X-ray survey of Wolf-Rayet stars in the Magellanic Clouds

M. A. Guerrero[1] and Y.-H. Chu[2]

[1]Instituto de Astrofísica de Andalucía,
Consejo Superior de Investigaciones Científicas (IAA-CSIC), Spain
[2]Department of Astronomy, University of Illinois at Urbana-Champaign, USA

Abstract: Systematic X-ray surveys of Wolf-Rayet (WR) stars in our Galaxy are hampered by the heavy obscuration in the Galactic plane, which prohibits the detections of WR stars, and by the uncertain distances to individual WR stars, which result in poorly determined luminosities. These problems are mitigated in the Large and Small Magellanic Clouds (MCs), because foreground and internal extinctions are small and distances are known. We have used archival *Chandra* ACIS and *ROSAT* PSPC and HRI observations of 128 WR stars in the MCs to search for X-ray emission from these stars. About 25% of the WR stars in this sample are detected with X-ray luminosities in the range 2×10^{32}–2×10^{35} ergs s^{-1}. The X-ray spectral analysis of the brightest WR stars reveals large absorption columns and high temperatures, similar to those seen in sources with colliding winds. The colliding-wind origin of the X-ray emission is further supported by the higher frequency of X-ray detections among WR stars in binary systems and by their higher X-ray luminosities compared to those of single WR stars. Among single WR stars, X-ray emission is mostly detected in WN6 stars, while single WC stars are not detected.

1 Introduction

A Wolf-Rayet (WR) star represents a late evolutionary stage of a massive star, when its H-rich envelope has been stripped off and CNO-Cylce H-burning (WN phase) or He-burning products (WC phase) are revealed at its surface. WR stars have the most powerful fast winds, with typical mass loss rates ($\dot{M}$) of a few $\times10^{-5}$ $M_\odot$ yr^{-1} (de Jager, Nieuwenhuijzen, & van der Hucht 1988) and terminal velocities (v_∞) of 1,000–3,000 km s^{-1} (Prinja, Barlow, & Howarth 1990), resulting in stellar wind mechanical luminosities ($L_{\rm w} \equiv \frac{1}{2}\dot{M}v_\infty^2$) 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: Shocks in the wind itself are produced by stochastic or radiatively-induced instabilities and the post-shock gas reaches X-ray-emitting temperatures (Lucy & White 1980; Gayley & Owocki 1995). This is basically the same X-ray emission mechanism as for O and early B stars (Berghöfer et al. 1997), but WR winds are heavily enriched in metals (C, N, O) so that their X-ray emission is highly absorbed.

- Colliding winds: 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, e.g., V444 Cygni (Corcoran et al. 1996). The physical conditions and X-ray luminosity of the hot gas at the collision zone vary along with the orbital phase of the binary system.

- Shocked wind in a circumstellar bubble: The fast wind of a WR star can blow a bubble in the ambient medium, and the bubble interior is filled with shocked stellar wind that emits X-rays (García-Segura, Mac Low, & Langer 1996). The X-ray emission is distributed and is expected to peak near the inner wall of the bubble shell.

Systematic X-ray surveys of WR stars using *Einstein* and *ROSAT* observations have been limited to our Galaxy (Pollock 1987; Pollock, Haberl, & Corcoran 1995; Wessolowski 1996). These studies suggest that (1) binary WR stars are brighter than single WR stars, (2) single WC stars are weaker X-ray sources than single WN stars, and (3) no simple $L_{\rm X}/L_{\rm bol}$ relationship appears to exist among single WN stars. These results did not take into account the unknown existence of binary companions, as Oskinova et al. (2003) and Oskinova (2005) have shown recently that *truly single* WC and late WN stars are not detectable in X-rays owing to the high opacity in their winds. It is difficult to extend X-ray observations to more WR stars in the Galaxy because the large absorption column densities in the Galactic plane prevent their detection. Furthermore, the uncertainties in the WR star distances directly affect the accuracy in their luminosity determination.

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 Large and Small Magellanic Clouds (LMC and SMC, or MCs), as illustrated recently by Portegies Zwart et al. (2002) and Nazé et al. (2002). The MCs have a foreground reddening $E_{B-V} \sim 0.04$–0.09 (Schwering & Israel 1991) and an internal reddening $E_{B-V} \sim 0.06$ (Bessell 1991), much smaller than the reddening in the Galactic plane, so the soft X-ray emission from single WR stars and WR bubbles can be more easily detected. Furthermore, WR stars in the MCs are at known distances, so their X-ray luminosities can be determined accurately. More importantly, there has been a systematic spectroscopic search for binarity for all WR stars in the MCs (Foellmi, Moffat, & Guerrero 2003a,b; Schnurr et al., in preparation), and this binary WR star database is invaluable in aiding the interpretation of their X-ray emission.

2 *Chandra* and *ROSAT* observations of WR stars in the Magellanic Clouds

The *Chandra* Archive[1] and *ROSAT* Archive[2] have been used to search for *Chandra* ACIS and *ROSAT* PSPC and HRI observations that include MC WR stars. Our search rendered 192 useful *Chandra* ACIS observations for 57 WR stars in the LMC and 9 WR stars in the SMC, *ROSAT* PSPC observations for 121 WR stars in the LMC and 11 WR stars in the SMC, and *ROSAT* HRI observations for 110 WR stars in the LMC and 11 WR stars in the SMC. This database includes X-ray observations of 128 WR stars, which correspond to ~90% of the known WR stars in the MCs.

[1] The *Chandra* Archive is available using the *Chandra* Search and Retrieval Interface (*ChaSeR*) at the *Chandra* X-ray Observatory site (http://asc.harvard.edu).

[2] *ROSAT* archival data can be obtained from the anonymous ftp site legacy.gsfc.nasa.gov, or downloaded from the web site http://heasarc.gsfc.nasa.gov/W3Browse, maintained by the High Energy Astrophysics Science Archive Research Center (HEASARC) of Goddard Space Flight Center, NASA.

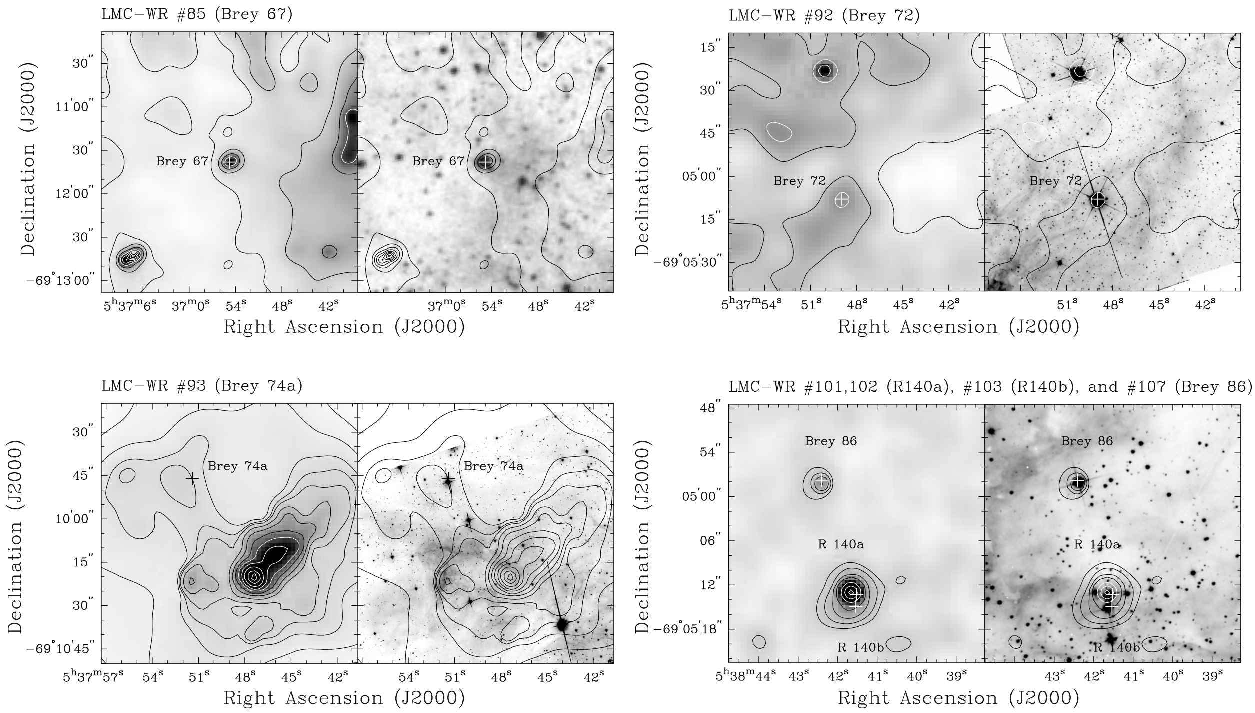

Figure 1: *Chandra* ACIS X-ray images in the 0.3–7.0 keV band and optical images of several WR stars in the LMC with detected X-ray emission. The position, number in the Breysacher et al. (1999) catalog, and names of the WR stars are marked. The contour levels have been chosen to highlight the X-ray emission and identification of WR stars.

To search for X-ray emission from WR stars in the MCs, we have extracted *Chandra* ACIS images in the 0.3–7.0 keV energy band, and *ROSAT* images in the 0.1–2.4 keV and 0.1–2.0 keV energy bands for the PSPC and HRI, respectively. We have used the positions of WR stars given by Breysacher, Azzopardi, & Testor (1999) in the LMC and by Massey, Olsen, & Parker (2003) in the SMC, and compared the X-ray images with optical images extracted from the Digitized Sky Survey[3] (DSS) or from the *Hubble Space Telescope* Archive when available. For each WR star, we have identified the star in the optical images and then searched for X-ray point source at the location of the star, and further searched for diffuse X-ray emission in its surroundings. Some examples of X-ray and optical images of WR stars with detected X-ray emission are shown in Figure 1.

X-ray emission is detected for the 34 WR stars listed in Table 1, which constitute ∼25% of all the MC WR stars surveyed. Table 1 also lists the spectral type, binarity or multiplicity status, and X-ray and bolometric luminosities of the WR stars. The bolometric luminosities have been compiled from the literature, or computed by applying a bolometric correction for WR stars as suggested by Schmutz, Hamann, & Wessolowski (1989) and Crowther & Smith (1997). For the latter case, we used v from Breysacher et al. (1999) and adopted a typical A_V

[3]The Digitized Sky Survey is based on photographic data obtained using the UK Schmidt Telescope and the Oschin Schmidt Telescope on Palomar Mountain. The UK Schmidt was operate 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 Digitized Sky Survey was produced at the Space Telescope Science Institute under US government grant NAGW-2166.

Table 1: Spectral Type, Binarity, L_X, and L_{bol} of WR Stars in the MCs with X-ray Emission

WR #	WR Name	Spec. Type	Binarity	L_X (ergs s^{-1})	L_{bol} (ergs s^{-1})
LMC-WR 10	Brey 9	WC5	M	$(6.7\pm1.1)\times10^{33}$	4.0×10^{38}
LMC-WR 19	Brey 16	WN4b+O5:	Y	$(3.2\pm0.4)\times10^{34}$	4.8×10^{39}
LMC-WR 20	Brey 16a	WC5+O	Y	$(8.4\pm1.3)\times10^{33}$	4.5×10^{38}
LMC-WR 38	Brey 31	WC4+O8I:	Y	$(5.4\pm1.4)\times10^{33}$	5.7×10^{39}
LMC-WR 39	Brey 32	WC4+O6V-III	Y	$(5.5\pm1.8)\times10^{33}$	2.2×10^{39}
LMC-WR 42	Brey 34	WN5b+(B3I)	Y	$(6.7\pm1.1)\times10^{33}$	2.5×10^{40}
LMC-WR 47	Brey 39	WN3	N	$(4.2\pm1.6)\times10^{33}$	6.8×10^{39}
LMC-WR 67	Brey 56	WN5ha	Y	$(1.2\pm0.2)\times10^{33}$	9.7×10^{38}
LMC-WR 77	Brey 65	WN7	Y	$(5\pm2)\times10^{32}$	1.0×10^{39}
LMC-WR 78	Brey 65b	WN6(+O8V)	Y	$(2.5\pm1.0)\times10^{32}$	1.3×10^{39}
LMC-WR 79	Brey 57	WN7h+OB	Y	$(5\pm2)\times10^{32}$	8.0×10^{38}
LMC-WR 80	Brey 65c	O4If/WN6	N	$(1.0\pm0.2)\times10^{33}$	1.2×10^{39}
LMC-WR 82	Brey 66	WN3b	N	$(5\pm2)\times10^{32}$	1.1×10^{39}
LMC-WR 85	Brey 67	WC4+OB	Y	$(8.6\pm0.9)\times10^{34}$	4.5×10^{39}
LMC-WR 92	Brey 72	WN6+B1Ia	Y	$(1.3\pm0.4)\times10^{33}$	5.9×10^{39}
LMC-WR 93	Brey 74a	O3If/WN6	N	$(8\pm3)\times10^{32}$	6.9×10^{38}
LMC-WR 99	Brey 78	O3If/WN6-A	N	$(1.3\pm0.2)\times10^{34}$	3.4×10^{39}
LMC-WR 100	Brey 75	WN6h	N	$(8\pm3)\times10^{32}$	2.8×10^{39}
LMC-WR 101,102	R140a	WN6	Y	$(1.5\pm0.1)\times10^{35}$	8.0×10^{39}
LMC-WR 103	R140b	WN6	Y	$(8\pm3)\times10^{32}$	1.5×10^{39}
LMC-WR 105	Brey 77	O3If/WN6-A	N	$(2.4\pm0.6)\times10^{33}$	8.8×10^{39}
LMC-WR 106,108,109,110	R136a	WN5h	Y	$(2.5\pm0.2)\times10^{34}$	1.9×10^{40}
LMC-WR 107	Brey 86	WNL/Of	Y	$(1.8\pm0.5)\times10^{33}$	1.0×10^{40}
LMC-WR 112	R136c	WN5h	M	$(6.1\pm0.4)\times10^{34}$	1.0×10^{40}
LMC-WR 114	Mk 35	O3If/WN6-A	N	$(1.0\pm0.3)\times10^{33}$	2.0×10^{39}
LMC-WR 116	Brey 84	WN5h	Y?	$(1.8\pm0.1)\times10^{35}$	1.2×10^{40}
LMC-WR 118	Brey 89	WN6h	N	$(1.5\pm0.5)\times10^{33}$	8.4×10^{39}
LMC-WR 119	Brey 90	WN6(h)	Y	$(1.2\pm0.4)\times10^{33}$	5.6×10^{39}
LMC-WR 125	Brey 94	WC5+O7	Y	$(1.6\pm0.3)\times10^{33}$	9.8×10^{38}
LMC-WR 126	Brey 95	WN4b+O8:	Y	$(1.6\pm0.4)\times10^{33}$	2.7×10^{39}
LMC-WR 127	Brey 95a	WC5+O6	Y	$(1.1\pm0.4)\times10^{33}$	1.1×10^{39}
SMC-WR 5	HD 5980	WN6h	Y	$(8.7\pm0.5)\times10^{33}$	1.2×10^{40}
SMC-WR 6	AV	WN4:+O6.5I:	Y	$(4.2\pm0.2)\times10^{34}$	7.1×10^{39}
SMC-WR 7	AV 336a	WN4+O6I(f)	Y	$(2.3\pm0.1)\times10^{33}$	4.0×10^{39}

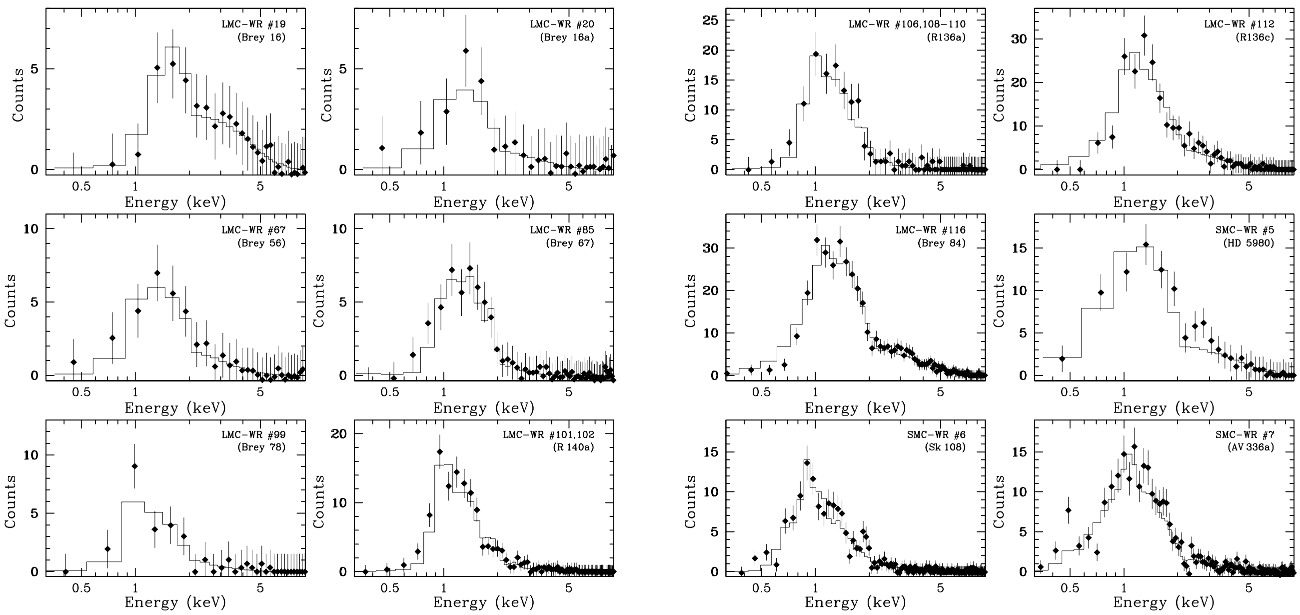

Figure 2: *Chandra* ACIS background-subtracted spectra of WR stars in the MCs with sufficient number of counts to allow a reliable spectral fit. The best-fit optically thin plasma emission models are overplotted on the X-ray spectra.

of 0.4 mag for the WR stars in the LMC, and used M_V from Massey et al. (2003) for the WR stars in the SMC. The X-ray luminosities of the WR stars in the MCs span a wide range, from a few $\times 10^{32}$ ergs s^{-1} to $\sim 10^{35}$ ergs s^{-1}.

3 X-ray spectral properties

The *Chandra* ACIS observations of WR stars with sufficient counts can be used to determine the physical properties of the X-ray-emitting gas and the amount of intervening absorbing material. The *Chandra* ACIS spectra of the 12 WR stars in the MCs with the largest number of counts are displayed in Figure 2. These spectra peak in the 0.7–2.0 keV band, with very few counts below 0.5 keV, and in some cases with high-energy tails extending above 5 keV. Interestingly, the integrated spectrum of all the X-ray-faint WR stars has a spectral shape similar to the spectra shown in Fig. 2. The X-ray spectral properties of the WR stars in the MCs are suggestive of high plasma temperatures and large amounts of absorption. This is confirmed by spectral fits to the observed background-subtracted spectra using an optically thin plasma emission model. The best-fits, overplotted on the spectra of Fig. 2, indicate plasma temperatures from $\sim$1 keV up to $\sim$7 keV, with absorption column densities much larger than the typical extinction for the MCs.

4 Frequency of X-ray detection

The frequency of X-ray detection among different subgroups of WR stars in the MCs is listed in Table 2. This table shows that detectable X-ray emission is more frequently associated with WR stars in known binary systems or WR stars with absorption lines that are commonly interpreted as evidence for binary companions. Indeed, all WC stars with detectable X-ray emission are in binary systems, and only 9 out of 80 putatively single WN stars show X-ray

Table 2: X-ray Detection Among Subgroups of WR Stars in the MCs

Sub-Group	Number of Detections	Number of WR Stars	Frequency
Single WR Stars	9	90	10±4%
Binary WR Stars	25	43	58±20%
WC Stars	7	21	33±20%
WN Stars	27	112	24±7%
Single WC Stars	0	9	0%
Single WN Stars	9	80	11±5%
Binary WC Stars	7	12	60±40%
Binary WN Stars	18	32	56±23%

emission. These results indicate that detectable X-ray emission from WR stars in the MCs is preferentially associated with binary systems, independent of whether they are of WN or WC types. It is understandable that if the X-ray emission from WR stars in binary systems arises from colliding stellar winds, the X-ray detection rate would not be strongly dependent on the spectral type of the WR stars. Indeed, Table 2 shows that binary WN stars and binary WC stars have similar X-ray detection rates.

The frequency of X-ray emission is subdivided by detailed spectral types and shown in Figure 3-*left*. X-ray emission from WR stars in the MCs is most frequently detected in WN6 stars, regardless of their binarity status. WC5 stars also have a high X-ray detection rate, but the sample has only four objects and all are in binary systems. WR stars with spectral type WN4, WN5, WN7, and WC4 are also detected frequently, but only in binary systems. It is noticeable that WN stars of spectral types WN2, WN3, and WN7–10 are rarely detected in X-rays: only 4 out of 36 are detected. WN4 is the most common spectral type, but WN4 stars have a similar low X-ray detection rate, $\sim$0.1.

The distributions of L_X and L_X/L_{bol} for WR stars in the MCs are shown in Fig. 3-*right*. The sharp fall-off of the L_X distribution at luminosities below 10^{33} ergs s^{-1} reflects the survey limit. At the high luminosity end, there is a significant fraction of WR stars with $L_X > 10^{34}$ ergs s^{-1}, well above the highest L_X observed for Galactic WR stars (Oskinova 2005). These X-ray-bright WR stars are all confirmed or likely members of binary systems or tight OB associations (Table 1). The distribution of L_X/L_{bol} shows a marked peak at $\sim 5\times10^{-7}$ and a secondary peak at $\sim 10^{-5}$ (Fig. 3). It is tempting to interpret this double-peaked distribution as a result of two different populations: X-ray-faint single WR stars and X-ray-bright binary WR stars. However, the L_X/L_{bol} distribution of WR stars in binary systems also shows a double-peaked shape, and the apparently single WR stars show only the $\sim 5\times10^{-7}$ peak. Therefore, we speculate that among WR stars in binary systems, the bright objects produce enhanced X-ray emission via colliding stellar winds, and the faint objects show X-ray emission from the WR stars themselves, similar to single WR stars.

5 Discussion

The X-ray survey of WR stars in the MCs has shown that WR stars in binary systems are much more frequently detected than single WR stars and that WR stars in binary systems have higher L_X/L_{bol} than the apparently single WR stars. Similar trends have been reported

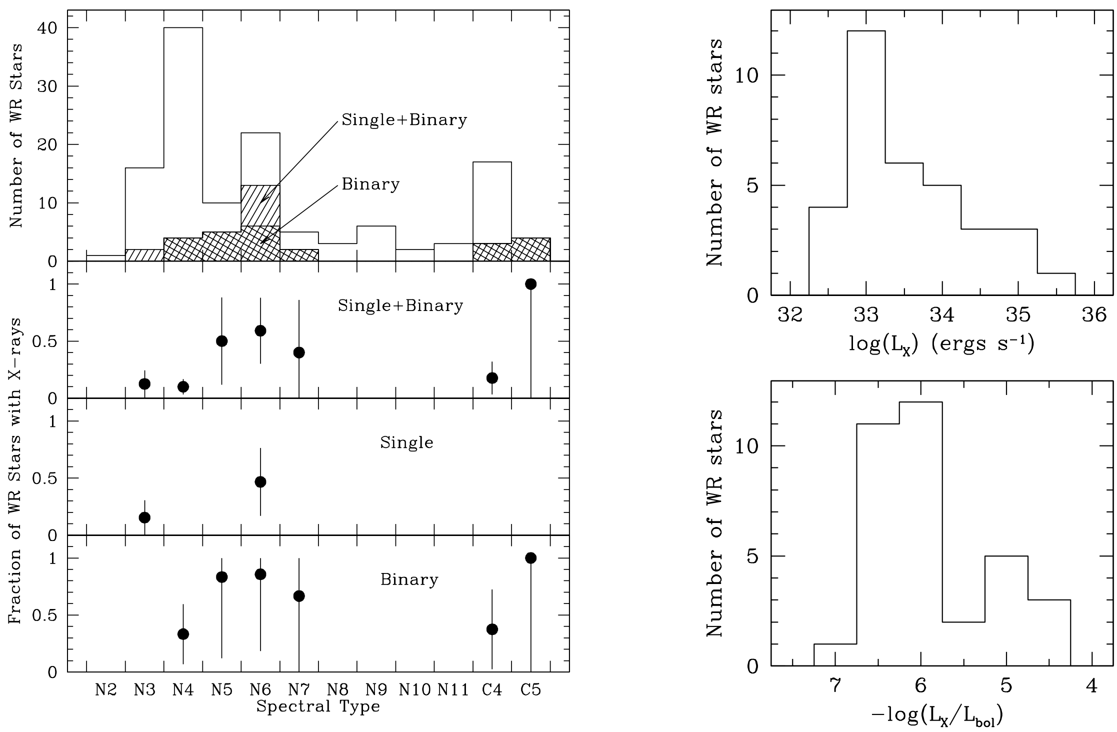

Figure 3: *(left)* Distribution and fraction of occurrence of X-ray emission from WR stars in the MCs by spectral sub-types *(top panels)*. The bottom panels separate the fraction of occurrence among single and binary WR stars. *(right)* $L_{\rm X}$ and $L_{\rm X}/L_{\rm bol}$ distributions of WR stars in the MCs with detected X-ray emission.

for Galactic WR stars (Pollock 1987), but it is possible to use the large number of WR stars in the MC sample to statistically examine their X-ray emission properties. In the MC sample, we find the X-ray-emitting WR stars in binary systems can be divided into two categories: (1) X-ray-faint binaries with $L_{\rm X}/L_{\rm bol} \sim 5\times10^{-7}$, and (2) X-ray-bright binaries with $L_{\rm X}/L_{\rm bol} \sim 10^{-5}$. The $L_{\rm X}/L_{\rm bol}$ relationship for X-ray-faint WR binaries is similar to this of apparently single WR stars in the MCs, but somewhat steeper than the $L_{\rm X}/L_{\rm bol} \sim 1.2\times10^{-7}$ relationship found for Galactic O stars (Sana 2005, this proceeding). Therefore, the colliding winds do not contribute significant emission to the X-ray-faint WR binaries in the MCs. In contrast, the X-ray-bright WR binaries in the MCs are 30 times brighter than the single WR stars in the MCs, and at least 10 times brighter than their Galactic counterparts. The enhanced X-ray luminosities of these X-ray-bright WR binaries are most likely contributed by the colliding stellar winds. This conclusion is supported by the high plasma temperatures and large absorption column densities indicated by the best-fit models for their *Chandra* ACIS spectra.

As for single WR stars in the MCs, this survey shows that detectable X-ray emission is present only for a narrow range of spectral types: WN3 and WN6. Most notably, single WC, late WN, WN4, and WN5 stars are not detected in X-rays, in spite of their large number in our MC survey sample. The lack of detectable X-ray emission from single WR stars of these spectral types is firmly established by this survey for the MCs. Similar results have been reported for Galactic WR stars. Oskinova et al. (2003) have determined that single Galactic WC stars lack X-ray emission and, more recently, Oskinova (2005) has shown that single Galactic WN8 stars also do not show detectable X-ray emission. The lack of X-ray emission from WC and late WN stars is most likely caused by the high opacity in their stellar winds, but it is not clear why single WN4 and WN5 stars do not have detectable X-ray emission.

Acknowledgements

This research was partially supported by NASA/CXO grant GO 0-1004X and by grant PNAYA 2002-00376 of the Spanish MEC (cofunded by FEDER funds). MAG also acknowledges support from the Spanish program Ramón y Cajal.

References

Berghöfer T.W., Schmitt J.H.M.M., Danner R., Cassinelli J.P., 1997, A&A, 322, 167

Bessel M.S., 1991, A&A 242, 17

Breysacher J., Azzopardi M., Testor G., 1999, A&AS, 137, 117

Corcoran M.F., Stevens I.R., Pollock A.M.T., Swank J.H., Shore S.N., Rawley G.L., 1996, ApJ, 464, 434

Crowther P.A., Smith L.J., 1997, A&A, 320, 500

de Jager C., Nieuwenhuijzen H., van der Hucht K.A., 1988, A&AS, 72, 259

Foellmi C., Moffat A.F.J., Guerrero M.A., 2003a, MNRAS, 338, 360

Foellmi C., Moffat A.F.J., Guerrero M.A., 2003b, MNRAS, 338, 1025

García-Segura G., Mac Low M.-M., Langer N., 1996, A&A, 305, 229

Gayley K.G., Owocki S.P., 1995, ApJ, 446, 801

Lucy L.B., White R.L., 1980, ApJ, 241, 300

Massey P., Olsen K.A.G., Parker J.Wm., 2003, PASP, 115, 1265

Nazé Y., Antokhin I.I., Rauw G., Chu Y.-H., Gosset E., Vreux J.-M., 2004, A&A, 418, 841

Oskinova L.M. 2005, MNRAS, 361, 679

Oskinova L.M., Ignace R., Hamann W.-R., Pollock A.M.T., Brown J.C., 2003, A&A, 402, 755

Pollock A.M.T., 1987, ApJ, 320, 283

Pollock A.M.T., Haberl F., Corcoran M.F., 1995, IAU Symposium, 163, 512

Prinja R.K., Barlow M.J., Howarth I.D., 1990, ApJ, 361, 607

Portegies Zwart S.F., Pooley D., Lewin W.H.G., 2002, ApJ, 574, 762

Schmutz W., Hamann W.-R., Wessolowski U., 1989, A&A, 210, 236

Schwering P.B.W., Israel F.P., 1991, A&A 246, 231

Wessolowski U., 1996, in *Röntgenstrahlung from the Universe*, Würzburg meeting proceedings, 75