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RING NEBULAE ASSOCIATED WITH WOLF-RAYET STARS IN THE LARGE MAGELLANIC CLOUD

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Eight ring-shaped nebulae associated with Wolf-Rayet stars are identified in the Large Magellanic Cloud. These nebulae are typically ten times larger than morphologically similar ones associated with Galactic Wolf-Rayet stars.

Key words: galaxies: Magellanic Clouds—nebulae: general—stars: Wolf-Rayet—interstellar matter

I. Introduction

Seven Galactic Wolf-Rayet (WR) stars are known to be associated with small symmetric nebulae having the shape of a ring or an arc centered on the WR star. These so-called "ring nebulae" are listed by Smith (1967). Crampton (1971) cataloged WR stars coincident with H II regions and proposed two more ring nebulae, but neither was as well-defined or convincing as the previous seven. The formation of ring nebulae is believed to be caused by interaction between stellar ejecta and the ambient interstellar material (Johnson and Hogg 1965). Observations of these rings have been presented and interpreted by numerous authors, including Johnson (1971), Wendker et al. (1975), Deharveng and Maucherat (1974), Israel and Felli (1976), Pismis, Recillas-Cruz, and Hasse (1977), and Kwitter (1979).

This paper proposes the identification of eight ring nebulae associated with WR stars in the Large Magellanic Cloud (LMC). These new nebulae are morphologically similar to the Galactic rings, but 2 to 20 times larger. A similar search for ring nebulae associated with WR stars in the Small Magellanic Cloud has been done; none were found.

II. WR Stars and Ring Nebulae in the LMC

A. *Surveys*

Fehrenbach, Duflot, and Acker (1976) published a catalog of 78 LMC WR stars (herein designated by FD numbers). Additional WR stars have been discovered by Walborn (1977), Melnick (1978), and Azzopardi and Breysacher (1979, 1980), bringing the current number of known WR stars in the LMC to 101. The sample is considered complete except for subclass WC5, for which the search technique was inadequate (Azzopardi and Breysacher 1979).

Modern cataloging of LMC H II regions begins with Henize (1956), who also tabulates the OB stars within the projected boundaries of the regions. The Hα survey of Davies, Elliott, and Meaburn (1976, hereafter DEM) has greater spatial resolution and a more extensive listing of nebulosities. These basic works are supplemented with surveys by Lasker (1979*a*,*b*) and Gull (1980). The former, which covers three passbands with moderate scale, is useful for distinguishing structures of different excitations; the latter is a very sensitive three-filter survey with somewhat lower spatial resolution.

The properties of these four surveys are summarized in Table I.[1]

B. *Selection Criteria*

We consider a WR star and nebula to be associated if the following criteria are satisfied:

1. The nebula has filamentary or shell structure and is isolated from other nebulosities. (The 30 Doradus region has been excluded from this study because of its complexity.)
2. The exciting WR star is located close to the center of a complete ring or close to the brightest part of an incomplete or nonuniform segment. (Anticipating the wind-shock picture of section III, we note that the brightest parts of the nebulae may be expected to have higher densities, to be accelerated less, and therefore to lie closer to the exciting stars.)
3. No other identifiable source of excitation exists for the nebula. That is, no other strong source of ionizing radiation (i.e., OB stars or stellar associations) exists at the preferred location (cf. criterion 2) within the projected boundary of the ring (Henize 1956; Lucke and

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[1] A further resource for this investigation was the SRC *J* survey of the ESO/SRC Southern Sky Atlas.

TABLE I

Characteristics of the H II Region Surveys

Survey	Henize 1956	DEM 1976	Lasker 1979b	Gull 1980
Telescope	10"	UK Schmidt	Curtis Schmidt	300mm lens*
Filter width (Å)				
Hα + [N II] λ6570	400	109	100	75
[O III] λ5007	---	---	100	28
[S II] λ6730	---	---	100	50
Emulsion	103a-E	098-04	098-04 (red 103a-D (yellow)	IIIa-J
Plate scale ("/mm)	159	67.2	96.4	730

* Plus Carnegie 33011 image tube; see Gull (1980) for a description of this system.

Hodge 1970), and the nebula is not a known supernova remnant (e.g., according to Mathewson and Clarke 1973).

4. The ratio of ([O III] λ5007)/(Hα + [N II]) is high. This ratio was estimated visually from the monochromatic plates cited above; ordinary LMC H II regions were taken as calibrators representative of more normal ratios. (The measured line ratios of [O III]/Hα are about 3 for Galactic ring nebulae associated with WR stars; such values greatly exceed the typical ratio of 1 or less for normal H II regions (Chopinet and Lortet-Zuckermann 1976).)

C. *Results*

The ring-nebulae and corresponding WR stars are shown in Figure 1, and further information about them is given in Table II.[2] Except as noted the charts are made from the [O III] plates of Lasker (1979*b*). Additional data can be found in DEM and Fehrenbach et al. (1976). The characteristics of the individual nebulae are discussed below.

1. DEM45 (N16A) – FD9

The morphology of DEM45 is very similar to that of NGC 3199, a galactic ring nebula excited by a WN5 star (cf. Deharveng and Maucherat 1974). DEM45's exciting star is offset toward the brighter south rim of the nebula; [O III] emission is very strong and is detected throughout the surface interior to the ring.

There are two star clusters, SL154 and SL162 (Shapley and Lindsay 1963), within the projected boundary of the ring. These clusters, which have no apparent preferred location with respect to the ring or bright rim, contain no bright stars and are probably at least 10^8 years old; they are unlikely to be physically significant to the excitation of the nebula.

2. DEM137 – FD22

DEM137 is the faintest of the ring-nebulae; it was proposed as a possible supernova remnant by DEM. The western portion of the nebula is fainter and less well defined than the eastern, which may receive additional excitation from the clusters NGC 1923 or LH43 (Lucke 1974; Lucke and Hodge 1970). (Note that the small compact H II region DEM137a is obviously associated with LH43.)

Lucke's (1974) HR diagram for LH43 shows a sparsely populated main sequence ending at $V \sim 13$ and having two giants at $(B-V) \sim 1.5$, $V \sim 13$. While LH43 and DEM137a probably do have some physical relation to DEM137, the central location of FD22 and the nearly perfect ring shape seem to justify our including this system in the present list.

3. DEM165 (N198) – FD24

The morphology of DEM165 is similar to that of NGC 6888, a well-known Galactic ring nebula excited by a WN6 star (Parker 1978, and references cited therein). The major part of DEM165 is elliptical with a bright cusp pointing toward the exciting star, FD24. In the high-sensitivity Hα + [N II] and [O III] plates of Gull, the entire area of the nebula north of the exciting star is filled in with nebular emission.

FD24 may be the first known WN7 star with an associated ring nebula; however, Conti (1980) recently classified FD24 as WN6. Previous belief has been that only WN5, 6, and 8 stars favor ring nebulae (Smith and Bat-

[2]DEM269, which includes a bright ring encircling two WR stars, was omitted from our list because the OB association NGC 2081 (see Lucke 1974) is an obvious source of excitation.

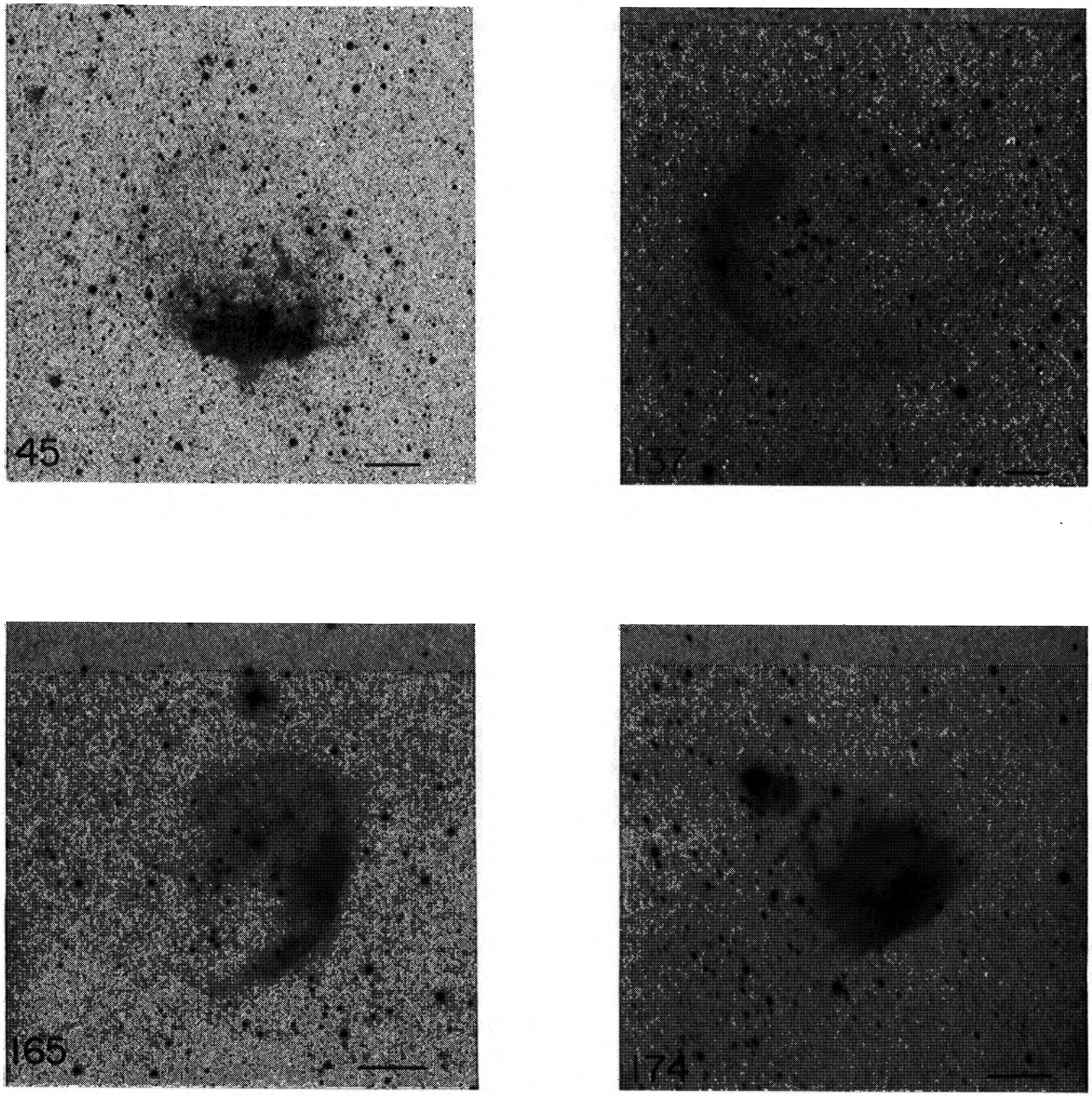

FIG. 1—Photographs of the ring nebulae in the light [O III] λ5007. The individual prints are identified with DEM numbers, the WR stars are located by marginal tick marks, and the horizontal bars indicate 2′ on the sky.

chelor 1970; but see also Crampton 1971).

4. DEM174 (N138) – FD27

DEM174 is more diffuse than filamentary, suggestive perhaps of a normal H II region instead of a wind-blown bubble. However, the surface brightness distribution still supports the existence of a "hole" in the vicinity of the star. The striations that cross DEM174 in P.A. 135° may be part of the larger filamentary network in this part of the LMC (e.g., DEM, Plate VII).

There is a star cluster HS272 (Hodge and Sexton 1966) outside the northwest rim of DEM174. The relative distances are unknown, but it is unlikely that HS272 excites DEM174.

5. DEM208 (N204) – FD33

DEM208, the largest nebula in our list, has a linear diameter of about 200 pc; it was listed as a possible SNR

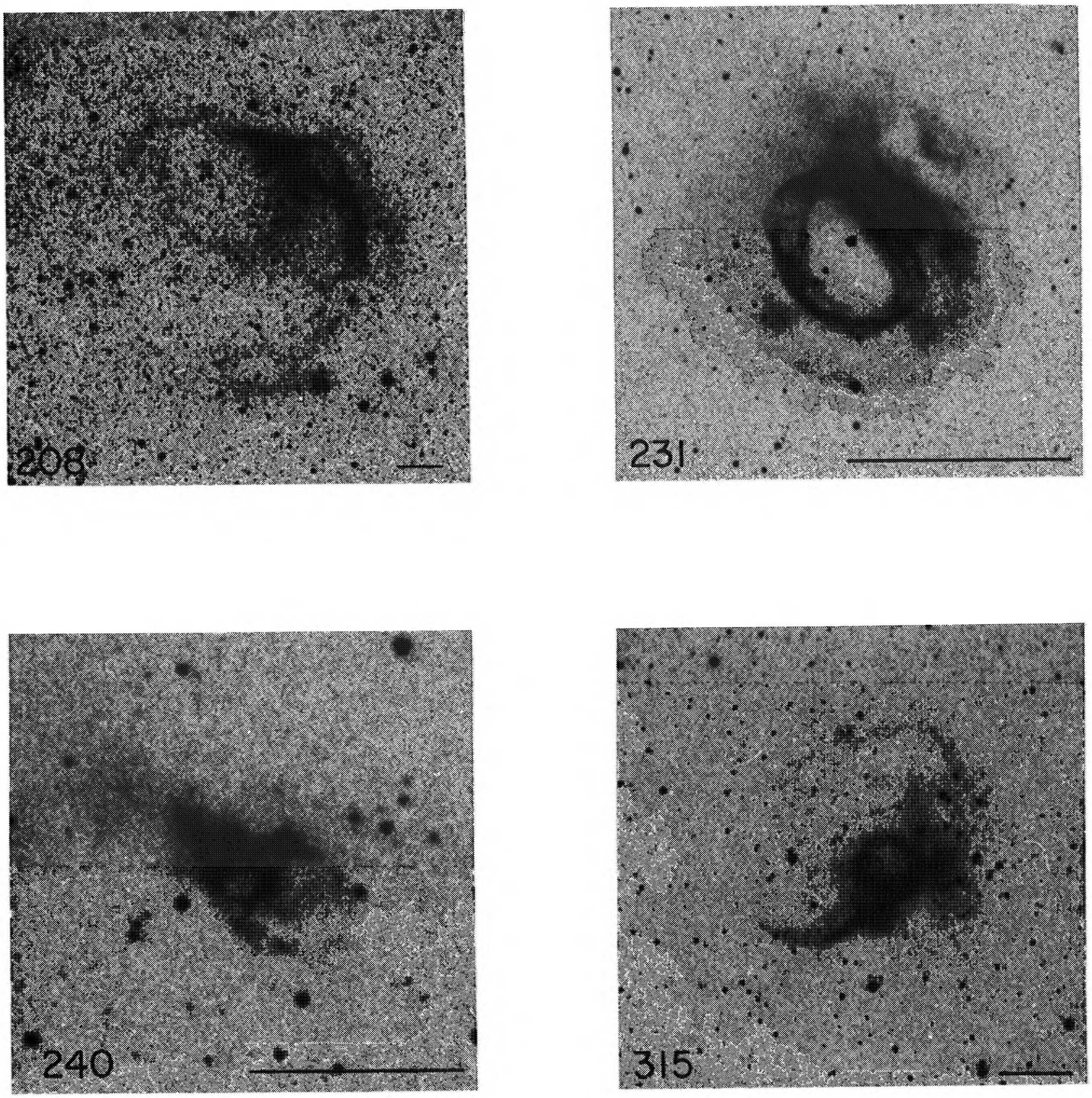

FIG. 1—Photographs of the ring nebulae in the light [O III] λ5007. The individual prints are identified with DEM numbers, the WR stars are located by marginal tick marks, and the horizontal bars indicate 2′ on the sky.

by DEM. There are two arcuate filaments branching from the inner wall of the northwest rim; the brighter one merges into the north rim; and the fainter, into the west.

The stellar association LH62 (Lucke and Hodge 1970; Lucke 1974) has a relation to DEM208 that is analogous to that of LH42 to DEM 137. However, the HR diagram, which is typical of those for young LMC associations, is quite sparsely populated.

6. DEM231 (N57C) – FD43

DEM231 is a bright ring embedded in a diffuse H II region that appears dusty. The ring per se is elliptical with dimensions 24 by 16 pc. It is unusually small for the LMC, being only slightly larger than its Galactic counterparts. The photograph of DEM231 in Figure 1 was made through a 5007 Å filter (100 Å FWHM) at the

TABLE II

Wolf-Rayet Stars and Associated Ring-Nebulae in the Large Magellanic Cloud

Star Names		FD9	FD22	FD24	FD27	FD33	FD43	FD47	FD80
	(a)	FD9	FD22	FD24	FD27	FD33	FD43	FD47	FD80
	(b)	WS7	WS17	WS19	WS22	WS28	----	----	WS53
	Other	HDE268847	----	HD36063	HDE269485	----	HDE269748	HV5947	HDE270149
α (1950)	(a)	$5^h00^m.0$	$5^h20^m.5$	$5^h23^m.2$	$5^h24^m.7$	$5^h28^m.2$	$5^h33^m.2$	$5^h35^m.0$	$5^h46^m.7$
δ (1950)	(a)	-68°01'	-65°31'	-71°38'	-68°34'	-70°39'	-67°45'	-67°23'	-67°11'
Sp. Type	(a)	WN3-5	WN3-5	WN7	WN3-5	WN3-5	WN3-5	WN3-5	WN3-5
	(c)	----	WN4	WN6	WN4	WN3	WN2-3	WN3 + O	WN4
m_v	(a)	14.36	14.95	12.72	14.80	14.18	13.01	13.2	14.63
H II region	(d)	DEM45	DEM137	DEM165	DEM174	DEM208	DEM231	DEM240	DEM315
	(e)	N16A	----	N198	N138	N204	N57C	N56	N74
Diameter	(d)	8 x 7'	17 x 13'	8 x 6'	4 x 4'	14 x 13'	4 x 3'	2 x 1.5'	7 x 6'
[S II] &[O III] Strengths	(f)	0, 3	1, 2	1, 2	1, 2	0, 1	0, 3	0, 3	0, 2-4

NOTES: (a) Fehrenbach et al. (1976), (b) Westerlund and Smith (1964), (c) Conti (1980), (d) Davies, Elliott and Meaburn (1976), (e) Henize (1956), and (f) Lasker (1979a). Except as noted in the text, all WS stars are designated as LMC "field" by Westerlund and Smith (1964).

prime focus of the CTIO 4-m telescope.

Recent works by Meaburn (1978) and by Meaburn and Blades (1980) interpret DEM231 as a wind-blown bubble encroaching into a cloud; this picture, which is supported by Taylor's (1978) recognition that the central star is a WR, is considered further in section III. This star, FD43 has been reclassified as WN3 (+OB?) by Walborn (1980), who also remarks that a radial-velocity study is required to determine whether its spectrum corresponds to one or two stars.

7. DEM240 (N56) – FD47

DEM240 is the smallest nebula in our list; it is very bright in [O III]. The two stars on the north rim are R120 (B8 I, 10.9 m_{pg}) and R121 (A2 I, 10.6 m_{pg}; Feast, Thackeray, and Wesselink 1960); while such stars are insignificant (compared to WRs) as UV sources, they can contribute a small amount to the mass flux into the nebula (Barlow and Cohen 1977).

Plate III of DEM shows that the northern edge of DEM240 (together with segments of DEM182, 200, 214, 212, 234, 257, 244, etc.) is on the periphery of the large (~ 1°) ring that lies about the blue stars in the southern part of Constellation III (Nail and Shapley 1953; sketched in Bok 1966).

8. DEM315 (N74) – FD80

The overall morphology of DEM315 is like that of NGC 2359 (Pismis et al 1977); it has an inner ring of higher excitation and an outer arcuate H II region of lower excitation. The inner shell of DEM315 has diameter of 25 pc; and the outer H II region, 100 pc. FD80 is categorized by Westerlund and Smith (1964, WS53) as belonging to an LMC association. However, such an association is not cataloged by Lucke and Hodge (1970); and its reality is not apparent to us.

III. Discussion

The survey of WR stars in the LMC is complete except possibly for subclass WC5. Given the number of WR stars outside the 30 Dor region and the area covered by all shell nebulae satisfying criteria 1, 3, and 4, the number of WR stars expected to lie randomly inside all of the shell nebulae is about 1. If only preferred configurations (i.e., with the star toward the center) are allowed, the expected number is reduced to a quarter or less; and the probability for 8 stars to lie in ring nebulae by chance is less than 10^{-9}. Selection criterion 3 may be stretched somewhat for the case of DEM137 (with respect to LH43), DEM208 (LH62), and perhaps, DEM240 (R120, R121); however, it seems to us prudent to leave them in the present set, at least provisionally. Even the rejection of one or two objects from our set of eight would not qualitatively alter this conclusion i.e., that the stars and the ring nebula are physically related.

Although it is plausible that the ring nebulae are made by their WR stars, another obvious possibility is that the two kinds of objects merely have a common origin in the star-forming processes. The dynamical time scale for a ring to dissipate, 100 pc/10 km s^{-1} = 10^7 yr, is comparable to, or larger than, the time scales for the evolution of massive stars. Thus the WR phase alone need not dominate the life cycle of a ring nebula; the nebula could also be affected by earlier phases of the star that is now a WR or by the evolution of stars formed coevally.

The rings associated with WR stars in the LMC are much larger than the analogous nebulae in our Galaxy.

The LMC diameters range from 20 pc to 200 pc, while those of the Galactic ring nebulae are typically 10 pc or less. A 10-pc nebula subtends 38″ at the distance of the LMC and would be resolved and easily detected by the DEM system. This discrepancy in size distribution appears to be a real effect.

Nevertheless, it is interesting to examine further the hypothesis that the ring nebulae in both galaxies are wind-blown bubbles consisting of swept-up interstellar gas; dimensional estimates of the kinetic energy in the nebulae then give results of the order of $10^{49}\ n_0\ (r/50\ \mathrm{pc})^3\ (v/10\ \mathrm{km\ s^{-1}})$ ergs, where n_0 is the density of the ambient medium, r is the nebular radius, and v is the expansion velocity. Given reasonable guesses for n_0 and v ($n_0 = 0.5\ \mathrm{cm^{-3}}$ and $v = 10\ \mathrm{km\ s^{-1}}$), the kinetic energy of the largest ring nebula is still moderate compared to other energetic processes in the interstellar medium [ISM]. Since there are no systematic differences in the physical properties of WR stars between the Galaxy and the LMC (Smith 1968), we may apply typical Galactic values of mass loss rate ($10^{-5}\ \mathfrak{M}_\odot\ \mathrm{yr^{-1}}$) and wind velocity (2000 km $\mathrm{s^{-1}}$) for WR stars (Kwitter 1979) to the LMC cases; the mechanical energy input to the nebulae from stellar winds during the lifetime of the star then exceeds the kinetic energy cited above. Energetically, the large sizes of the LMC ring nebulae are acceptable. However, such large sizes require that the density in the ISM of the LMC be unacceptably small. The McGee and Milton (1964) 21-cm LMC survey gives interstellar densities of the order of 0.5–1 $\mathrm{cm^{-3}}$, whereas the factor of 10 discrepancy in ring sizes between the Galaxy and the LMC would require a LMC density of the order of 10^{-5} $\mathrm{cm^{-3}}$ in the Weaver et al. (1977) bubble model.

The rings around WR stars may also be considered in the broader context that the LMC contains other large ring-like objects that are not obvious supernova remnants (DEM). Apparently, conditions in the ISM of the LMC are more favorable to the appearance of large ring (or bubble) nebulae. Perhaps the ISM in the LMC contains large bubbles which appear as optical rings only when they are excited by UV radiation or winds from stars. Alternatively, perhaps the ISM consists of a highly porous arrangement of ordinary H I ($\sim 1\ \mathrm{cm^{-3}}$) and a rarefied hotter medium in pressure equilibrium, such that the dominant density for wind-driven dynamics is the lower one.

To the extent that the phenomena discussed here suggest that the ISM in the LMC may have significant spatial differences from that of the Galaxy, the most promising avenue for further understanding is likely to be new 21-cm work, perhaps combined with studies of the history of star formation (over, say, 10^6 yr) in regions where bubbles are detected.

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Note added in proof: Heckathorn and Gull (*Bull. A.A.S.* 12, 458, 1980) report some possible new Galactic WR rings; only two of them have photometric distances available, and the radii are less than 20 pc. These discoveries do not affect the conclusions in this paper.