7.6                  |
|           |            |                |                | 5137    | ACIS-I    | I3   | 8.0                  | 8.0                  |
|           |            |                |                | 5138    | ACIS-I    | I3   | 7.7                  | 7.6                  |
|           |            |                |                | 5139    | ACIS-I    | I2   | 20.4                 | 20.3                 |
|           |            |                |                | 5141    | ACIS-I    | S3   | 7.7                  | 7.6                  |
|           |            |                |                | 5142    | ACIS-I    | S3   | 7.7                  | 7.6                  |
|           |            |                |                | 5143    | ACIS-I    | I2   | 7.4                  | 7.3                  |
|           |            |                |                | 5144    | ACIS-I    | I3   | 7.1                  | 7.1                  |
|           |            |                |                | 5146    | ACIS-I    | I1   | 8.1                  | 8.0                  |
|           |            |                |                | 5147    | ACIS-I    | I1   | 7.9                  | 7.9                  |
|           |            |                |                | 5148    | ACIS-I    | I0   | 19.3                 | 19.3                 |
|           |            |                |                | 5149    | ACIS-I    | I1   | 7.6                  | 7.5                  |
|           |            |                |                | 5150    | ACIS-I    | I1   | 7.6                  | 7.5                  |
|           |            |                |                | 5151    | ACIS-I    | I3   | 7.6                  | 7.5                  |
|           |            |                |                | 5154    | ACIS-I    | I0   | 7.5                  | 7.4                  |
and Brey 95a in spite of the large offsets between these WR stars and the X-ray sources associated with them.

Columns (7), (8), and (9) of Tables 3 and 4 provide the net exposure, the background-subtracted count rate, and counts, respectively. The 1σ deviations given in column (9) are calculated adding quadratically the background rms and the Poisson error of the source count number estimated using the approximation given by equation (7) of Gehrels (1986). Basic spectral information is provided by columns (10) and (11), which list the hardness ratio (defined as the number of counts in the 2.0–7.0 keV band divided by the number of counts in the 0.3–7.0 keV band) and the median energy in the 0.3–7.0 keV band, respectively.

Some of the WR stars in Tables 3 and 4 have been reported previously to be associated with X-ray sources. HD 5980 in the SMC is superposed on a supernova remnant; its stellar X-ray emission was resolved from the supernova remnant for the first time by the Chandra observations reported by Nazé et al. (2002). Wang (1995) used ROSAT Position Sensitive Proportional Counter (PSPC) observations of the 30 Doradus nebula to study the spectral properties of the X-ray bright Brey 84 and R140a. More recently, Portegies Zwart et al. (2002) and Townsley et al. (2006) have analyzed a Chandra observation of the same region and detected X-ray emission from 10 to 20 WR stars. Finally, Feilmeier et al. (2003a, 2003b) have reported preliminary results of the survey presented in this paper. Further comparisons with the results presented in these papers are made in § 3.2.1. The WR stars that are not detected by Chandra ACIS observations are listed in Table 5. The WR star identification is given in

### Table 3

| WR No. | WR Name | Δα (arcsec) | Δδ (arcsec) | Aim Point | CCD | t_exp (ks) | Count Rate (counts s⁻¹) | Counts | Hardness Ratio | Median Energy (keV) |
|--------|---------|-------------|-------------|-----------|-----|-----------|------------------------|--------|----------------|-------------------|
| LMC-WR 19 | Brey 16 | -0.79 | +0.11 | ACIS-S | S2 | 30.4 | 1.3 x 10⁻³ | 40 ± 7 | 0.71 | 2.5 |
| LMC-WR 20 | Brey 16a | -2.39 | -0.25 | ACIS-S | S2 | 29.6 | 2.4 x 10⁻³ | 70 ± 10 | 0.56 | 2.3 |
| LMC-WR 67 | Brey 56 | +0.07 | -0.66 | ACIS-S | S3 | 271.2 | 3.6 x 10⁻³ | 97 ± 14 | 0.29 | 1.6 |
| LMC-WR 78 | Brey 65b | -0.52 | -1.21 | ACIS-S | S3 | 91.7 | 1.2 x 10⁻⁴ | 11 ± 3 | 0.27 | 1.6 |
| LMC-WR 79 | Brey 57 | -0.48 | -1.79 | ACIS-S | S3 | 58.0 | 1.7 x 10⁻⁴ | 10 ± 6 | 0.43 | 1.1 |
| LMC-WR 80 | Brey 65c | -0.63 | -0.85 | ACIS-S | S3 | 91.7 | 4.9 x 10⁻⁴ | 45 ± 9 | 0.31 | 1.4 |
| LMC-WR 85 | Brey 67 | +1.28 | +0.49 | ACIS-S | S2, S4 | 154.6 | 9.2 x 10⁻⁴ | 147 ± 15 | 0.10 | 1.4 |
| LMC-WR 92 | Brey 72 | +0.29 | -0.22 | ACIS-I | I3 | 17.6 | 6.7 x 10⁻⁴ | 12 ± 4 | 0.26 | 1.1 |
| LMC-WR 99 | Brey 78 | -0.20 | +0.33 | ACIS-I | I3 | 17.6 | 4.4 x 10⁻⁴ | 77 ± 9 | 0.17 | 1.3 |
| LMC-WR 100 | Brey 75 | +0.53 | +0.14 | ACIS-I | I3 | 17.6 | 4.1 x 10⁻⁴ | 8 ± 3 | 0.07 | 1.3 |
| LMC-WR 101, 102 | R140a | -0.11 | +0.05 | ACIS-I | I3 | 17.6 | 1.9 x 10⁻⁵ | 330 ± 20 | 0.16 | 1.3 |
| LMC-WR 105 | R136a | -0.12 | -0.05 | ACIS-I | I3 | 17.6 | 1.2 x 10⁻³ | 21 ± 5 | 0.27 | 1.0 |
| LMC-WR 106, 108–110 | Brey 86 | +0.40 | -0.52 | ACIS-I | I2 | 17.6 | 9.2 x 10⁻⁴ | 16 ± 4 | 0.16 | 1.3 |
| LMC-WR 112 | R136c | -0.08 | -0.11 | ACIS-I | I3 | 17.6 | 1.9 x 10⁻⁶ | 330 ± 20 | 0.31 | 1.5 |
| LMC-WR 114 | Mkr 35 | +0.31 | +0.36 | ACIS-I | I3 | 17.6 | 5.1 x 10⁻⁴ | 9 ± 3 | 0.38 | 1.4 |
| LMC-WR 116 | Brey 84 | +0.13 | +0.19 | ACIS-I | I3 | 17.6 | 4.9 x 10⁻⁴ | 860 ± 30 | 0.34 | 1.6 |
| LMC-WR 118 | Brey 89 | -1.07 | -1.26 | ACIS-I | I10–I12 | 17.6 | 7.5 x 10⁻⁴ | 13 ± 4 | 0.12 | 1.0 |
| LMC-WR 119 | Brey 90 | -0.09 | +0.60 | ACIS-I | I3 | 17.6 | 6.1 x 10⁻⁴ | 11 ± 4 | 0.62 | 1.8 |
| LMC-WR 125 | Brey 94 | -1.27 | -0.55 | ACIS-S | S3 | 27.7 | 1.0 x 10⁻³ | 29 ± 6 | 0.39 | 1.6 |
| LMC-WR 126 | Brey 95 | -1.13 | -0.99 | ACIS-S | S3 | 27.7 | 9.8 x 10⁻⁴ | 27 ± 6 | 0.0 | 0.9 |
| LMC-WR 127 | Brey 95a | -3.65 | -1.51 | ACIS-S | S3 | 27.7 | 6.9 x 10⁻⁴ | 19 ± 6 | 0.53 | 1.2 |
| SMC-WR 5 | HD 5980 | -1.49 | +0.77 | ACIS-I | I1 | 98.5 | 2.7 x 10⁻³ | 265 ± 15 | 0.39 | 1.7 |
| SMC-WR 6 | Sk 108 | +0.15 | -0.44 | ACIS | I1, S2 | 448.4 | 9.5 x 10⁻⁴ | 430 ± 20 | 0.12 | 1.2 |
| SMC-WR 7 | AV 336a | -0.01 | -0.52 | ACIS-S | S1, S3 | 69.9 | 1.5 x 10⁻⁴ | 108 ± 13 | 0.12 | 1.1 |

### Table 4

| WR No. | WR Name | Δα (arcsec) | Δδ (arcsec) | Aim Point | CCD | t_exp (ks) | Count Rate (counts s⁻¹) | Counts | Hardness Ratio | Median Energy (keV) |
|--------|---------|-------------|-------------|-----------|-----|-----------|------------------------|--------|----------------|-------------------|
| LMC-WR 77 | Brey 65 | +0.07 | -0.66 | ACIS-S | S3 | 58.0 | 3.1 x 10⁻⁴ | 18 ± 7 | 0.35 | 1.7 |
| LMC-WR 82 | Brey 66 | -0.05 | -0.66 | ACIS-S | I3, S1, S4 | 61.4 | 2.6 x 10⁻⁴ | 16 ± 7 | 0.00 | 1.0 |
| LMC-WR 93 | Brey 74a | +4.71 | -1.15 | ACIS-S | S3 | 48.2 | 5.0 x 10⁻⁴ | 24 ± 9 | 0.22 | 1.1 |
| LMC-WR 103 | R140b | -0.11 | +0.06 | ACIS-I | I2 | 17.6 | 3.8 x 10⁻⁴ | 7 ± 3 | 0.44 | 1.3 |
Fig. 1.—(a) Chandra ACIS X-ray images in the 0.5–7.0 keV band and optical images overlaid with X-ray contours for Brey 16 and Brey 16a (top left), Brey 56 (top right), Brey 65b, and Brey 65c (bottom left), and Brey 66 (bottom right). Brey 58 and TSWR 4, close to a bright X-ray source, are also shown. The positions of the WR stars given by Breysacher et al. (1999) and Massey et al. (2003) are marked with a plus sign. HST broadband images were used for Brey 56 and Brey 58 (PI: Kirshner), and for Brey 57, Brey 65, Brey 65b, and Brey 65c (PI: Casertano); otherwise, DSS optical images were used. The contour levels have been chosen to highlight the X-ray emission and identification of WR stars. (b) Same as (a), but for Brey 67 (top left), Brey 72 (top right), Brey 74a (bottom left), and R140a, R140b, and Brey 86 (bottom right). HST broadband images were used for Brey 72 (PI: Rhoads), Brey 74a (PI: Mignani), and R140a, R140b, and Brey 86 (PI: Trauger, Walborn, Westphal); a DSS optical image was used for Brey 67. (c) Same as (a), but for Brey 89 (top left), Brey 90 (top right), Brey 94, Brey 95, and Brey 95a (bottom left), and HD 5980 (bottom right). An HST broadband image was used for Brey 90 (PI: Trauger, Walborn, Westphal); otherwise, DSS optical images were used. (d) Same as (a), but for Brey 75, Brey 76, Brey 77, Brey 84, Mk 35, R136a, and R136c. An HST broadband image was used for the optical image (PI: Trauger, Walborn, Westphal). R136b and Brey 83, close to bright X-ray sources, are also shown. (e) Chandra ACIS-S (left) and ACIS-I (center) X-ray images in the 0.5–7.0 keV band and DSS optical (right) images overlaid with ACIS-S X-ray contours of (top) Sk 108 and (bottom) AV 336a.
columns (1) and (2); the instrument at the telescope aim point and
detector used in columns (3) and (4), respectively; the exposure
time in column (5), and the $3 \sigma$ upper limit in column (6). The $3 \sigma$
upper limit is calculated from the rms of the local background,
scaling it to the size of the source aperture. Three of these unde-
tected WR stars, LMC-WR 68 (Brey 89), LMC-WR 69 (TSWR 4),
and LMC-WR 115 (Brey 83), are located close to bright X-ray
sources but outside their error radii. Similarly, LMC-WR 111
(R136b) is located between two bright X-ray sources, R136a, at
the center of the R136 star cluster, and R136c, but no X-ray
point source is detected at the location of R136b.

3.2. Spectral Analysis of Individual Wolf-Rayet Stars
in the Magellanic Clouds

The X-ray spectra of the WR stars in Tables 3 and 4 can be
used to determine the physical conditions of the X-ray–emitting
gas and the absorption column density ($N_H$) of the intervening
material, which in turn can help us understand the origin of the
X-ray emission. Spectral analysis is achieved by modeling the observed spectra, convolving absorbed plasma emission models with the instrumental response, and using \( \chi^2 \) statistics to determine the model parameters that best fit an observed spectrum. Meaningful spectral analysis with \( \chi^2 \) statistics can be performed only when an adequate number of source counts are detected. For WR stars whose spectra have a low number of counts, a CSTAT fitting of an absorbed plasma emission model or a spline fitting can be performed to the unbinned spectrum to derive their observed luminosities.

To carry out these different levels of spectral analysis for the WR stars detected in X-rays, we have divided these WR stars into two subgroups: the high-count X-ray WR stars whose observations detected at least 70 counts and the low-count X-ray WR stars whose observations detected fewer than 70 counts. As we show below, the high-count WR stars are generally brighter than the low-count WR stars, but a few high-count WR stars have been observed with very long exposures, and they are actually as X-ray faint as those in the low-count subsample.

### 3.2.1. The Subsample of High-Count X-Ray Wolf-Rayet Stars in the Magellanic Clouds

The background-subtracted X-ray spectra of WR stars in the high-count subsample are presented in Figure 2. These spectra show that most of the counts are detected in the 0.7–2.0 keV energy range and that very few counts are detected below 0.5 keV. Some spectra show high-energy tails extending beyond 5 keV. These spectral features are suggestive of high levels of absorption and high-temperature X-ray-emitting gas (\( kT \gtrsim 1 \) keV).

To model the spectra of these stars, we have first created the response matrix and effective area files (the so-called redistribution matrix file [RMF] and auxiliary response file [ARF]) associated with each spectrum. If a WR star has multiple short observations (e.g., SMC-WR 6 and SMC-WR 7), we compute the RMF and ARF files individually for each observation and take the exposure-weighted average of them all.

Our selection of appropriate spectral models for plasma emission and absorption along the line of sight is guided by the detailed spectral analysis of Chandra and XMM-Newton observations of Galactic WR stars available in the literature. The X-ray spectra of the Galactic WR binaries WR 25 and \( \theta^2 \) Velorum can be described by thin plasma emission at temperatures \( kT \approx 0.3–0.7 \) and \( 2–3 \) keV, respectively (Raassen et al. 2003; Skinner et al. 2001). Similarly, the X-ray spectra of the presumably single Galactic WR stars WR 110 and EZ CMa show both cool and hot plasma components, suggesting either the presence of an unknown close stellar companion or the possibility that hard X-rays can be produced by single WR stars (Skinner et al. 2002a, 2002b). We note that the observations of WR stars in the MCs do not detect as many X-ray photons as the observations of Galactic WR stars considered above. Moreover, after rebinning the spectra of WR stars in the MCs to \( \geq 16 \) counts per energy bin, as required for a reliable spectral fit using the \( \chi^2 \) statistics, the spectral resolution also becomes lower. Therefore, as the spectra of WR stars in the MCs have insufficient quality for modeling with multiple temperature components, we have adopted a single-temperature MEKAL, optically thin plasma emission model (Kaastra & Mewe 1993; Liedahl et al. 1995). As for the absorption along the line of
X-RAYS FROM WR STARS IN THE MCs. I.

TABLE 5
WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS UNDETECTED IN X-RAYS

| WR No. (1) | WR Name (2) | Aim Point (3) | CCD (4) | $t_{exp}$ (5) | 3 $\sigma$ Upper Limit (counts s$^{-1}$) |
|------------|-------------|---------------|---------|---------------|----------------------------------------|
| LMC-WR 31 | Brey 25     | ACIS-S        | S3      | 18.6          | 1.1 $\times$ 10$^{-3}$                  |
| LMC-WR 49 | Brey 40a    | ACIS-S        | I3      | 67.8          | 3.6 $\times$ 10$^{-4}$                  |
| LMC-WR 60 | Brey 49     | ACIS-I        | I1      | 8.4           | 9.5 $\times$ 10$^{-4}$                  |
| LMC-WR 61 | Brey 50     | ACIS-S        | S2      | 59.4          | 3.0 $\times$ 10$^{-4}$                  |
| LMC-WR 64 | Brey 53     | ACIS-S        | I1      | 59.2          | 2.3 $\times$ 10$^{-4}$                  |
| LMC-WR 65 | Brey 55     | ACIS-I        | S3      | 15.5          | 9.0 $\times$ 10$^{-4}$                  |
| LMC-WR 70 | Brey 62     | ACIS-S        | I2, I3  | 105.7         | 2.0 $\times$ 10$^{-4}$                  |
| LMC-WR 83 | HD 269858   | ACIS-S        | I2, S5  | 174.6         | 1.3 $\times$ 10$^{-4}$                  |
| LMC-WR 84 | Brey 68     | ACIS-S        | I2, S5  | 174.6         | 1.6 $\times$ 10$^{-4}$                  |
| LMC-WR 86 | Brey 69     | ACIS-S        | I2, S4  | 62.2          | 2.2 $\times$ 10$^{-4}$                  |
| LMC-WR 87 | Brey 70     | ACIS-S        | S1      | 46.4          | 4.2 $\times$ 10$^{-4}$                  |
| LMC-WR 88 | Brey 70a    | ACIS-I        | I3, S4  | 32.2          | 3.4 $\times$ 10$^{-4}$                  |
| LMC-WR 89 | Brey 71     | ACIS-I        | I3, S4  | 29.3          | 4.1 $\times$ 10$^{-4}$                  |
| LMC-WR 90 | Brey 74     | ACIS-S        | S1      | 119.5         | 3.7 $\times$ 10$^{-4}$                  |
| LMC-WR 91 | Brey 73     | ACIS-I        | I3      | 17.6          | 6.3 $\times$ 10$^{-4}$                  |
| LMC-WR 94 | Brey 85     | ACIS-S        | I1, S3  | 48.2          | 5.0 $\times$ 10$^{-4}$                  |
| LMC-WR 95 | Brey 80     | ACIS-I        | I2      | 17.6          | 3.2 $\times$ 10$^{-4}$                  |
| LMC-WR 96 | Brey 81     | ACIS-I        | I3      | 17.6          | 3.5 $\times$ 10$^{-4}$                  |
| LMC-WR 97 | Mk 51       | ACIS-I        | I3      | 17.6          | 3.1 $\times$ 10$^{-4}$                  |
| LMC-WR 98 | Brey 79     | ACIS-I        | I3      | 17.6          | 3.6 $\times$ 10$^{-4}$                  |
| LMC-WR 104 | Brey 76    | ACIS-I        | I3      | 17.6          | 5.1 $\times$ 10$^{-4}$                  |
| LMC-WR 113 | Mk 30     | ACIS-I        | I2      | 17.6          | 6.4 $\times$ 10$^{-4}$                  |
| LMC-WR 115 | Brey 83    | ACIS-I        | I3      | 17.6          | 7.2 $\times$ 10$^{-4}$                  |
| LMC-WR 117 | Brey 88    | ACIS-I        | I2      | 17.6          | 6.6 $\times$ 10$^{-4}$                  |
| LMC-WR 120 | Brey 91    | ACIS-S        | S1, S3  | 6.4           | 2.3 $\times$ 10$^{-3}$                  |
| LMC-WR 121 | Brey 90a   | ACIS-I        | I0      | 17.6          | 2.5 $\times$ 10$^{-4}$                  |
| LMC-WR 122 | Brey 92    | ACIS-I        | I0      | 17.6          | 4.3 $\times$ 10$^{-4}$                  |
| LMC-WR 124 | Brey 93a   | ACIS-S        | I2, S2, S4, S5 | 11.3 | 6.0 $\times$ 10$^{-4}$                  |
| SMC-WR 2 | AV 39a      | ACIS-I        | I3      | 11.6          | 4.8 $\times$ 10$^{-4}$                  |
| SMC-WR 3 | AV 60a      | ACIS-I        | I0      | 11.6          | 7.7 $\times$ 10$^{-4}$                  |
| SMC-WR 9 | MG 9        | ACIS-I        | I1      | 9.3           | 6.0 $\times$ 10$^{-4}$                  |
| SMC-WR 10 | ACIS-I      | I3            | 74.2    | 1.1 $\times$ 10$^{-4}$                  |
| SMC-WR 11 | ACIS-I      | I2            | 9.3     | 6.0 $\times$ 10$^{-4}$                  |
| SMC-WR 12 | SMC-054730  | ACIS-I        | I1, S2  | 390.1         | 5.8 $\times$ 10$^{-5}$                  |
| SMC-WR 12 | ACIS-I      | S1, S3        | 45.6    | 4.0 $\times$ 10$^{-4}$                  |

The X-ray–emitting material in the WR winds is expected to be highly enriched; however, detailed spectral fitting of high-dispersion X-ray spectra of the bright Galactic WR star WR 25 did not find strong metal enrichment (Raslev et al. 2003). Given the limited quality of the X-ray spectra of the WR stars in the MCs, we have chosen to simply use the canonical abundances of the MCs. While our adopted abundances may potentially yield unreliable best-fit parameters, the derived X-ray luminosities are not very sensitive to the chemical abundances of X-ray–emitting and absorbing material.

The X-ray–emitting plasma and of the absorbing intervening material were fixed to be 0.33 $Z_\odot$ for the LMC and 0.25 $Z_\odot$ for the SMC. The absorption due to contamination buildup on the filters of the ACIS detectors is already taken into account by the ARF for these data sets reprocessed with CIAO version 3.1 and CALDB version 2.28. For those other data sets obtained at a focal plane temperature different than 7.0 keV, the absorption adjusted by the date of the observation.

Further information on the low-energy quantum-efficiency degradation of ACIS can be obtained at http://asc.harvard.edu/cal/ACIS/Cal-prods/qeDeg.

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7 The X-ray–emitting material in the WR winds is expected to be highly enriched; however, detailed spectral fitting of high-dispersion X-ray spectra of the bright Galactic WR star WR 25 did not find strong metal enrichment (Raslev et al. 2003). Given the limited quality of the X-ray spectra of the WR stars in the MCs, we have chosen to simply use the canonical abundances of the MCs. While our adopted abundances may potentially yield unreliable best-fit parameters, the derived X-ray luminosities are not very sensitive to the chemical abundances of X-ray–emitting and absorbing material.

8 Further information on the low-energy quantum-efficiency degradation of ACIS can be obtained at http://asc.harvard.edu/cal/ACIS/Cal-prods/qeDeg.
and consequently the quality of their spectral fits is poor. Spectral fits were not statistically improved by adding a second thin plasma emission component at a different temperature, except for SMC-WR 6 (Sk 108) for which a soft component heavily extincted provided a formally better fit. This second component, however, increases dramatically the intrinsic X-ray luminosity of Sk 108 and has been considered unrealistic.

It is worthwhile comparing the parameters of the best-fit models and X-ray luminosities listed in Table 6 with those derived by other authors. Table 7 compiles the relevant fit parameters and total unabsorbed X-ray luminosities of the WR stars in the MCs in common with Nazé et al. (2002), Portegies Zwart et al. (2002), and Townsley et al. (2006). Nazé et al. (2002) analyzed the X-ray spectrum of HD 5980 (SMC-WR 5) and derived a temperature and an absorption column density within 1σ of our best-fit values; their X-ray luminosity of HD 5980 is ~50% higher, but for a wider energy band, 0.3–10.0 keV. In the 30 Doradus nebula, Portegies Zwart et al. (2002) and Townsley et al. (2006) have analyzed the X-ray spectra of Brey 78, R140a, R136a, R136c, and Brey 84. While the details of their spectral fits and ours are different, the best-fit parameters (N_H and kT) are within 1σ in all cases. Moreover, the total unabsorbed X-ray luminosities reported from the above studies are generally consistent with ours within a factor of ~2. Differences in calibrations and in the
### Table 6

**Best-Fit Parameters of High-Count X-Ray Wolf-Rayet Stars in the Magellanic Clouds**

| WR No. | WR Name | Counts | $\chi^2$/DOF | $kT$ (keV) | $N_H$ (cm$^{-2}$) | $f_t$ (ergs cm$^{-2}$ s$^{-1}$) | $L_t$ (ergs s$^{-1}$) | $L_s$ (ergs s$^{-1}$) |
|--------|---------|--------|-------------|------------|----------------|-------------------------------|----------------|----------------|
| LMC-WR 19 | Brey 16 | 110 | 3.1/11 = 0.3 | $7^{+15}_{-4}$ | $(3^{+1}_{-1}) \times 10^{22}$ | $6.1 \times 10^{-14}$ | $3.8 \times 10^{34}$ | $1.4 \times 10^{34}$ |
| LMC-WR 20 | Brey 16a | 71 | 5.6/5 = 1.1 | $3^{+9}_{-3}$ | $(6^{+2}_{-2}) \times 10^{21}$ | $1.7 \times 10^{-14}$ | $9.1 \times 10^{33}$ | $4.7 \times 10^{33}$ |
| LMC-WR 67 | Brey 56 | 97 | 8.7/13 = 0.7 | $2.3^{+4}_{-1}$ | $(1.4^{+2}_{-1}) \times 10^{22}$ | $2.3 \times 10^{-15}$ | $1.7 \times 10^{33}$ | $1.0 \times 10^{33}$ |
| LMC-WR 85 | Brey 67 | 147 | 13.5/16 = 0.8 | $1.0_{-0.6}^{+0.8}$ | $(2.0_{-0.3}^{+0.5}) \times 10^{22}$ | $4.9 \times 10^{-14}$ | $6.3 \times 10^{34}$ | $5.6 \times 10^{34}$ |
| LMC-WR 99 | Brey 78 | 77 | 1.0/1 = 1.0 | $1.1_{-1}^{+1}$ | $(4_{-3}^{+2}) \times 10^{21}$ | $2.4 \times 10^{-14}$ | $1.7 \times 10^{34}$ | $1.5 \times 10^{34}$ |
| LMC-WR 101, 102 | R146a | 330 | 31.0/17 = 0.8 | $0.9 \pm 0.2$ | $(9 \pm 2) \times 10^{21}$ | $9.6 \times 10^{-14}$ | $1.6 \times 10^{35}$ | $1.5 \times 10^{35}$ |
| LMC-WR 106, 108–110 | R136a | 164 | 8.5/13 = 0.7 | $2.1_{-0.5}^{+0.8}$ | $(1.9^{+2.0}_{-1.8}) \times 10^{21}$ | $6.8 \times 10^{-14}$ | $2.4 \times 10^{34}$ | $1.5 \times 10^{34}$ |
| LMC-WR 112 | R136c | 330 | 19.8/16 = 1.2 | $2.9_{-1.5}^{+1.2}$ | $(2.8^{+3.0}_{-2.8}) \times 10^{21}$ | $1.5 \times 10^{-13}$ | $6.2 \times 10^{34}$ | $3.3 \times 10^{34}$ |
| LMC-WR 116 | Brey 84 | 860 | 31.4/43 = 0.7 | $4.9_{-0.6}^{+0.7}$ | $(2.6^{+1.0}_{-0.9}) \times 10^{21}$ | $4.8 \times 10^{-13}$ | $1.8 \times 10^{35}$ | $7.2 \times 10^{34}$ |
| SMC-WR 5 | HD 5980 | 265 | 21.6/14 = 1.5 | $7^{+2}_{-2}$ | $(3^{+2}_{-1}) \times 10^{21}$ | $2.5 \times 10^{-14}$ | $1.2 \times 10^{34}$ | $4.9 \times 10^{33}$ |
| SMC-WR 6 | Sk 108 | 500 | 52.5/37 = 1.5 | $1.1_{-0.4}^{+0.7}$ | $(2.0^{+3.1}_{-1.2}) \times 10^{21}$ | $5.6 \times 10^{-15}$ | $2.8 \times 10^{33}$ | $2.1 \times 10^{33}$ |
| SMC-WR 7 | AV 336a | 775 | 75.9/70 = 1.1 | $2.2_{-0.4}^{+0.2}$ | $(6_{-2}^{+3}) \times 10^{20}$ | $7.2 \times 10^{-15}$ | $3.3 \times 10^{33}$ | $2.0 \times 10^{33}$ |
and that our results are not systematically different from theirs.

Portegies Zwart et al. (2002) also show similar level of differences we note that the results reported by Townsley et al. (2006) and by for the detailed differences between our results and others.

count for the detailed differences between our results and others.

details of the spectral fits (e.g., the energy band used for the spectral fit, the background region used, and the number of counts per spectral bin required for the spectral fit) and the use of chemical abundances of the MCs for the intervening material may account for the physical conditions of the X-ray–emitting plasma, although no goodness of fit can be obtained. Spectral fits using the CSTAT statistic and a MEKAL absorbed thin-plasma emission model have been attempted, but the best-fit models resulted in unphysical values of the hydrogen column density. Furthermore, spectral fits could not be achieved in several of these WR stars. In these cases, a spline fit can be used to model the spectral shape and compute at least the X-ray flux, but the intervening column density of hydrogen is also needed in these cases to derive the intrinsic X-ray luminosity.

In order to fit the X-ray spectra of the low-count subsample of WR stars in the MCs, we need to adopt values of the intervening absorption column density. To derive an average absorption column density, we have combined the spectra of all MCs WR stars in the low-count subsample and performed a joint spectral fit of the BI and FI spectra using a common absorbed MEKAL thin-plasma emission model and calibration matrices obtained by adding the calibration matrices of each individual spectrum weighted by their background-subtracted counts. The best-fit model (Fig. 3), with a plasma temperature of $kT = 1.6$ keV, has an absorption column density of $\sim 3 \times 10^{21}$ cm$^{-2}$, which will be adopted for spectral fits using either a MEKAL thin-plasma emission model or a spline function.

Table 8 lists the best-fit parameters, observed X-ray flux, and intrinsic X-ray luminosity in the 0.5–7.0 keV ($L_x$) and 0.5–2.0 keV ($L_x$) energy bands as defined for Table 6. When a spline function

![Fig. 3.—Combined Chandra ACIS BI and FI spectra of the low-count WR stars in the MCs, with <70 counts, overplotted with the best-fit model. For plotting purposes, the bin width is 150 eV.](image-url)
was used to fit the spectral shape, no best-fit temperature is provided. It is interesting to compare the X-ray luminosities of the high- and low-count WR stars in the MCs to search for systematic differences in the emission models describing the spectral properties of these two samples. Figure 4 plots the intrinsic X-ray luminosity against the count rate for these two subsamples of WR stars. It is apparent that WR stars in the low-count subsample follow the same trend shown by the high-count subsample of WR stars to have higher X-ray luminosities for higher count rates, although they show a larger dispersion around the linear relationship. Figure 4 also shows that Brey 16, Brey 67, and R140a are much more luminous than expected from a linear relationship between X-ray luminosity and count rate. These large discrepancies are caused by the large absorption column toward Brey 16 and low plasma temperatures for Brey 67 and R140a, for which a greater correction from observed flux (i.e., count rate) to unabsorbed flux is required.

3.2.3. The Undetected X-Ray Wolf-Rayet Stars in the Magellanic Clouds

WR stars in the MCs that have been observed but not detected by Chandra ACIS are listed in Table 5, together with the 3 σ upper limits of their X-ray count rates. To further investigate the X-ray faintest population of WR stars in the MCs, we have stacked together all the spectra of the undetected WR stars and obtained combined BI and FI spectra (Fig. 5). There is a clear detection of X-ray emission in the FI spectrum of 90 ± 20 counts, with a total count rate of (1.4 ± 0.3) × 10^-4 counts s^-1 for a total exposure time of 673.1 ks. In the BI spectrum, with a shorter integration time of 183.8 ks, the detection is unclear, although the spectral shape is tantalizing. We have then performed a joint spectral fit of these two spectra using a common absorbed MEKAL thin-plasma emission model and calibration matrices obtained by adding the calibration matrices of each individual spectrum weighted by their net exposure times. The spectral fit could not constrain the absorption column density, so we adopted 3 × 10^{21} cm^-2, the averaged absorption column density derived for the low-count sources in §3.2.2. The best-fit model, overplotted in Figure 5, has a two-component plasma with temperatures $kT_1 = 0.4$ keV and $kT_2 = 3$ keV. The mean intrinsic luminosity in the energy bands 0.5–7.0 and 0.5–20 keV are $1.5 \times 10^{31}$ and $1.1 \times 10^{31}$ ergs s^-1, respectively.

3.3. Count Rate and Intrinsic X-Ray Luminosity Distributions

The histograms in Figure 6 show the distributions of the count rate (top) and intrinsic X-ray luminosity (bottom) for WR stars in the MCs that have been detected by Chandra ACIS observations. The solid and dotted curves represent the high- and low-count subsamples of WR stars in the MCs, respectively. WR stars in the high-count subsample are generally more luminous than the WR stars in the low-count subsample, although there is some overlap. We do not detect any source with a count rate lower than $\approx 1 \times 10^{-4}$ counts s^-1, or $\approx 6 \times 10^{-2}$ ergs s^-1 in X-ray luminosity. The vertical dashed line shown in the plot of count

![Graph](image-url)
rate distributions marks the average count rate of the undetected sources derived in § 3.2.3.

3.4. X-Ray Variability

X-ray variability can be investigated for WR stars detected with large numbers of counts. Note that count rates for multiple observations of a WR star made with different detectors or with the star at different offsets from the telescope aim point cannot be compared directly. Instead, we compared photon flux, in units of photons cm$^{-2}$s$^{-1}$, derived from each observation by dividing the number of source counts by the effective exposure time and the aperture area. To analyze the X-ray variability of the whole sample of sources in a homogeneous manner, we use photon fluxes also for those with a single, long observation for which count rates could have been used directly for light-curve analysis. The light curves of the WR stars with sufficient number of counts and time coverage are shown in Figure 7. The photon fluxes of the WR stars with low number of counts or few time points are listed in Table 9.

The light curves of Brey 56, Brey 78, R140a, R136a, and Sk 108 in Figure 7, and the photon fluxes at different epochs of Brey 65b and Brey 67 in Table 9 are consistent with a constant level of X-ray emission. On the other hand, the light curves of Brey 84 and R136c in the LMC and AV 336a and HD 5980 in the SMC show small variations that are indicative of X-ray variability: Brey 84 presents a modulation in its light curve with a period of ~2 hr, as revealed by the task efsearch of the HEASOFT XRONOS package; the R136c light curve shows similar flux drops separated by ~5 hr; the AV 336a light curve shows an apparent modulation consistent with the orbital period of this binary system, 19.560 days (Niemela et al. 2002); and HD 5980’s count rate progressively increased by a factor of 2 during its observation (Naze et al. 2002). Furthermore, the count rates of Brey 16 and Brey 16a listed in Table 9 varied significantly from 1999 December to 2003 February: the photon flux of Brey 16 increased...
by a factor of 2, while that of Brey 16a decreased by about the same factor in 2003.

3.5. Individual Objects

Brey 16 (LMC-WR 19) is a WN4b+O5: spectroscopic binary (Smith et al. 1996) that was recently revealed to be an eclipsing binary (Foellmi et al. 2003a). The double eclipse seen in its optical light curve and the sinusoidal variations of its radial velocity indicate an orbital period of \( \approx 18.0 \) days. The short orbital period makes Brey 16 a good candidate for a colliding-wind binary. Indeed, the hardness of the X-ray spectrum of LMC-WR 19 and the high temperature of the plasma emission are consistent with the emission expected from a colliding-wind binary (Pittard & Stevens 1997). Moreover, the Chandra observations at two different epochs show a photon flux increase by a factor of 2 that suggests an X-ray variability of this system that can be associated with the orbital phase. Using the orbital parameters of Brey 16 derived by Foellmi et al. (2003a), we find that Chandra’s first epoch observation spanned from orbital phase \( \approx 0.06 \) to \( \approx 0.075 \), i.e., it sampled the start of the secondary eclipse shown in the Brey 16 light curve, while Chandra’s second-epoch observation occurred at orbital phase \( 0.40 \)–\( 0.42 \), at an intermediate phase between the two eclipses. Therefore, there is evidence that the X-ray variability of Brey 16 is phase locked: the passage of one star in front of the other during the secondary eclipse also implies the absorption of a significant fraction of the X-ray emission from the colliding-wind zone.

R140a (LMC-WR 101, 102) and R140b (LMC-WR 103) are the WR components of the visual multiple system R140 in the 30 Doradus region. R140a1 (LMC-WR 101) is a WC5+O(?) binary system, and R140a2 (LMC-WR 102) is a WN6+O binary system with an orbital period of \( \approx 2.76 \) days (Moffat 1989), while R140b is not known to be binary (Breysacher et al. 1999). R140a (not resolved by Chandra ACIS) is one of the brightest X-ray sources in the 30 Doradus region, while R140b is only tentatively detected with \( \approx 7 \) counts. It must be noted that Townsley et al. (2006) reported a firm detection of R140b with \( \approx 15 \) counts. The origin of this discrepancy is unclear, but the proximity of R140b to the bright X-ray source R140a made us use a conservatively small aperture that may have missed a fraction of its flux, while Townsley et al. (2006) refined the event positions using a subpixel positioning technique that is best suited for selecting photons from a faint source near a bright one.

Fig. 7.—Light curves of the WR stars in the MCs detected in X-rays with sufficient number of counts and time coverage. Count rates have been converted to photon fluxes to allow a fair comparison among observations of a WR star obtained with different detectors and offsets from the telescope aim point. Sk 108 and AV 336a have multiple observations, but while observations close in time to those of Sk 108 had similar flux levels and were combined to improve the data quality, the multiple observations of AV 336a show variations and were folded with its orbital period. The dotted sinusoidal curves overplotted on the light curves of Brey 84 and AV 336a represent tentative fittings.
R136a (LMC-WR 106, 108-110), R136b (LMC-WR 111), and R136c (LMC-WR 112) are the WR components of the central cluster of 30 Doradus. R136a is a bright X-ray source, and there is evidence for X-ray variability with a short period of \( \leq 5 \) hr. The detailed spatial analysis of this region by Townsley et al. (2006) was able to resolve it into several of its components. Similarly, the improved spatial resolution of Townsley et al. (2006) images made possible the detection of R136b, too near to the X-ray bright R136a to be resolved by us.

Brey 84 (LMC-WR 116) is the brightest X-ray source in the 30 Doradus region, and, due to its high X-ray luminosity, its true nature has been disputed. Based on ROSAT observations, Wang (1995) proposed it to be a high-mass X-ray binary composed of a WR star and a black hole. The Chandra ACIS X-ray spectrum,

| WR No. | WR Name | Observation Date | Observation Time (UT) | Aim Point and Detector | \( t_{\text{exp}} \) (ks) | Counts | Photon Flux (photons cm\(^{-2}\) s\(^{-1}\)) |
|--------|---------|------------------|-----------------------|------------------------|-----------------|-------|---------------------------------------------|
| LMC-WR 19 | Brey 16 | 1999 Dec 04 | 12:28 | ACIS-I, I2 | 30.4 | 40 ± 7 | \( (2.0 \pm 0.4) \times 10^{-6} \) |
| LMC-WR 20 | Brey 16a | 2003 Feb 07 | 01:51 | ACIS-S, S2 | 29.6 | 70 ± 10 | \( (4.4 \pm 0.6) \times 10^{-6} \) |
| LMC-WR 78 | Brey 65b | 2000 Dec 07 | 19:26 | ACIS-S, S2 | 91.7 | 11 ± 3 | \( (2.1 \pm 0.9) \times 10^{-7} \) |
| LMC-WR 85 | Brey 67 | 2001 Dec 07 | 14:59 | ACIS-S, S2 | 49.1 | 27 ± 8 | \( (1.20 \pm 0.34) \times 10^{-6} \) |
We have modeled the X-ray spectra of the 12 WR stars that have sufficient number of counts for spectral analysis. The majority of the best-fit models show high plasma temperatures and large absorption column densities. Similar X-ray spectral behavior is exhibited in the integrated spectrum of the WR stars detected with small number of counts.

The X-ray variability of WR stars in the MCs has also been investigated. R136c and Brey 84, among the X-ray brightest WR stars in the LMC, show evidence of short-term variability with periods of $\sim 5$ and $\sim 2$ hr, respectively. Brey 16 and Brey 16a in the LMC also show variations of a factor of 2 in their X-ray emission between two observations separated by 3.2 yr. The variations observed in Brey 16 are consistent with the orbital period of $\sim 18$ days of this binary system, thus suggesting that its X-ray variability is phase locked. Similarly, the variations observed in the X-ray light curve of the binary system AV 336a in the SMC are consistent with its orbital period of 19.560 days. Finally, HD 5980 in the SMC also appears to vary.

In subsequent papers, we will use X-ray observations of WR stars in the MCs available in the ROSAT and XMM-Newton archives to acquire the most comprehensive view of X-ray emission from WR stars in the MCs. This work will be used to investigate the occurrence, luminosity, and variability of X-ray emission in WR stars with their spectral type and binarity properties. The final results will help us determine the X-ray properties of the WR stars in the MCs and allow comparisons with their Galactic counterparts.

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