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An X-ray Survey of Colliding Wind Binaries

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Abstract. We have compiled a list of 35 O+O binaries and 86 Wolf-Rayet binaries in the Milky Way and Magellanic clouds detected with the *Chandra*, *XMM-Newton* and *ROSAT* satellites to probe the connection between their X-ray properties and their system characteristics. Of the Wolf-Rayet binaries with published model parameters, all have $\log L_X > 32$, $kT > 1$ keV and $\log L_X/L_{bol} > -7$. The most X-ray luminous W-R binaries are typically very long period systems. The WR binaries show a nearly four-order of magnitude spread in X-ray luminosity, even among among systems with very similar W-R primaries. Among the O+O binaries, short-period systems have soft X-ray spectra and longer period systems show harder X-ray spectra again with a large spread in L_X/L_{bol}.

1. Introduction

X-rays from non-magnetic massive stars are thought to be produced two ways: via embedded wind shocks in the radiately driven wind close to the star, and, in massive binaries, via shocks in the wind collision zone between the two stars (Stevens et al. 1992). 3D numerical simulations of colliding wind shocks in η Carinae and the WC8 binary WR 140 (Russell et al. 2010; Parkin et al. 2011b) correctly predict the characteristic rise, rapid decline, and recovery of the X-ray light curve as these highly eccentric, long-period, adiabatic systems approach and emerge from periastron. 3D simulations of O+O binaries by (Pittard & Parkin 2010) reproduce the overall X-ray luminosity and post-shock temperatures of a number of systems spanning a range of mass-loss rates, orbital periods and eccentricities. In particular, they were able to produce the strong, but relatively soft X-ray emission seen in some highly radiative, short-period systems. On the other hand, the 3D model for WR 22 (WN7h + O9 III-V) over-predicts the observed L_X by an order of magnitude or more (Parkin & Gosset 2011).

The O+O binaries in the *Chandra* Carina Complex project showed a wide range of L_X/L_{bol} (Nazé et al. 2011), and (Gagné et al. 2011) found that the short-period systems have significantly softer X-ray spectra than the longer-period systems. As Owocki discusses in these proceedings, thin-shell mixing may play in important role in setting the scaling between L_X and L_{bol} in the winds of single stars, and could produce significant cooling in the wind collision zone of close, massive binaries. Motivated by these results, we undertook a survey of all known Wolf-Rayet and O+O binaries with X-ray fluxes measured with the *Chandra* X-ray Observatory or the *XMM-Newton* satellite.

Table 1. Known X-ray Luminous O+O binaries

Name	Primary SpType	Second. SpType	Period (days)	Dist. (kpc)	kT (keV)	L_X (cgs)	L_X/L_{bol}	Ref. Note
HD 215835	O5.5 V((f))	O6.5 V((f))	2.11	3.5	0.3	33.73	−6.16	acly
Cyg OB2 9	O5 If	O6-7	852.9	1.2	1.2	33.52	−6.30	dfmz
HD 47129	O7.5 I	O6 I	14.4	1.5	1.3	33.36	−6.02	kq
CEN 1B	O4	?	...	1.6	2.3	33.28	−6.00	it
HD 165052	O6.5 V	O6.5 V	6.14	1.6	0.6	33.18	−6.00	aclwyp
HD 93250	O4 III(fc)	O	250	2.3	2.3	33.18	−6.41	su1
CEN 1A	O4	?	...	1.6	6.5	33.16	−6.12	it
HD 101436	O6.5 V	O7 V	37.37	2.3	...	33.11	−6.17	b
HD 93403	O5.5 I	O7 V	15.093	2.3	1.0	33.11	−6.41	sxu
HD 159176	O6 V	O6 V	3.36677	0.8	0.3	33.07	−5.89	ael
HD 101131	O6.5 V ((f))	O8.5 V	9.65	2.3	...	32.98	−6.33	b
V729 Cyg	O7 f	O6 f	6.5978	1.8	0.6	32.96	−6.74	p
HD 101205	O7 IIIn((f))	O	2.45	2.3	...	32.95	−6.54	b
HD 1337	O9 III	O9 III	3.52	3.9	...	32.90	−6.65	acl
Cyg OB2 8A	O5.5 I(f)	O6	21.907	1.2	1.0	32.88	−6.75	mnz
MT91 516	O5.5 V	?	...	1.2	0.5	32.73	−6.79	mz
HD 101413	O8 V	B3: V	150	2.3	...	32.68	−6.09	b
HD 100213	O7 V	O8 V	1.38729	2.1	...	32.63	−5.95	al
HD 93205	O3 V	O8 V	6.0803	2.3	0.3	32.55	−6.82	$sux
QZ Car	O9.7 Ib:(n)	O9 III	20.72	2.3	1.0	32.55	−7.26	sN
HD 101190	O4 V((f+))	O7-7.5 V	6.05	2.3	...	32.52	−6.74	b
CPR2002 A11	O7.5 Ibf	?	...	1.2	1.6	32.47	−6.64	mz
HD 57060	O7 f	O7	4.39	1.5	0.7	32.43	−7.38	aclx
HD 97484	O7.5	O8.5	3.41428	3.2	0.6	32.41	−6.87	p
HD 206267	O6.5 V((f))	O9	3.71	0.8	0.6	32.36	−6.89	alp
HD 93161A	O8 V	O9 V	8.566	2.3	0.5	31.94	−6.92	osu
HD 152218	O9 IV	O9.7 V	5.6	1.6	0.5	31.93	−6.85	pv
TR 16-110	O7 V	O8 V, O9 V	3.62864	2.3	0.6	31.74	−7.24	sxu
HD 93343	O8 V	O7-8.5 V	44.15	2.3	3.2	31.66	−6.98	sxu
TR 16-34	O8 V	O9.5 V	2.9995	2.3	0.6	31.56	−7.23	gsu
TR 16-104	O7 V	O9.5 V, B0.2	2.1529	2.3	0.5	31.38	−7.29	jsxu
FO 15	O5.5 V	O9.5 V	1.1414	2.3	0.5	31.24	−7.65	rsu
TR 16-1	O9.5 V	B0.3 V	1.4693	2.3	0.3	30.87	−7.30	hsxu

2. Methodology

To begin, we searched the literature for *Chandra* and *XMM* analyses of WR and O+O binaries. To those, we added X-ray sources in the XMM-Newton Serendipitous Source Catalog (2XMMi), in the *XMM-Newton* XAssist Source List, or in the *Chandra* XAssist Source List, within 15″ of positions in the 7th catalog of WR stars (van der Hucht 2001) and O+O binaries in the SB9 catalog of spectroscopic binaries (Pourbaix et al. 2009). For the O+O binaries with reliable X-ray fluxes, column densities, and distances, we calculated a 0.5–8 keV X-ray flux. These results and the corresponding X-ray, optical, and distance references are reported in Table 1. Reference codes are noted in parentheses in the references section. Similarly, results for the known WR binaries are reported in Table 2. In some cases, WR binary X-ray luminosities were taken from the *ROSAT* survey of Ignace et al. (2000). In cases where stars (e.g., WR 101k) in the *Chandra* or *XMM* XAssist source lists were detected in many observations, or by multiple cameras on *XMM*, we report L_X based on a median unabsorbed X-ray flux.

Table 2. Known X-ray Luminous WR binaries

Name	Primary SpType	Second. SpType	Dist. (kpc)	Period (days)	kT (keV)	L_X (cgs)	L_X/L_{bol}	Ref.
WR 48a	WC8ed	?	3.8	7800	2.3	35.39	−4.00	@
Mk34	WN6(h)	?	51.0	1134	2.3	35.38	−4.72	3l
η Car	LBV	O	2.3	2024	4.4	35.26	−5.02	7
R 140a	WC5	WN4	51.0	880	0.9	35.25	−4.65	l
WR 25	WN6h	O4 f	2.3	207.8	1.3	35.11	−5.49	3M
R 136c	WN5h	?	51.0	998	3.0	35.04	−4.96	3lQ
CXO J1745-28	WN9h	O?	7.6	189	2.7	35.04	−4.78	3WP
WR 28	WN6(h)	OB?	10.8	…	…	34.86	…	F
WR 43c	WN6+abs	?	7.6	8.89	…	34.85	−5.33	KV3
WR 140	WC7pd	O4-5	1.1	2900	…	34.68	−4.75	GHJS
Mk33Sa	WC5	O3 IIIf*	51.0	1120	0.6	34.63	−4.87	l
Brey 16	WN4b	O5:	51.0	18	7.0	34.58	−4.30	BT
WR 43a	WN6ha	?	10.1	3.772	…	34.30	−6.30	I
R 136a	WN5		51.0	…	1.8	34.28	−5.92	l
WR 29	WN7h	O	17.2	3.16415	…	34.21	…	FH4
WR 101k	WN9-11	?	8.0	9.72	…	34.12	…	J
Mk39	WN6	O3 If	51.0	92.6	1.6	34.11	−5.89	3l
HD 5980	WN3	OB	61.0	19.266	7.0	34.08	−5.90	T
WR 121a	WN7	a/OB	5.6	…	…	34.07	…	J
Arches-F6	WN9h	?	8.0	…	1.9	34.04	…	RU
R 136a3	WN5h		51.0	…	4.2	33.93	…	3
WR 20a	WN6ha	WN6ha	8.0	3.68	0.5	33.90	−6.15	X
WR 65	WC9d	OB	5.0	…	…	33.90	…	J
Arches-F7	WN9h	?	8.0	…	2.1	33.86	…	RU
WR 20b	WN6ha	?	8.0	…	3.6	33.81	−6.16	3X
Brey 10a	O3If*/WN6		51.0	3.23	…	33.80	…	3
WR 87	WN7h	OB	2.9	…	…	33.75	−5.75	FG
WR 93	WC7	O7-9	2.5	…	…	33.74	…	J
Mk33Na	O6.5V	O3 If*	51.0	1140	1.3	33.72	−6.08	l
BAT99-32	WN6(h)		51.0	1.91	…	33.70	…	3
Arches-F9	WN9h		8.0	…	3.3	33.66	−6.22	RU
Brey 26	WN6(h)	?	51.0	1.91	…	33.65	…	0
WR 71	WN6	OB?	9.0	7.69	…	33.63	…	AF
WR 63	WN7	OB	3.9	…	…	33.63	…	F
R 144	WN6	?	51.0	…	…	33.52	…	30Q
Cyg OB2 12	B5 Ie	?	…	1.2	1.1	33.61	−6.10	z
Av 336a	WN	O6	61.0	19.56	2.2	33.52	…	T
WR 35	WN6h	OB?	17.9	…	…	33.47	−5.51	F
WR 145	WN7/WCE	?	1.2	20	…	33.43	…	J
WR 51	WN4	OB?	8.1	…	…	33.26	−5.82	F
Brey 56	WN6	?	51.0	…	2.3	33.23	−5.75	BT
WR 66	WN8(h)	cc?	3.3	3.515	…	33.21	−6.17	F
WR 48	WC6	O9.5/B0Iab	2.2	18.341	…	33.20	…	H
R 134	WN6(h)	?	51.0	786	1.1	33.18	−6.92	l
WR 11	WC8	O7.5 III-V	0.3	78.53	1.0	33.17	−5.39	GHJ
Mk42	WN6	O3 If	51.0	922	1.1	33.15	−6.85	l
Mk30	WN6	O3 If*	51.0	4.7	…	33.11	…	0
R 139	WN	O6 Iaf	51.0	952	1.8	33.08	−6.92	l
WR 47	WN6	O5 V	3.8	6.2393	1.1	33.05	−6.55	AHp2
WR 67	WN6	OB?	3.3	…	…	33.04	−5.64	F
R 145	WN6h	?	51.0	158.8	1.6	33.00	…	Q6
WR 133	WN5	O9 I	2.1	112.4	…	33.00	−6.36	EHp
WR 21a	WN6	O/a	3.0	31.673	3.3	33.00	−5.78	OY3
WR 22	WN7h	O9 III-V	2.3	80.336	1.4	32.95	−6.90	3Hp5
WR 158	WN7h	Be?	7.9	…	…	32.93	−6.55	F
R 140b	WN6h	?	51.0	2.76	…	32.90	…	T
WR 89	WN8h	OB	2.9	…	…	32.90	−6.98	F
WR 46	WN3p	OB?	4.1	0.2825	…	32.87	−6.22	CZ
R 135	WN7h	?	51.0	2.11	…	32.78	…	0
WR 148	WN8h	B3 IV/BH	8.3	4.317364	…	32.78	−6.80	FH
WR 132	WC6	?	3.9	8.16	…	32.75	−5.93	F
WR 36	WN5-6	OB?	8.5	…	…	32.74	−6.14	F
WR 146	WC6	O8	1.2	1235	…	32.73	…	J
WR 24	WN6ha	?	2.3	…	1.7	32.71	−6.93	8
Brey 65	WN7ha	?	51.0	3	…	32.70	…	30

Table 2. Known X-ray Luminous WR binaries (continued)

Name	Primary SpType	Second. SpType	Dist. (kpc)	Period (days)	kT (keV)	L_X (cgs)	L_X/L_{bol}	Ref.
WR 147N	WN8(h)	B0.5 V	0.6	2880	1.8	32.67	−7.01	p9
WR 44	WN4	OB?	10.0	...	...	32.64	−6.54	F
WR 155	WN6	O9 II-Ib	2.8	1.641244	...	32.64	−6.44	EHp
WR 108	WN9h	OB	5.6	...	...	32.62	−6.76	F
WR 1	WN4	?	0.7	6.1	...	32.50	...	X!
WR 139	WN5	O6 III-V	1.9	4.212435	3.3	32.50	−6.40	EHZ2
WR 125	WC7ed	O9 III	3.1	6600	...	32.49	−6.29	F
WR 12	WN8h	?	5.0	23.923	...	32.48	−6.90	3AF
WR 114	WC5	OB?	2.0	...	...	32.41	−5.87	F
WR 138	WN5	B?	1.3	1538	...	32.20	−6.68	GH
WR 79	WC7	O5-8	2.0	8.8908	...	32.18	...	HJ
WR 6	WN4b	?	0.9	3.765	...	32.12	...	H
WR 115	WN6	OB?	2.0	...	...	32.08	−6.90	FG
WR 141	WN5	O5 V-III	1.3	21.6895	...	31.99	−7.98	EHX
WR 39	WC7	OB?	5.5	...	...	31.92	−6.76	F
WR 3	WN3	O4	5.9	46.85	...	31.91	−7.27	F
WR 14	WC7	?	2.0	2.42	...	31.90	−6.58	F
WR 128	WN4(h)	OB?	9.4	3.56	...	31.75	−7.33	F
WR 86	WC7	B0 III-I	2.9	...	...	31.72	−7.36	F
WR 136	WN6h	?	1.6	...	2.2	31.51	−7.47	8
WR 121	WC9d	?	1.8	...	...	31.49	−7.40	EL
WR 4	WC5	?	2.4	2.4096	...	31.37	−7.21	FH
WR 143	WC4	OB?	1.1	...	...	31.22	−7.36	F

3. Results and Discussion

We emphasize that the results presented in Tables 1 and 2 are preliminary. Moreover, mass-loss rates, orbital parameters, and accurate X-ray spectral parameters are needed for a number of systems. Nonetheless, it is clear that the most X-ray luminous W-R binaries, like the LBV binary η Car, are typically very long period systems. The exceptions, which include the 8.9-day WN6 binary WR 43c=NGC 3603-A1 with $\log L_X/L_{bol} = -5.3$, are remarkable, and merit further study. Though the spectral type of the secondary is often not known, we note that WR systems with known early-O and supergiant secondaries often have $\log L_X > 33$. Other systems, e.g., WR 101k, which was observed repeatedly as part of the *XMM* and *Chandra* galactic center surveys, are variable from observation to observation. WR 48a, the most X-ray luminous WR binary in Table 2, has undergone a dramatic decline in X-ray flux in 2011 in the *Swift* XRT (A. M. T. Pollock, private communication).

Because of their lower mass-loss rates, the O+O binaries in Table 1 have far lower L_X, with $\log L_X/L_{bol}$ in the range −5.9 to −7.7 than the WR stars in Table 2. Short-period O+O systems ($P < 10$ days) have soft X-ray spectra ($kT < 0.8$ keV) and longer period systems show harder X-ray spectra ($kT > 1$ keV). This suggests that in close O+O binaries, the higher density shocks, on average, undergo significant cooling, e.g., as a result of thin-shell mixing. For O+O systems with $\log L_X/L_{bol} < 7$, embedded wind shocks may account for a large fraction of the X-ray luminosity.

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Discussion

Damineli: In your log L_X vs. log T_{eff} plot there are eccentric binaries. Do they switch from one regime to the other, since they behave both as long- and short-period binaries?

Gagné: The diagram was generated from literature data. In some cases (V444 Cyg, WR25, WR140, η Car) the literature contains much phase resolved information. In some cases they switch (V444 Cyg, CD Cru).

Nathan Smith: I was going to ask more or less the same thing as Augusto, namely, how does variability in X-rays affect the scatter in your plots? (I.e. what if you plotted them all at the same orbital phase?)

Gagné: The L_X and kT were averaged (by emission measure) at more or less random phases. In most cases we don't have precise orbits/eccentricities. So, short of doing a serious analysis, I'd say 25-50% scatter. But that won't explain a 10^3 scatter in L_X/L_{bol}!

Walborn: The hardest X-rays in η Car come from shocks in the circumstellar ejecta. Are they excluded in your analysis? The same might be true for HD 5980, which had an outburst in 1994. Are there X-ray observations prior to that? Has it changed?

Gagné: Yes. Whenever possible we looked for papers where the X-ray spectra from Chandra were extracted from the point source, not the X-ray nebula. though η Car and HD 5980 have X-ray nebulae, most WR binaries do not.

Sana: For the short-period O+O binaries you mentioned that they have typically soft X-rays. Did you consider the possibility that the winds in those short systems collide before reaching terminal velocity, so they don't have enough energy to produce hard X-rays?

Gagné: Yes, we suggested two possible effects in Gagné et al. (2011): wind collision zone inside the acceleration zone, leading to lower kT *and* wind inhibition leading to lower L_X/L_{bol}.