RING NEBULAE ASSOCIATED WITH WOLF-RAYET STARS

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Using strict selection criteria, we have searched for ring nebulae associated with Wolf-Rayet stars in the Galaxy and the Magellanic Clouds. In our search, 15 WR ring nebulae are identified in the Galaxy (Chu 1981a; Chu 1981b, Paper G1), 9 in the Large Magellanic Cloud, and none in the Small Magellanic Cloud (Chu and Lasker 1980, Paper L1; Chu 1981a). We have subsequently observed the morphology and kinematics of these 24 nebulae to study their nature. The data and analyses are reported in G (galactic) and L (LMC) series of papers. These nebulae and their references are listed in Table 1. This table is nearly, but not quite, complete. An extremely careful search might result in more cases, e.g., NGC6357 (Lortet et al. 1981). In a later search by Heckathorn et al. (1982), more ring nebulae are suggested; however, only three cases (associated with HD92740, HD187282, and HD211564) are more convincing. We have obtained some data for these nebulae and will discuss them in a conclusion paper of the galactic series (Chu et al. 1982, Paper G8).

The presence of ring nebulae around WR stars is suggestive of interaction between the central stars and their ambient interstellar medium. The interaction can be performed by three means, viz., stellar UV radiation, ejecta, and winds. The nebulae dominated by these different interactions have different dynamic properties. From analyzing the morphological and kinematic data, we are able to sort out the dominant mode of interaction, and classify the nebulae into three categories accordingly: R - radiatively excited HII region, E - stellar ejecta, and W - wind blown bubble. The R-type nebulae are further split into two subtypes according to their morphology: R_a - amorphous HII region and R_s - shell structured HII region. It has to be born in mind that the three main categories are not absolutely exclusive of one another, since obviously all WR stars have strong UV radiation. The characteristics of these different types of nebulae and classification schemes are described by Chu (1981, Paper G1); while the detailed arguments for the classification of each individual nebula are in several subsequent papers, see Table 1 for their references.

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TABLE 1. RING NEBULAE ASSOCIATED WITH WR STARS[a]

No.		STAR NAME	SPECTRAL TYPE	NEBULAR NAME	NEBULAR TYPE	REFERENCE[b,c]
Galaxy	1	HD50896	WN5	S308	W	G4
	2	HD56925	WN4	NGC2359	W	G5
	3	HD89358	WN5	NGC3199	W	G6
	4	HD92809	WC6	anon	W	G6
	5	HD96548	WN8	RCW58	E	G6
	6	HD113904	WC6+09.5I	anon	R_s	G3
	7	HD115473	WC5	anon	R_s	G3
	8	HD117688	WN8	RCW78	R_a	G3
	9	HD147419	WN4	RCW104	W	G6
	10	LSS3982	WN6	RCW118	R_s	G3
	11	LSS4368	$WC4_p$	G2.4+1.4	R_s	G7
	12	209 BAC	WN8	M1-67	E	G2
	13	MR97	WN7	L69.8+1.7	R_a	G3
	14	HD191765	WN6	(S109)	W	G5
	15	HD192163	WN6	NGC6888	W	G5
LMC	1	HD32402	WC5	DEM39	W	L3
	2	HDE268847	WN3-5	DEM45	(R)	L2
	3	FD22	WN4	DEM137	(R_s)	L2
	4	HD36063	WN6	DEM165	(R)	L2
	5	HDE269485	WN4	DEM174	R_a	L2
	6	FD33	WN3	DEM208	(R_s)	L2
	7	HDE269748	WN2-3	DEM231	W/R_s	L3
	8	FD47	WN3+0	DEM240	?	L3
	9	HDE270149	WN4	DEM315	W	L3

[a]Details and description of this table can be found in reference G1 and L1.

[b]G1: Chu 1981b, Ap. J., 249, 195.
G2: Chu and Treffers 1981a, Ap. J., 249, 586.
G3: Chu and Treffers 1981b, Ap. J., 250, 615.
G4: Chu et al. 1982a, Ap. J., 254, in press.
G5: Treffers and Chu 1982a, Ap. J., 253, in press.
G6: Chu 1982a, Ap. J., 254, in press.
G7: Treffers and Chu 1982b, Ap. J., 254, in press.
G8: Chu et al. 1982b, in preparation.
L1: Chu and Lasker 1980, Pub.A.S.P., 92, 730.
L2: Chu 1982b, Ap. J., 255, in press.
L3: Chu 1982c, in preparation.

[c]Almost all information contained in these papers can be found in Chu 1981a, dissertation. University of California, Berkeley.

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Listing the spectral types of the central WR stars for each category of the ring nebulae, we can see an obvious correlation between the spectral and nebular types. See Table 2. For the galactic WR ring nebulae, apparently R_a-type nebulae are preferentially associated with late type WN stars, R_s-type nebulae with WC stars, E-type nebulae with WN8 stars, and W-type nebulae with early type WN stars. For the LMC WR rings, no comparable correlation is found because of poor statistics - only three genuine cases are classified unambiguously. The four largest nebulae, with nebular type enclosed in parentheses in Table 2, have been puzzling because their diameters range between 100 and 200 pc, much larger than the galactic counterparts. However, recent studies indicate that they are not genuine WR ring nebulae in the strict sense and should not be included in Table 2 (Chu 1982b, Paper L2).

TABLE 2. CORRELATION BETWEEN SPECTRAL AND NEBULAR TYPES

	R_a	R_s	E	W
Galaxy	WN8	WC6+09.51	WN8	WN5
	WN7	WC5	WN8	WN4
		WN6[a]		WN5
		$WC4_p$		WC6
				WN4
				WN6
				WN6
LMC	WN4			WC4
				WN4

[a]The association of RCW118 with LSS3982 is uncertain because of the presence of a small group of B stars around. See Chu (1981b) for the details.

Although the correlations look attractive and the dynamical evolution of the nebular types (Chu 1981b) is consistent with the scenario that late-type WN stars evolve into early-type WN stars, then into WC stars; only the W- and R_s-type nebulae have probable statistical significance, and we can only state that WC stars have older environment than early type WN stars. R_s-type nebulae are $> 10^6$ years old, while W-type nebulae are 10^4-10^5 years old.

There are a lot of WR stars that do not have any visible nebulosity around. It is probably because they are in a hot low density medium, with $n_H \approx n_e < 0.004$ cm^{-3} (Chu 1981b). If dense molecular clouds with recent star formation are defined "young", then the hot

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low density medium (called "HIM" by McKee and Ostriker 1977) has obviously been cooked by energetic events like supernova explosions or stellar winds and is considered "old". Chu (1981b) derived filling factors of HIM in the spaces WN stars and WC stars occupy to be about 0.55 to 0.61 and 0.64 to 0.71, respectively. More WN stars are in gas rich regions, i.e., younger interstellar environment. Again, we reach the conclusion that WC stars usually have older environment than WN stars.

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DISCUSSION FOLLOWING CHU

Niemela: HD 117688 has a brighter visual companion, which is an early B supergiant and may contribute to the ionization of the H II region.

Hogg: If the winds of WR stars have more or less the same luminosity, then does the correlation of W type nebulae with early WN stars imply that the winds have been blowing for a longer time?

Chu: Possible. RCW 78 and L69.8+1.74, two Ra-type nebulae, have central stars WN8 and WN7, respectively. The central stars have stellar winds and there is plenty of interstellar material around, however, there are no wind-blown bubbles yet. This probably implies that the late-type WN stars (at least for these two central stars) have strong stellar winds turned on more recently than the early-type WN stars.

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