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A SURVEY OF NEBULAE AROUND GALACTIC WOLF-RAYET STARS IN THE SOUTHERN SKY. I.[1]

A. P. MARSTON
Department of Physics and Astronomy, Drake University, Des Moines, IA 50311

AND

Y.-H. CHU AND G. GARCIA-SEGURA
Department of Astronomy, University of Illinois, Urbana, IL 61801
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ABSTRACT

Images are presented from the first half of a survey of all Galactic Wolf-Rayet stars in the catalog of van der Hucht et al. (1981) residing in the southern skies. Previous surveys used only existing broad-band photographic plates. Encouraged by successes using CCD imaging with interference filters of the LMC and northern Galaxy (Miller & Chu 1993), we have expanded the survey to the southern hemisphere. In the first half of our southern survey, Hα and [O III] narrow-band CCD images of fields centered on known Wolf-Rayet stars have indicated the existence of six new ring nebulae as well as revealing previously unobserved morphological features in the known ring nebulae. An example of this is an almost perfect ring of [O III] emission residing interior to the previously observed Hα filaments of the Wolf-Rayet ring nebulae RCW 104.

Our surveys to date indicate that 21% of all Wolf-Rayet stars have ring nebulae, with WN-type Wolf-Rayet stars having a greater likelihood for an associated ring.

Subject headings: ISM: general — stars: Wolf-Rayet

1. INTRODUCTION

Wolf-Rayet stars are some of the most powerful sources of stellar winds and ionizing ultraviolet radiation among massive early-type stars (Barlow 1982; Abbott & Conti 1987). As such, they frequently can have a profound effect on the surrounding interstellar medium, an example of which is the production of ring nebulae. Ring nebulae have been discovered around a number of Wolf-Rayet stars in systematic searches (Smith 1967; Chu 1981; Heckathorn, Bruhweiler, & Gull 1982) as well as serendipidously (e.g., Lortet, Niemela, & Tarsia 1980; Gonzalez & Rosado 1984). Table 1 of Miller & Chu (1993; hereafter MC) lists Wolf-Rayet stars in our Galaxy suggested as residing in ring nebulae. More detailed studies suggest that there are several types of ring nebulae (Chu 1990). Some ring nebulae contain interstellar material, and others containly mostly stellar material; some are shaped by the Wolf-Rayet wind and others by a progenitor wind.

These various types of ring nebulae may be used to study a number of astrophysical phenomena, such as the dynamical interactions of stellar winds with the interstellar medium and stellar ejecta materials. Photoionization models also allow the determination of effective temperatures (Rosa & Mathis 1990) and spectral shape of the photoionizing continuum of the central Wolf-Rayet stars.

Original ring nebula surveys used broad-band filters and photographic plates. These allowed low surface brightness nebulae to remain undetected. In our present study we improve our sensitivity to low surface brightness objects by using sensitive CCD detectors together with narrow-band filters centered on the Hα and [O III] 5007 Å optical emission-line wavelengths. MC have reported previously on the northern galaxy half of a complete survey of all Galactic Wolf-Rayet stars cataloged by van der Hucht et al. (1981). Here we report on the first part of our survey of the Wolf-Rayet stars of the southern Galaxy. Our survey's intent is to search for new ring nebulae, obtain high-quality images of known ring nebulae, and to examine the environments of all southern Galactic Wolf-Rayet stars. Our data will enable us to obtain better statistics on the occurrence of the different types of ring nebulae and any association that may exist between ring nebula type and Wolf-Rayet type. It will also indicate the kinds of environments in which Wolf-Rayet stars are likely to be found and which allow the production of ring nebulae.

In this paper describing the results from the first half of our southern survey, § 2 describes the observations and presents the results, § 3 discusses the ring nebulae observed, and § 4 summarizes our observations and results.

2. OBSERVATIONS AND RESULTS

The observations used in this paper were made during two service nights, 1992 April 22/23 and April 23/24, at the Curtis-Schmidt telescope of the Cerro Tololo InterAmerican Observatory (CTIO), Chile. Images were obtained using a Thomson 1024 × 1024 CCD with 19 μm pixels. The total field size was 31′, corresponding to a pixel size of 1″84 on the sky. Two filters, with bandwidths centered on the optical emission-line rest wavelengths of Hα (bandwidth = 17 Å) and [O III] 5007 Å (bandwidth = 22 Å) were used for imaging. Exposures of 600 s were used with the Hα filter. When nebulosity associated with

[1] Based on observations made at the Curtis Schmidt, CTIO. CTIO is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

the Wolf-Rayet stars were noted, further exposures were made in the light of the [O III] emission line. Exposures using the [O III] filter were of either 600 or 900 s. The strength of the [O III] line image relative to the Hα image was used as an indication of the degree of excitation level across the nebulae.

Data reduction included the standard bias subtraction and flat-fielding. This was performed under the IRAF (Interactive Reduction and Analysis Facility) system.

A total of 40 Wolf-Rayet stars were observed, comprising a total of 35% of all known Wolf-Rayet stars below a declination of $-10°$. Of these, seven showed evidence for surrounding ring nebulae and a further 21 were in areas of diffuse emission-line nebulosity. A summary of the observations made is presented in Table 1: column (1) lists the catalog number of the Wolf-Rayet star (van der Hucht et al. 1981); column (2) lists other names of the star; column (3) lists the spectral type of the star, as given by van der Hucht et al. (1988); columns (4) and (5) give the exposure times in the Hα + [N II] and [O III] filters, respectively; column (6) gives the figure number, if images are presented in this paper; column (7) presents brief comments on the results. Comments on the field indicate the presence, or otherwise, of nebulosity in the fields and its possible association with the central Wolf-Rayet star.

Images of objects with visible nebulosity are shown in Figures 1–10. On all images north is up, and east is to the left.

3. OBSERVED WOLF-RAYET RING NEBULAE

Eleven of the 40 Wolf-Rayet stars surveyed exhibited ring nebulae phenomena. Of these, five were previously known, and six are probable or possible new ring nebula. One of the five previously known nebulae has now been shown to have an almost complete [O III] ring which was not seen previously. In this section we shall discuss the observed ring nebulae in turn.

WR 6—S308.—This previously known ring nebula is actually too large for the array used and is only partially observed in our survey. Our imaging was done solely in Hα. Detailed observations were previously made by (Chu et al. 1982). A new CCD image of this nebula was obtained by Miller (1993).

WR 7—NGC 2359.—See Figure 1 (Plate 7). The dynamics of this complex nebula were studied by Treffers & Chu (1982) who indicated it was a slowly expanding shell. To the east, the ring nebula shell is apparently interacting with a dense molecular cloud (Schneps et al. 1981). Marston (1991) suggests the ring nebula contains several hundred solar masses, inferred from far-infrared measurements, mostly in the form of neutral material. Our new Hα and [O III] CCD images show extended (~10 pc across) nebulosity associated with the nebula. The filaments show a very anisotropic distribution. The lack of [O III] emission in these filaments indicates they are of low excitation.

TABLE 1

SUMMARY OF THE SOUTHERN SURVEY DATA TAKEN IN 1992 APRIL

Star	Other Designation	WR type	Hα (secs)	[OIII] (secs)	Fig. #	Comments
WR6	EZ CMa	WN5	600	-		S308; ring nebula
WR7	HD56925	WN4	600	600	1	NGC 2359; ring nebula
WR8	HD62910	WN6+WN4	600	600		Superposed on diffuse HII
WR9	HD63099	WC5+O7	600	-		Near diffuse nebulosity
WR10	AS 193	WN4.5	600	-		No nebulosity
WR12	Ve 5-5	WN7	600	600		Superposed on extended diffuse Hα; filamentary [0 III]
WR13	Ve 6-15	WC6	600	-		Maybe diffuse nebulosity superposed on SNR
WR23	HD92809	WC6	600	600	2	Anon (MR26); ring nebula
WR24	HD93131	WN7+abs	600	600		In Carina Neb; no ring nebula
WR25	HD93162	WN7+abs	600	600		In Carina Neb; no ring nebula
WR26	-	WCE+WN5	600	600		In faint diffuse nebulosity; no/faint [0 III]
WR27	-	WC6+abs	600	600		North of Carina; superposed in diffuse emission
WR28	TH 35-112	WN7	600	900		Northern Carina; dusty; [0 III] emission; no sharp features
WR29	TH 35-117	WN7	600	600		Superposed on eastern Carina; faint/no [0 III]
WR41	-	WC5	600	600		Superposed on extended HII region; faint [0 III]
WR45	-	WC6	600	600		Superposed N of RCW62; no [0 III]
WR46	HD104994	WN3pec	600	-		No nebulosity
WR49	TH 17-22	WN5	600	600		In diffuse Hα; extended [0 III] filaments; SNR?
WR50	TH 17-84	WC7+abs	600	600		Near RCW75; background Hα; no [0 III]
WR51	TH 17-85	WN4	600	600		Near RCW75; background
WR52	HD115473	WC4	600	600	3	Diffuse ring nebula in MR46; faint [0 III]
WR53	TH 17-88	WC8	600	600		Diffuse HII; no [0 III]
WR54	TH 17-89	WN4	600	900	4	Possible new ring seen in Hα; no [0 III]
WR55	TH 17-90	WN7	600	900	5	RCW78; ring HII; some diffuse [0 III]
WR62	WRA 16-154	WN6	600	-		No nebulosity
WR63	-	WN6	600	600		Diffuse Hα; no [0 III]
WR64	-	WC7	600	-		No nebulosity at all
WR65	WRA 1297	WC9	600	600	6	Possible new ring in diffuse Hα; dusty; no [0 III]
WR67	-	WN6	600	600		The star is to the south of the CCD frame.
WR68	-	WC7	600	600	7	Possible new ring! no [0 III]
WR74	-	WN7	600	600		Near diffuse HII; no [0 III]
WR75	HD147419	WN5	600	900	8	RCW104; ring nebula; beautiful [0 III] ring
WR76	-	WC9	600	900		In faint diffuse Hα; no [0 III]
WR85	HR6392B	WN6	600	600	9	Ring associated with RCW118; no filaments; no [0 III]
WR86	TH 10-11	WC7+abs	600	600		Near RCW130; diffuse Hα; no [0 III]
WR88	The 1	WC9	600	600		In diffuse HII; dusty; no [0 III]
WR90	HD156385	WC7	600	600		In diffuse Hα; no [0 III]
WR95	He 3-1434	WC9	600	900		In dusty region; diffuse Hα; faint/no [0 III]
WR98	HDE318016	WC7+WN6	600	600	10	Diffuse ring of Hα; dusty; very faint [0 III]
WR100	HDE318139	WN6	600	900		Maybe diffuse Hα; no [0 III]

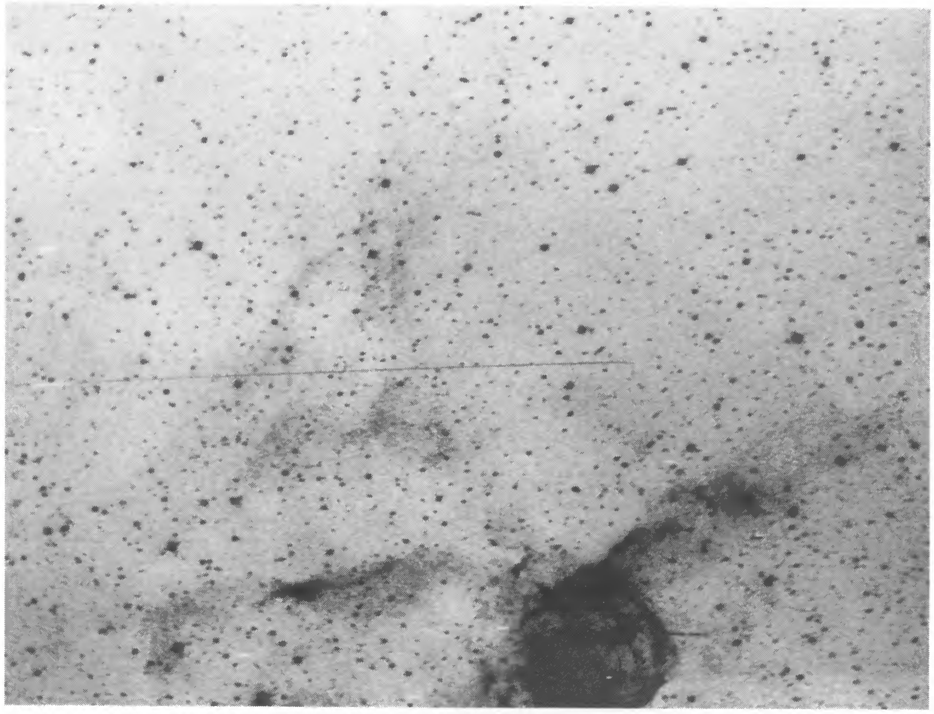

FIG. 1.—An Hα image of the nebula NGC 2359 surrounding the Wolf-Rayet star HD 56925. Diffuse ionized filaments are seen to extend distances of approximately 15 pc from the star (assuming a distance of 5 kpc).

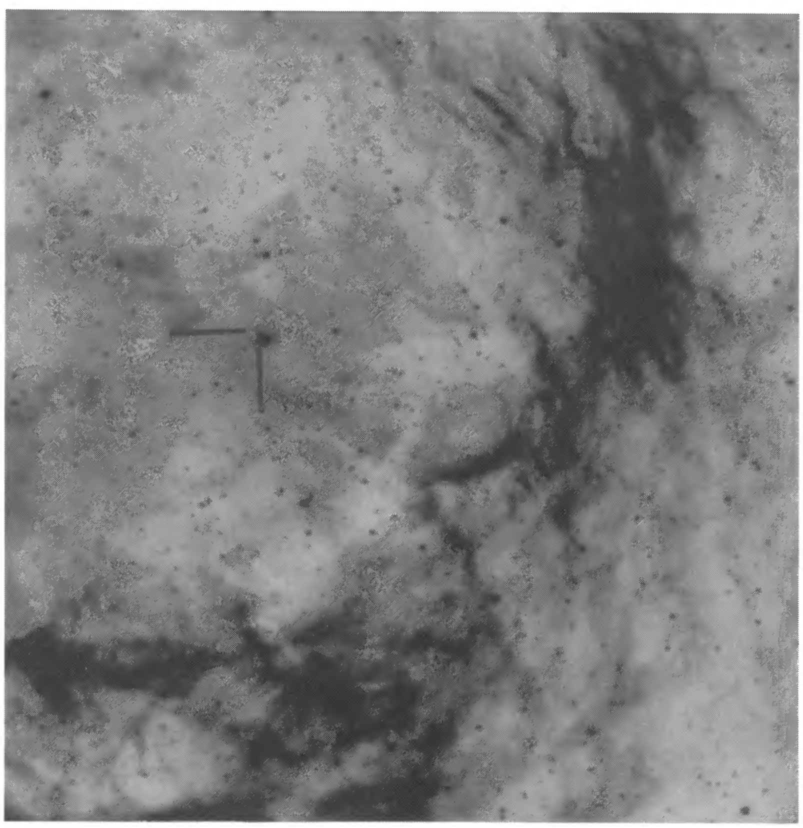

FIG. 2.—Hα image of MR 26 about the Wolf-Rayet star HD 92809. The apparent size of the shell is larger than that of the array. A strong, filamentary ridge of emission is noted to the west of the Wolf-Rayet star.

See MARSTON, CHU, & GARCIA-SEGURA (93, 230&231)

WR 23—Anon (MR 26).—See Figure 2 (Plate 7). Our Hα image of this nebula, centered on the Wolf-Rayet star WR 23, shows a shell >30′ across which appears unbroken. Only part of the ring is seen, with WR 23 being off center. The [O III] image shows more diffuse emission toward the western edge, with a similar morphology to that of the Hα.

The comparative morphologies of the Hα and [O III] suggest that the nebula contains clumps of low excitation materials. In NGC 6888, Marston & Meaburn (1988) showed that clumps of lower velocity gas had high [N II]/Hα ratios. They suggested that this was due to the ring of NGC 6888 expanding past clumps of more dense interstellar gas which would slow the expansion and have reduced excitation levels. Something similar may well be happening in MR 26, with low-excitation material existing in parts of the nebula where expansion is being made into denser parts of the surrounding medium.

WR 52—Anon (MR 46).—See Figure 3 (Plate 8). A possible new ring nebula. A faint shell with an apparent size bigger than the CCD array is visible in the Hα image. Our CCD view shows the southern half of the ring which is also shows up faintly in [O III].

WR 54—Anon.—See Figure 4 (Plate 8). A possible new ring. A faint Hα ring, highly elongated (axial ratio of 2, $20' \times 10'$, PA $\sim 45°$) centered on the Wolf-Rayet star. An area of diffuse emission to the north east of the CCD frame obscures the northern edge of the ring.

WR 55—RCW 78.—See Figure 5 (Plate 9). The WR star WR 55 sits toward one edge of the nebula RCW 78. The faint Hα loops appear to surround the star, although the eastern edge of the nebula cannot be seen on our image. The western rim of the nebula is much brighter than the eastern rim. This may be attributed to the proximity of the exciting WR star. However, the nebular morphology is very reminiscent of NGC 3199, where it has been suggested that the nebula is partially the product of a bow shock in front of the fast-moving WR star WR 18 (Dyson & Ghanbari 1989). Alternatively, a major density gradient may exist in the ambient medium, where higher density ISM to the west of WR 55 has prevented the ring nebula from expanding very far, while to the east expansion is occurring at a faster rate.

Diffuse [O III] emission is seen in the western rim of the ring. No [O III] emission is noted outside the ring. All higher excitation materials therefore appear to be inside RCW 78.

WR 65—Anon.—See Figure 6 (Plate 9). WR 65 has a possible new ring nebula associated with it. A diffuse ring of Hα emission arcs exists around WR 65 to the east and south of the star. However, the existence of a large patch of Galactic Hα emission along the eastern edge of our Hα CCD image makes the identification of a ring more tentative. No [O III] emission is present.

WR 68—Anon.—See Figure 7 (Plate 10). Nebulosity surrounding WR 68 suggests the existence of another new ring nebula. Loops of Hα emission are seen to the east of WR 68. These continue around to a more diffuse loop to the south of the star.

Significant dust is noted in images of the region which may be causing the obscuration of the western portion of the nebula and which may also lead to the lack of observed [O III] emission.

WR 75—RCW 104.—See Figure 8 (Plate 11). Our Hα image shows a filamentary nebula associated with WR 75. Towards the south and north of the nebula there is a conspicuous lack of filaments which suggests a possible blow-out. The deep Hα image shows the nebula to be an irregularly shaped bubble with several sharp filaments which suggest ionization or shock fronts. Our [O III] image presents a very different picture. The [O III] emission forms an almost complete ring around WR 75, which is located only slightly toward the western edge of the ring. The [O III] bubble appears to reside inside the Hα filaments. Its sharp edge suggests that an ionization/shock front resides inside the extended Hα filaments. Comparing the Hα and [O III] images, the [O III] emission lying just interior to a diffuse inner Hα ridge rather than the bright, outer filaments.

In Marston (1991) an excitation stratification was suggested for a number of ring nebulae, based on far-infrared emission from the nebulae, and the likelihood of associated neutral gas mass. RCW 104 shows clear evidence for just such an excitation stratification. The structure also suggests the creation of a fast Wolf-Rayet wind inside a previously existing cloud matter possibly coming from the red supergiant ejecta produced by the star at an earlier epoch (Garcia-Segura & Mac Low 1993).

WR 85—RCW 118.—See Figure 9 (Plate 12). A ring nebula noted by Heckathorn et al. (1982). The bright Wolf-Rayet star, WR 85, is off-center in our image. A diffuse ring of Hα emission makes an almost complete semicircle approximately 25′ in diameter about the star. A similar ring is hinted in the [O III] image.

WR 98—Anon.—See Figure 10 (Plate 12). A possible new ring. A faint ring is discernible to the south and east of large-scale Galactic emission, with the Wolf-Rayet star off-center to the north. The ring is approximately 10′ across.

4. DISCUSSION AND SUMMARY

We have presented results from the first half of our survey for ring nebulae around Wolf-Rayet stars in the southern galaxy. It has revealed the presence of five probable or possible new ring nebulae and a previously unknown [O III] shell in the filamentary ring nebula RCW 104.

Of the five new ring nebulae observed one is associated with a WN- and three with WC-type central stars, while one exists around a WN+WC pair (WR 98). A total of 21 ring nebulae have been observed in our galactic surveys to date (12 from MC, and 11 in this paper, two overlap). These comprise 21% of the 99 galactic Wolf-Rayet stars surveyed so far. Of these, 13 are associated with WN stars (24% of those observed), six with WC stars (15% of those observed), one with a WO star (50% of those observed) and one ring exists around a WN+WC pair. The results so far suggest a bias exists toward the creation of ring nebulae around WN stars.

Garcia-Segura & Mac Low (1993) suggest that Wolf-Rayet ring nebulae produce expanding bubbles which interact with an anisotropic distribution of materials surrounding the star previously left behind by the slow, heavy, red supergiant wind. The fast wind of the Wolf-Rayet phase then forms the ring inside this environment. This may explain the morphology of NGC 2359 where a shell can be seen formed inside a region of

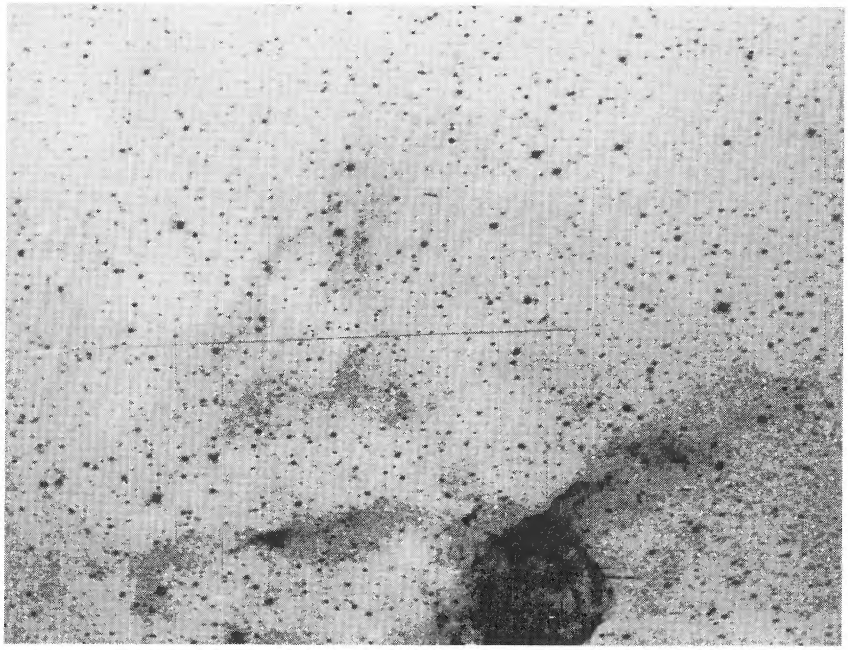

FIG. 1.—An Hα image of the nebula NGC 2359 surrounding the Wolf-Rayet star HD 56925. Diffuse ionized filaments are seen to extend distances of approximately 15 pc from the star (assuming a distance of 5 kpc).

FIG. 2.—Hα image of MR 26 about the Wolf-Rayet star HD 92809. The apparent size of the shell is larger than that of the array. A strong, filamentary ridge of emission is noted to the west of the Wolf-Rayet star.

See MARSTON, CHU, & GARCIA-SEGURA (93, 230&231)

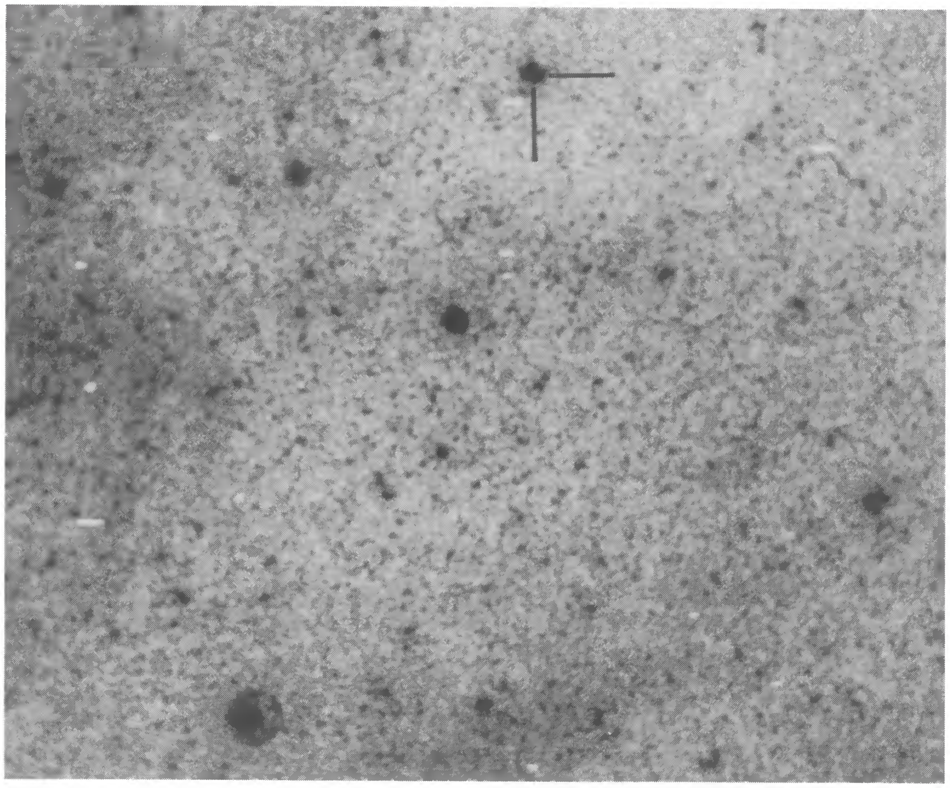

FIG. 3.—Our Hα image shows a possible ring nebula associated with HD 115473 with an angular size larger than our array. Our image shows the southern portion of this ring.

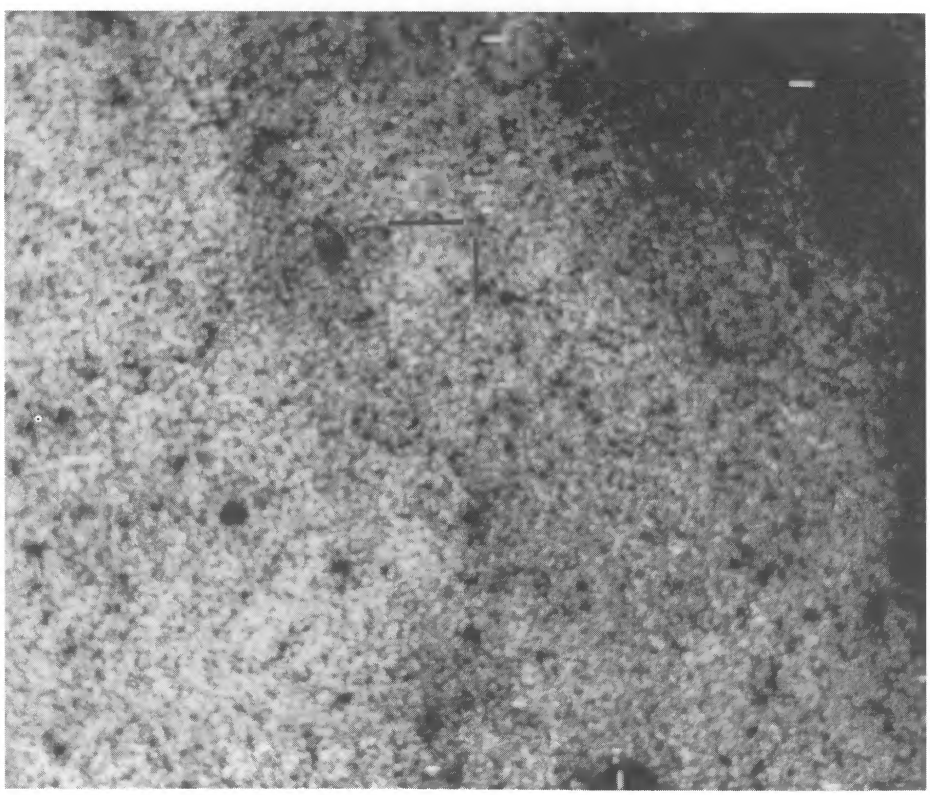

FIG. 4.—A possible new ring nebula around the WR star TH 17-89 is shown faintly in Hα

See MARSTON, CHU, & GARCIA-SEGURA (93, 231)

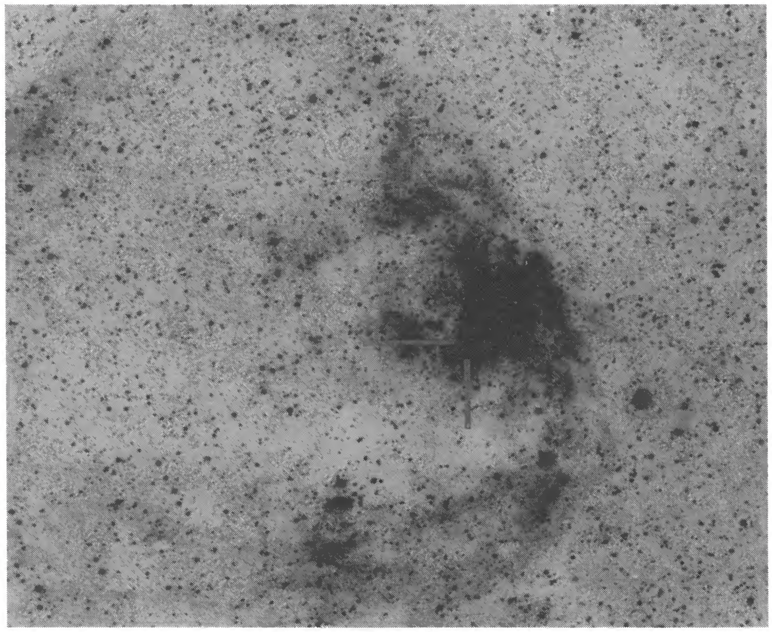

FIG. 5.—The nebula RCW 78 surrounding the WR star TH 17-90 seen in Hα

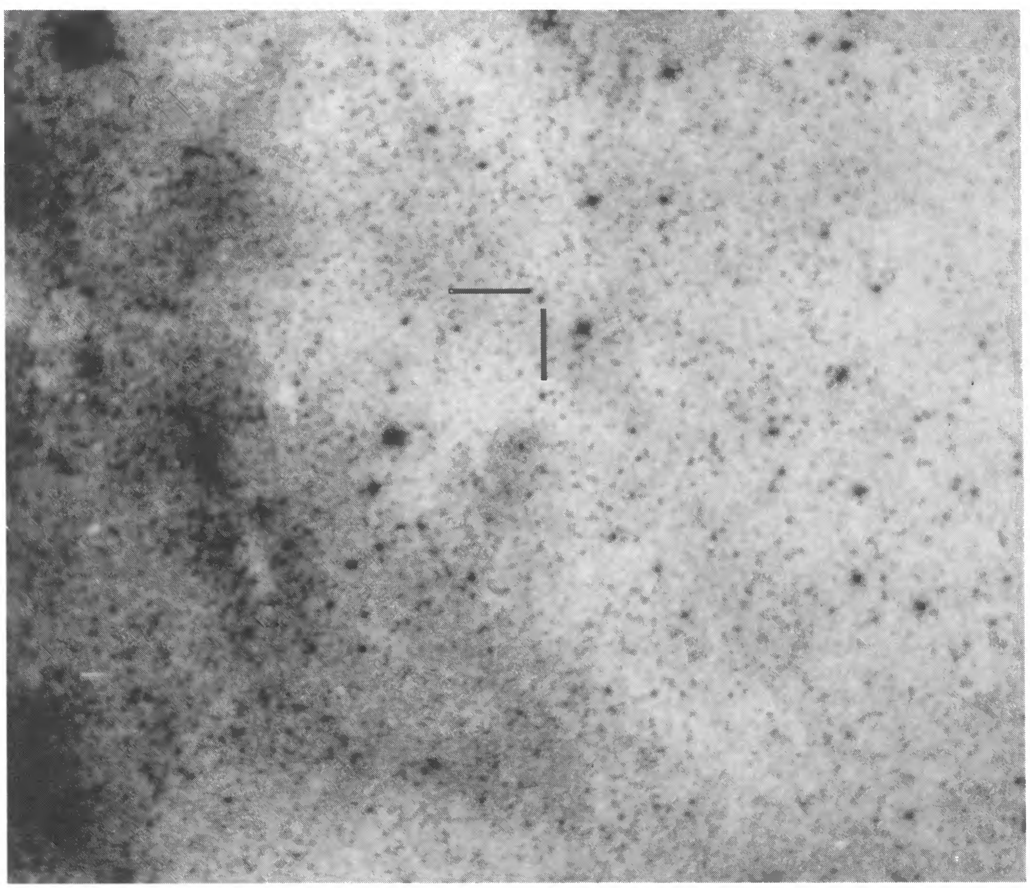

FIG. 6.—Another possible new ring nebula, here seen in Hα around the WR star WRA 1297

See MARSTON, CHU, & GARCIA-SEGURA (93, 231)

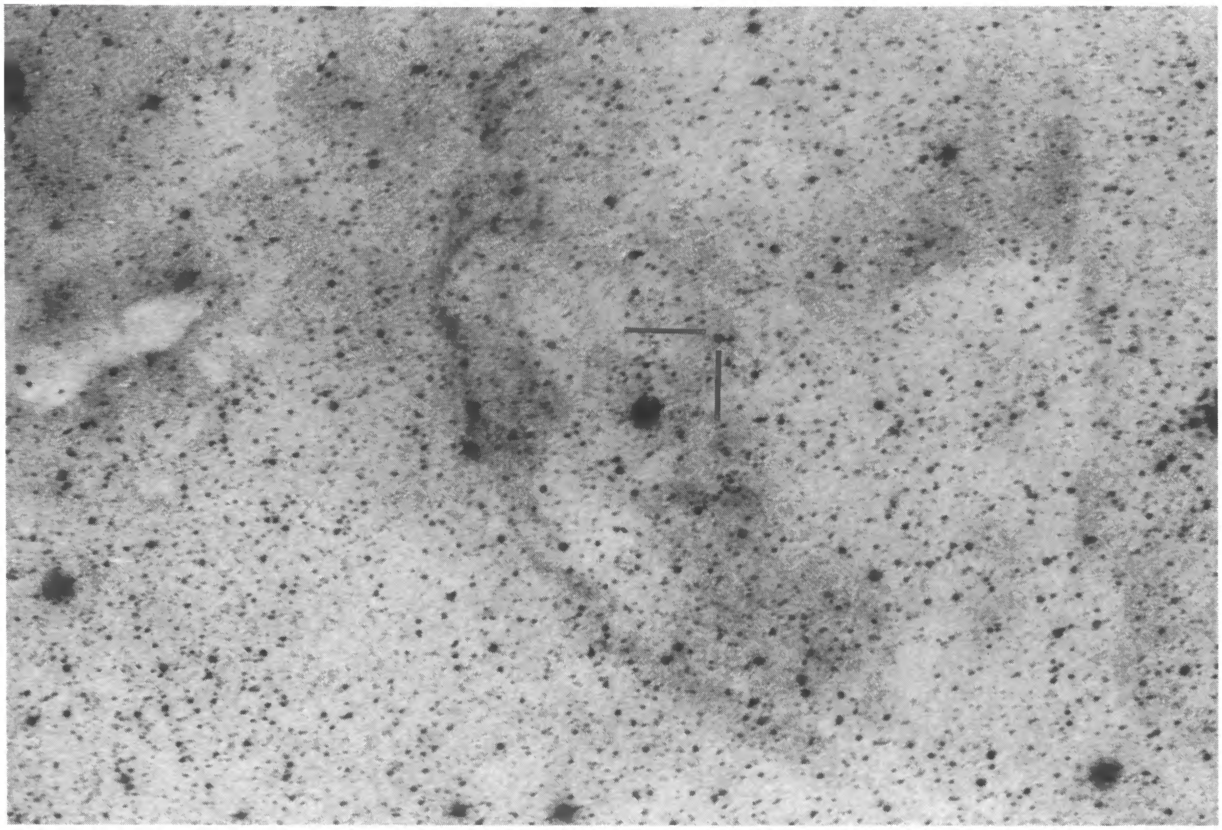

FIG. 7.—A new ring nebula surrounding WR 68 seen in Hα

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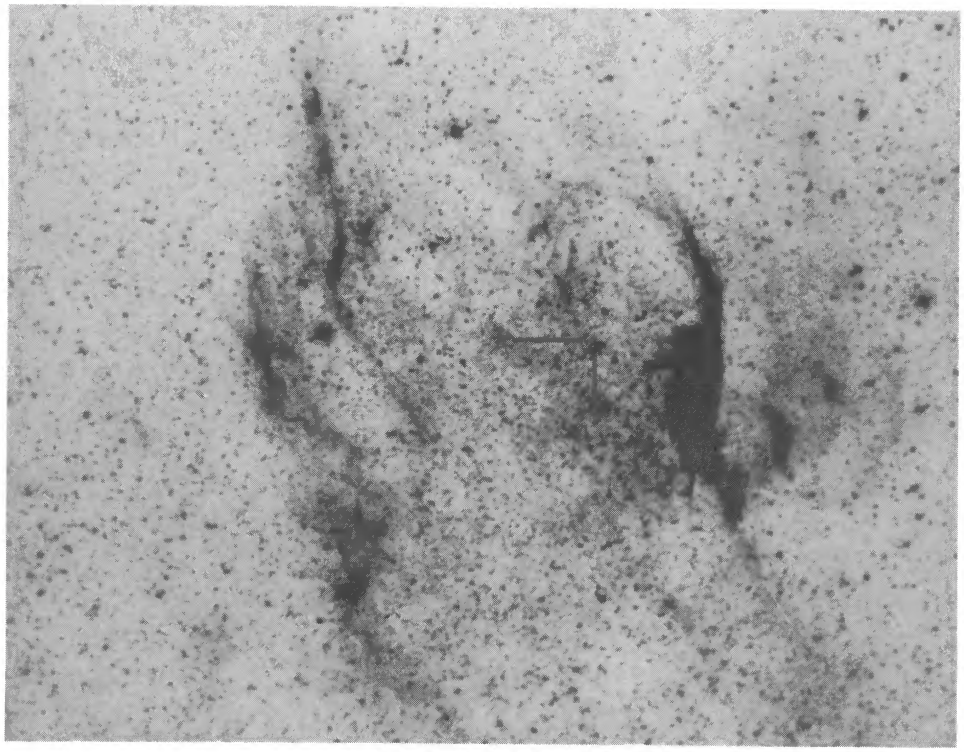

FIG. 8*a*

FIG. 8*b*

FIG. 8.—The ring nebula RCW 104 around the W-R star HD 147419 seen in Hα (*a*) and [O III] (*b*). The [O III] ring interior to the nebula is shown for the first time. It resides interior to the Hα filaments and suggests an excitation stratifiation exists in the nebula.

See MARSTON, CHU, & GARCIA-SEGURA (93, 231)

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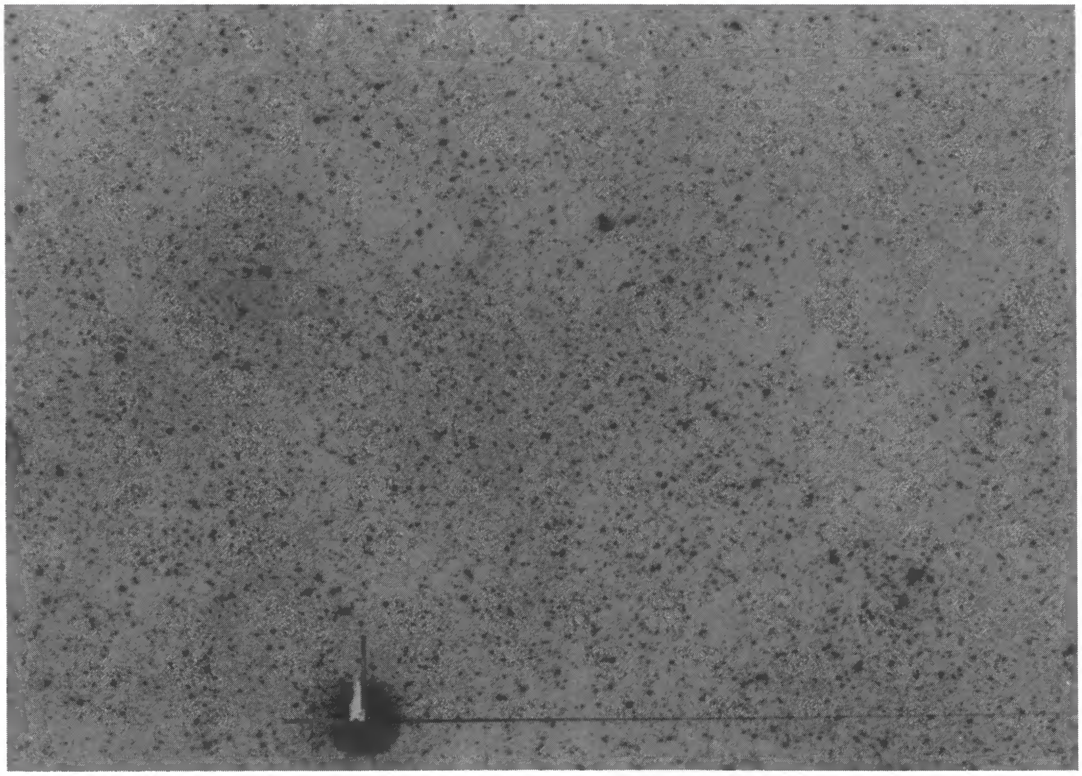

FIG. 9.—Ring nebula seen in Hα, approximately 25′ across, associated with HR 6392B

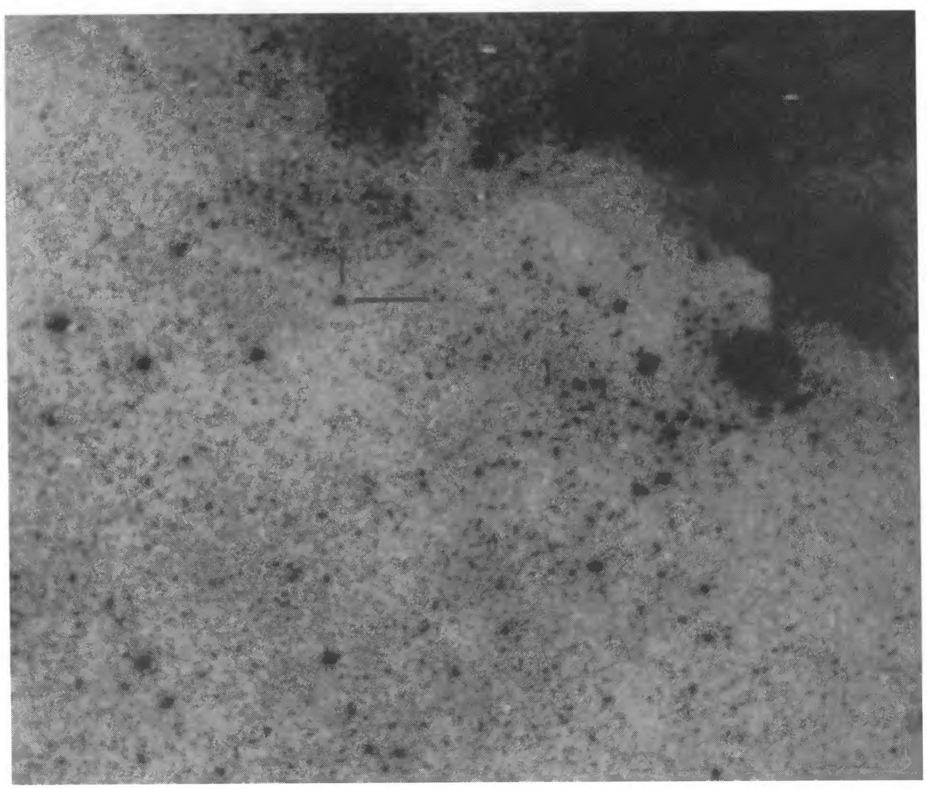

FIG. 10.—A faint ring nebula seen in Hα around HDE 318016

See MARSTON, CHU, & GARCIA-SEGURA (93, 231)

diffuse emission distributed about the central Wolf-Rayet star. Diffuse Hα emission associated with Wolf-Rayet stars, such as NGC 2359, is likely caused by the ionization of surrounding interstellar matter.

The sharp ring of [O III] emission associated with RCW 104 suggests an ionization front exists in the nebula for high-excitation photons. The nebula is so dense that all the high-excitation photons are used up in a thin layer (which is similar to the proposal by Marston 1991). This layer could be formed close to the boundary of the Wolf-Rayet ring and the outer, undisturbed red supergiant debris.

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