An X-Ray Survey of Wolf-Rayet Stars in the Magellanic Clouds

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X-RAY EMISSION FROM WOLF-RAYET STARS

Wolf-Rayet (WR) stars exhibit extremely powerful stellar winds. Three types of X-ray sources have been attributed to their stellar winds:
(1) Shocking Winds: Shocks within the WR wind.
(2) Colliding Winds: Interaction with the stellar wind of an OB companion.
(3) Wind-Blown Bubbles: Interaction with the circumstellar medium.

Therefore, X-ray observations of WR stars probe the opacity of their stellar winds, the orbital configuration of a WR+OB binary system, and the stellar mechanical energy injection into the interstellar medium.

X-ray studies of Galactic WR stars are difficult because their X-ray emission is heavily absorbed in the Galactic plane, accuracy in their L_x is affected by the uncertainty in distances, and the unknown existence of binary companions confuses the assessment of origin of X-ray emission.

X-ray studies of WR stars in the Magellanic Clouds (MCs) are interesting because their foreground and internal extinctions are low, the X-ray luminosities can be derived accurately as distances are well known, and their low metallicities probe abundance effects on the stellar winds.

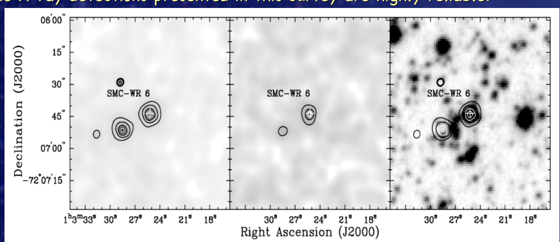
THE X-RAY SURVEY OF WR STARS IN THE MCs

The ROSAT, Chandra, and XMM-Newton archives have been used to search for X-ray emission from WR stars in the MCs. The data set is composed of:

- All ROSAT PSPC and HRI pointed observations in the ROSAT Archive with t_{exp}>1 ks, including 121 WR stars in the LMC and 11 in the SMC.
- Chandra ACIS observations of 61 WR stars in the LMC and 9 in the SMC available by 2004 October.
- XMM-Newton EPIC/pn and EPIC/MOS observations of 67 WR stars in the LMC and 8 in the SMC available by 2008 March.

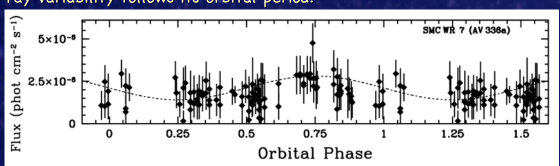
The survey includes observations for 126 WR stars in the LMC and 11 in the SMC, i.e., >90 percent of the 134 WR stars in the LMC (Breysacher et al. 1999) and 12 WR stars in the SMC (Massey et al. 2003).

The high quality of the observations and the use of data from different archives has allowed us to critically assess some X-ray detections. For instance, the X-ray source near LMC-WR 10 (Brey 9) is found to be associated to the OB association LH 9 in N11, while the bright source near LMC-WR 68 (Brey 58) and 69 (TSWR 4) is clearly offset from these stars. The X-ray detections presented in this survey are highly reliable.



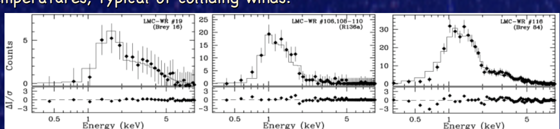
Example of X-ray detection: SMC-WR 6 (Sk 106) ACIS-S (left) and ACIS-I (center) X-ray images, and DSS optical image (right) over-plotted with ACIS-S X-ray contours.

The X-ray variability of stars with multiple or long observations has also been investigated. One of the most outstanding cases of X-ray variability is LMC-WR 19 (Brey 16). Chandra observations of this star reveal an increase of its X-ray flux from 2.0x10^{-6} to 4.4x10^{-6} phot cm^{-2} s^{-1} from Dec. 1999 to Feb. 2002. An XMM-Newton EPIC observation in Jul. 2000 did not detect any emission from this star. Another example is SMC-WR 7 (AV 336a) whose X-ray variability follows its orbital period.



X-ray light curve of SMC-WR 7 (AV 336a), a WN+O6 spectroscopic binary, folded with its 19.560 days orbital period (Niemela et al. 2002; Foellmi et al. 2003).

The detection of a sufficient number of counts has made possible the spectral analysis of some of the WR stars in the MCs. In most cases, the spectra are indicative of highly absorbed emission from a thin plasma at high temperatures, typical of colliding winds.



(top) Chandra ACIS X-ray spectra of LMC-WR 19 (Brey 16), 106,108-110 (R 136a), and 116 (Brey 84) over-plotted with the best-fit models. (bottom) Residuals of the fits in terms of the bin sigmas.

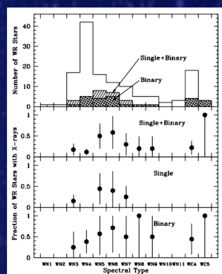
X-RAY DETECTIONS

X-ray emission is detected from 35 WR stars (or WR-stars associations) in the MCs out of the 136 WR stars with useful observations. The detection rates in the SMC (3/11~27%) and LMC (32/125~26%) are rather similar. Below we list the WR stars in the MCs with X-ray emission, together with their spectral types, binary status, L_x and L_{bol}.

WR #	WR Name	Spec. Type	Binarity	L_X (ergs s^{-1})	L_{bol} (ergs s^{-1})
LMC-WR 19	Brey 16	WN4b+O5:	Binary	$(3.2\pm0.4)\times10^{34}$	4.8×10^{39} (1)
LMC-WR 20	Brey 16a	WC5+O	Binary	$(8.4\pm1.3)\times10^{33}$	4.5×10^{38}
LMC-WR 28	Brey 22	WC4+O5-6V-III	Binary	$(2.2\pm0.7)\times10^{34}$	3.0×10^{39}
LMC-WR 38	Brey 31	WC4+O8I:	Binary	$(5.4\pm1.4)\times10^{33}$	5.7×10^{39}
LMC-WR 39	Brey 32	WC4+O6V-III	Binary	$(5.5\pm1.8)\times10^{33}$	2.2×10^{39}
LMC-WR 42	Brey 34	WN5b+(B3I)	Visual Companion	$(6.7\pm1.1)\times10^{33}$	2.5×10^{40}
LMC-WR 47	Brey 39	WN3	Single	$(4.2\pm1.6)\times10^{33}$	6.8×10^{39}
LMC-WR 59	Brey 48	WN4b+O8:	Binary	$(2.0\pm0.7)\times10^{34}$	2.8×10^{39}
LMC-WR 67	Brey 56	WN5ha	Single	$(1.2\pm0.2)\times10^{33}$	9.7×10^{38} (2)
LMC-WR 77	Brey 65	WN7ha	Binary	$(5\pm2)\times10^{32}$	1.0×10^{39}
LMC-WR 78	Brey 65b	WN6(+O8V)	Binary	$(2.5\pm1.0)\times10^{32}$	1.3×10^{39}
LMC-WR 79	Brey 57	WN7ha+OB	Single	$(5\pm2)\times10^{32}$	8.0×10^{38}
LMC-WR 80	Brey 65c	WN5h:a	Single	$(1.0\pm0.2)\times10^{33}$	1.2×10^{39}
LMC-WR 82	Brey 66	WN3b	Single	$(5\pm2)\times10^{32}$	1.1×10^{39}
LMC-WR 85	Brey 67	WC4+OB	Binary	$(8.6\pm0.9)\times10^{34}$	4.5×10^{39}
LMC-WR 92	Brey 72	WN3:b(+O)+B1Ia	Binary	$(1.3\pm0.4)\times10^{33}$	5.9×10^{39}
LMC-WR 93	Brey 74a	O3If/WN6	Single	$(8\pm3)\times10^{32}$	6.9×10^{38}
LMC-WR 99	Brey 78	O3If* /WN6	Binary	$(1.3\pm0.2)\times10^{34}$	3.4×10^{39}
LMC-WR 100	Brey 75	WN7	Single	$(8\pm3)\times10^{32}$	2.8×10^{39} (3)
LMC-WR 101,102	R140a	WN6	Binary?	$(1.5\pm0.1)\times10^{35}$	8.0×10^{39}
LMC-WR 103	R140b	WN6	Binary?	$(8\pm3)\times10^{32}$	1.5×10^{39}
LMC-WR 105	Brey 77	WN7	Single	$(2.4\pm0.6)\times10^{33}$	8.8×10^{39} (4)
LMC-WR 106,108,109,110	R136a	WN5h	Stellar Group	$(2.5\pm0.2)\times10^{34}$	1.9×10^{40} (5,6)
LMC-WR 107	Brey 86	WN9h::a	Single	$(1.8\pm0.5)\times10^{33}$	1.0×10^{40}
LMC-WR 112	R136c	WN5h	Single	$(6.1\pm0.4)\times10^{34}$	1.0×10^{40}
LMC-WR 114	Mk 35	O3If* /WN6	Single	$(1.0\pm0.3)\times10^{33}$	2.0×10^{39}
LMC-WR 116	Brey 84	WN5h:a	?	$(1.8\pm0.1)\times10^{35}$	1.2×10^{40}
LMC-WR 118	Brey 89	WN6h	?	$(1.5\pm0.5)\times10^{33}$	8.4×10^{39} (5)
LMC-WR 119	Brey 90	WN6(h)	Binary	$(1.2\pm0.4)\times10^{33}$	5.6×10^{39}
LMC-WR 125	Brey 94	WC5+O7	Binary	$(1.6\pm0.3)\times10^{33}$	9.8×10^{38}
LMC-WR 126	Brey 95	WN4b+O8:	Binary	$(1.6\pm0.4)\times10^{33}$	2.7×10^{39}
LMC-WR 127	Brey 95a	WC5+O6	Binary	$(1.1\pm0.4)\times10^{33}$	1.1×10^{39}
SMC-WR 5	HD 5980	WN6h	Binary	$(8.7\pm0.5)\times10^{33}$	1.2×10^{40} (7)
SMC-WR 6	AV	WN4:+O6.5I:	Binary	$(4.2\pm0.2)\times10^{34}$	7.1×10^{39}
SMC-WR 7	AV 336a	WN4+O6I(f)	Binary	$(2.3\pm0.1)\times10^{33}$	4.0×10^{39}

References. — (1) Hamann & Koesterke (2000), (2) Koesterke et al. (1991), (3) Crowther & Smith (1997), (4) Heap et al. (1991), (5) Crowther & Dessart (1998), (6) Heap et al. (1994), (7) Koenigsberger et al. (1998).

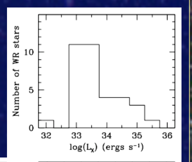
RESULTS



X-ray emission from WR stars in the MCs is more frequently associated with binary stars (~50%) than with single stars (~10%). None of the single WC stars shows detectable X-ray emission, and only ~15% of single WN stars are detected in X-rays.

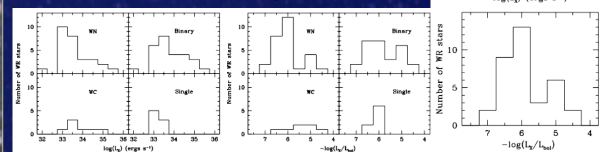
There is also a correlation between X-ray emission and spectral types of the WR stars In the MCs. X-ray emission is preferentially shown by stars of spectral types WN5-6, and WC5, i.e., WR stars with large terminal velocity stellar winds. WR stars of spectral types WN3-4, WN7-9, and WC4 have lower detection rates, while none of the 7 WN1-2 and WN10-11 are detected.

The L_x distribution shows a broad peak at ~3x10^{33} ergs s^{-1} and a tail extending towards higher L_x. The peak in the L_x distribution is present for both single and binary WR stars, and thus its origin is uncertain. The high-L_x tail seems to be associated with binary systems.

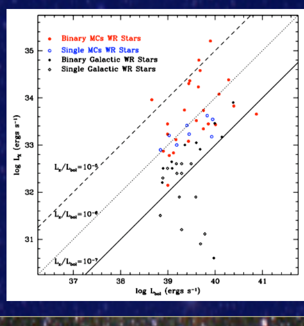


The L_x/L_{bol} distribution shows two peaks, at ~ 10^{-6} and at ~ 10^{-5}. The lower L_x/L_{bol} peak corresponds to single WR stars, while the L_x/L_{bol} distribution of binary WR stars exhibit both peaks.

While some of the binary WR stars in the MCs emit up to 100 time more X-rays than their single counterparts, some other binary WR stars have very similar X-ray levels than single WR stars.



In many respects, the X-ray properties of WR stars in the MCs are similar to these of their Galactic counterparts:
(1) no single WC star is detected in X-rays,
(2) single early type WN5-6 stars are preferentially detected,
(3) binary WR stars show higher L_x and L_x/L_{bol}.



However, Galactic WR stars have lower L_x and L_x/L_{bol} (~10$^{-6.5}$) than their MCs counterparts. The higher L_x of WR stars in the MCs can be attributed to the lower oppacity of their stellar winds (because the lower metallicity of the MCs).

The highest X-ray luminosity WR stars in the MCs (L_x > 10^{34} ergs s^{-1}) may be indicative of high-mass X-ray binaries (HMXB) in which the companion of the WR star is a neutron star or a black hole.

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