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A NEW SEARCH FOR NEBULAE SURROUNDING WOLF-RAYET STARS

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ABSTRACT

We have used a comprehensive narrow band emission line survey of the Milky Way to search for nebulosities surrounding Wolf-Rayet stars. Fifteen ring nebulae have been definitely identified, including five previously unreported shell structures. An additional 30 nebulosities have been classified as "probable" or "possible" ring nebulae. Angular diameter, sharpness or diffuseness, and level of brightness in three emission line bandpasses (Hα + [N II], [O III], and [S II]) have been determined for each nebulosity detected. Eleven of the 15 definite ring nebulae are as bright or brighter in the [O III] λ5007 bandpass than in Hα + [N II], and are filamentary in [O III]. Five selected shell structures are discussed in detail.

Analysis of these data reveals a tendency for nebulae surrounding early WN stars to be brighter in [O III] than in Hα + [N II], while nebulae surrounding late WN stars tend to be brighter in Hα + [N II] than in [O III]. Of the ring nebulae presently identified, three are associated with WC stars, and at least two are binaries.

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

I. INTRODUCTION

Observational data on Wolf-Rayet stars and associated nebulae present an intriguing array of astrophysical problems. Radio and infrared data show the mass loss rate of a typical Wolf-Rayet star to be $\dot{M} \sim 3 \times 10^{-5} M_{\odot}$ yr^{-1} (Barlow, Smith, and Willis 1981), which is much greater than that of a normal O star ($\dot{M} \sim 10^{-6} M_{\odot} \mathrm{yr}^{-1}$). Ultraviolet and visual spectroscopy have presented line profiles consistent with high velocity ($1\text{–}3 \times 10^3$ km s^{-1}) stellar winds (Barlow, Smith, and Willis 1981). Such stellar winds should interact with the surrounding interstellar medium forming shock fronts or interstellar bubbles (Weaver *et al.* 1977). Evidence of such shock fronts is visible in both broad and narrow bandpass imagery. Indeed, ring nebulae or shell-like structures have been observed around a few Wolf-Rayet stars in the past.

Most of the previous searches for these ring nebulae have depended upon the red plates of the Palomar Observatory Sky Survey (POSS) for the part of the sky observable from the northern hemisphere, and upon the Hα emission line survey of Rodgers, Campbell and Whiteoak (1960, herein RCW) for the southern Milky Way. The two major searches for nebulosities noted nine possible ring nebulae (Smith 1967; Crampton 1971). Several individual reportings in recent years have brought the number of known ring nebulae around Wolf-Rayet stars to thirteen (van der Hucht *et al.* 1981).

The data for these previous searches were not uniform for the entire Milky Way. The red plates of the POSS, while having a few arc seconds of angular resolution, were recorded through a filter with a passband extending over several hundred angstroms. The RCW survey, however, was recorded using a 100 Å wide passband filter, but with the angular resolution on the order of a few arc minutes.

II. THE SURVEY DATA

We determined to search again for ring nebulae, using the most up-to-date list of Wolf-Rayet stars (van der Hucht *et al.* 1981) and a uniform set of plate data. We used the narrow passband, low resolution survey plate data as published by Parker, Gull and Kirshner (1979 hereafter PGK). The data were recorded by a special wide angle telescope composed of interference filters before a 300 mm F2.8 Nikon lens coupled to a two stage image intensifier. The selected set of narrow passband interference filters was centered about the nebular emission lines of [S II] $\lambda = 6730$ ($\Delta\lambda = 50$ Å); Hα + [N II], $\lambda = 6570$ ($\Delta\lambda = 75$ Å); [O III] $\lambda = 5007$ ($\Delta\lambda = 28$ Å); Hβ $\lambda = 4861$ ($\Delta\lambda = 28$ Å); and the continuum at $\lambda = 4225$ ($\Delta\lambda = 60$ Å). The fields are 7°.1 in diameter positioned every 5° along the plane of the Galaxy at $b = 0°$ and also at $b = -5°$ and $+5°$ field centers. Angular resolution is about 30–40″ or better. Additional properties of the survey data are summarized in PGK.

The emission lines isolated by the filters were chosen to enable us to learn as much as possible about the ionized gas structures in the interstellar medium by using some of the brightest characteristic nebular emission lines. Generally, detectable Hα + [N II] emission implies ionized

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gas with an emission measure $> 25\ \text{cm}^{-6}$ pc (Chu 1981). Diffuse [O III] emission probably indicates photoionization with significant far ultraviolet radiation present. Sharp filamentary [O III] structure in the absence of diffuse [O III] emission, however, indicates shock driven gas with a shock velocity $> 70\ \text{km s}^{-1}$. Interstellar bubbles have been detected as hollow cavities bounded by sharp [O III] filaments within H II regions (Bruhweiler *et al.* 1981; Gull and Sophia 1979). The [S II] emission is characteristic of low photoionization, of ionization boundaries, or of slow shock velocities. Where much Hα + [N II] emission was noted, additional passbands isolating Hβ and blue continuum were used to review the structural data.

III. OBSERVED NEBULOSITIES

The PGK survey includes all but three of the 159 Wolf-Rayet stars listed by van der Hucht *et al.* (1981) within its boundaries. The excluded stars are HD 50896, WRA 16-206, and Sanduleak 3. We present additional data for HD 50896 and for γ^2 Vel which were obtained after the PGK survey was completed.

We searched for shell nebulae in the following manner. First, we adapted FINDER, which is an overlay program utilizing the SAO catalogue to plot adjustable field sizes and plate scales. This program was kindly provided by D. C. Wells. We used this FINDER program to create a computer-generated overlay for each Wolf-Rayet star with the coordinates listed by van der Hucht *et al.* (1981). This finding chart, plotted at the PGK Atlas scale, was overlaid onto first positive prints in order to locate the Wolf-Rayet star. Then, a visual inspection was made of each field using the original plates in all bandpasses. The entire field was searched for nebulosity and for any hint of shell structure or related symmetrical nebulosity that might be associated with the star.

We delineate between structures that are formed by the weak shocks of expanding H II regions (Lasker 1966, 1967) and the strong shock processes linked to high velocity stellar winds. While low density cavities result from both mechanisms, the strong shock processes leave a hot, extremely low density cavity devoid of any diffuse nebular emission abruptly bounded by an observable shell composed of swept-up interstellar debris (Weaver *et al.* 1977). The strongest of these wind-driven shock processes can result in a filamentary appearance to the surrounding shell. It is these shells which show trademarks of high mass loss that are the object of our search.

Table 1 contains the results of this search for all Wolf-Rayet stars that showed any hint of shell structure.[3] Columns (1)–(3) are pertinent data concerning each star, as given in van der Hucht *et al.* (1981). The nebulosity information deduced from each bandpass is given in columns (4)–(6). The brightness evaluation is designated by a seven-level system, ranging from "vvb" (brightest) to "vvf" (faintest). Nondetection is indicated by "nd." Whether the nebulosity is sharp (s) or diffuse (d) is also noted. The diameter of the observed emission in arc minutes is recorded. This information is provided for each emission line plate: Hα + [N II], [O III], and [S II].

In column (7), a "credibility" rating was assigned. Three major criteria were used to evaluate each nebulosity:

1. Sharp, filamentary structure present in any or all passbands. Filamentary structure in [O III] carried the most weight in this portion of the evaluation; Hα filaments were secondary; and [S II] filamentary structure carried the least weight.
2. Wolf-Rayet star centered in projected nebulosity or, if off-center, the segment of the ring nearest the star proportionally brighter than the rest of the ring.
3. Absence of O stars within the nebulosity, or O star in off-centered position not adjacent to the brightest or sharpest portion of the ring.

Values of "5" to "1" were assigned depending of how well the nebulosity satisfied the criteria named above. Values of "5" and "4" were interpreted to mean definite, well defined shell structures on the original plate data of PGK. A credibility rating of "3" represented a probable shell structure, although the available evidence is not conclusive. Ratings of "2" or "1" indicated possible shell structures, or possible association of a shell structure with the Wolf-Rayet star. Many of these structures with ratings of "3" or below are diffuse in nature and may result purely from photoionization without contributions from strong shock processes. Also, a number of these latter structures are possibly associated with an O star. Distances have been calculated for the Wolf-Rayet stars in Table 1 having an absolute magnitude calibration in the system of Turner and Smith as quoted by van der Hucht *et al.* (1981). The distances are recorded in column (8), and the linear diameters of the nebulosities are given in column (9).

Identification of nebulosity near a Wolf-Rayet star does not prove that the nebulosity is a product of the Wolf-Rayet star interacting with the interstellar medium. Indeed, an O star or an OB association just may be the primary source of ultraviolet radiation, stellar winds, etc. All O stars cataloged by Goy (1973) have been identified on prints and/or original plate material of PGK. We have noted those nebulosities in column (10) that contain an O star and that have at least an equal chance of being attributable to the O star or the Wolf-Rayet star.

The discovery papers for the previously identified Wolf-Rayet stars with ring nebulae have been indicated in column (11).

IV. DESCRIPTION OF SELECTED SHELLS

In Table 2 we have listed all Wolf-Rayet stars definitely associated with ring nebulae, and all Wolf-Rayet stars probably associated with ring nebulae, as determined in this paper. Below we discuss individually those stars having ring nebulae definitely associated with them and not previously identified in the literature.

[3] 209 Bac is one of the thirteen objects listed by van der Hucht *et al.* 1981 as having a symmetrical nebula. This star is not included among those identified with nebulosities in Table 1 because we could not detect a nebulosity using the low resolution PGK Survey. We are aware that nebulosity has been observed around this object, and we refer the reader to the relevant literature as outlined by van der Hucht *et al.* 1981.

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TABLE 1

NEBULOSITIES ASSOCIATED WITH WOLF-RAYET STARS

Name (1)	H II Region (2)	Sp. Type (3)	Brightness (4)	Diffuse or Sharp (5)	Diameter (arcmin) (6)	Credibility (7)	Distance (kpc) (8)	Diameter (pc) (9)	O Star (10)	Ref. (11)
HD 6327	...	WN2	Hα: f	d	85	1	...	...	...	
			[O III]: nd							
			[S II]: vf	d	85					
HD 50896	S308	WN5	Hα: bf	s	40	5	2.0	24	...	1,2
			[O III]: vg	s	40					
			[S II]: vf	s	40					
HD 56925	NGC 2359	WN4	Hα: f	d	26.8	5	5.3	41	...	1,2
			[O III]: vb	d	26.8					
			[S II]: vf	d	26.8					
			Hα: bf	s	7.3	...	...	11.3	...	
			[O III]: vb	s	12.2					
			[S II]: f	s	7.3					
HD 68273 .... = γ^2 Vel	"Gum"	WC8 + O9I	Hα: vvf	d	400	1	0.48	56	...	
			[O III]: nd							
			[S II]: nd							
			Hα: bf	s	176	3	0.48	25	...	
			[O III]: bf	s	176					
			[S II]: nd							
HD 76536	Gum 21	WC6	Hα: vb	s	3.7	1	3.5	3.8	x	
			[O III]: nd							
			[S II]: vf		3.7					
			Hα: vf	d	109	...	...	111	...	
			[O III]: vvf	s	109					
			[S II]: vvf	d	109					
HD 79573	...	WC6	Hα: vf	d	73	1	3.2	68	...	
			[O III]: nd							
			[S II]: vvf	d	73					
HD 88500	...	WC5	Hα: bf	s	85 × 158	1	8.0	198 × 368	...	
			[O III]: vvf	d	85 × 158					
			[S II]: vf	d	85 × 158					
HD 89358	NGC 3199	WN5	Hα: b	s	15.8 × 18	5	3.5	16 × 18	x	1
			[O III]: vb	s	15.8 × 18					
			[S II]: bf	s	15.8 × 18					
HD 92740	NGC 3372	WN7 + abs	Hα: b	s	30	5	2.3	20	...	
			[O III]: vb	s	24					
			[S II]: b	s	30					
HD 92809	Anon	WC6	Hα: vb	s	37	5	4.9	52	...	3
			[O III]: vf	d	30					
			[S II]: b	s	37					
HD 93131	NGC 3372	WN7 + abs	Hα: b	s	44 × 68	3	2.8	40 × 50	x	
			[O III]: vb	s	44 × 68					
			[S II]: vb	s	49 × 60					

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TABLE 1—*Continued*

Name (1)	H II Region (2)	Sp-Type (3)	Brightness (4)	Diffuse or Sharp (5)	Diameter (arcmin) (6)	Credibility (7)	Distance (kpc) (8)	Diameter (pc) (9)	O Star (10)	Ref. (11)
MS 5	...	WC5	Hα: bf	s	24	2	...	...	x	
			[O III]: bf	d	24					
			[S II]: f	d	24					
LS 6	...	WN4	Hα: bf	s	37	1	5.5	58	...	
			[O III]: bf	d	37					
			[S II]: bf	d	37					
HD 96548	RCW58	WN8	Hα: vb	s	6.1	5	4.1	7.3	...	1
			[O III]: f	s	6.1					
			[S II]: nd							
HD 97152	...	WC7 + O5 − 7	Hα: bf	s	7.2	2	...	...	...	
			[O III]: vf	s	7.2					
			[S II]: nd							
LSS 2423	...	WC6	Hα: f	d	2.5	2	9.9	7.2	x	
			[O III]: nd							
			[S II]: vf	d	2.5					
HD 113904 = 0 Mus	...	WC6 + O9.51	Hα: bf	s	73	5	...	...	...	
			[O III]: bf	s	67					
			[S II]: nd							
MR 44	RCW 75	WC6 + abs	Hα: b	s	8.5	1	6.8	13.8	x	
MR 45	RCW 75	WN4	[O III]: f	s	12.2					
			[S II]: bf	s	8.5					
HD 115473	...	WC5	Hα: bf	s	27	3	3.8	30	...	
			[O III]: f	d	27					
			[S II]: vvf	d	27					
HD 117688	RCW 78	WN8	Hα: bf	d	39	5	9.5	108	x	1
			[O III]: nd							
			[S II]: vvf	d	39					
			Hα: vb	s	6.1	...	...	17	...	
			[O III]: f	d	6.1					
			[S II]: vvf	d	6.1					
MR 55	...	WN6	Hα: f	s	22	2	...	...	...	
			[O III]: vvf	s	20					
			[S II]: vf	s	20					
HD 147419	RCW 104	WN4	Hα: bf	d	61	5	2.6	46	...	1
			[O III]: nd							
			[S II]: nd							
			Hα: vb	s	9.7	...	...	...	...	
			[O III]: f	d	8.5					
			[S II]: vf	d	8.5					
HD 151932	RCW 113	WN7	Hα: vb	s	195 × 158	1	1.8	102 × 83	x	
HD 152270	RCW 113	WC7 + O5 − 8	[O III]: nd							
			[S II]: vvf	d	195 × 158					
(HD 155603B)	RCW 118	WN6	Hα: bf	d	27	3	2.6	20	...	
			[O III]: f	d	27					
			[S II]: bf	d	27					

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TABLE 1—*Continued*

Name (1)	H II Region (2)	Sp-Type (3)	Brightness (4)	Diffuse or Sharp (5)	Diameter (arcmin) (6)	Credibility (7)	Distance (kpc) (8)	Diameter (pc) (9)	O Star (10)	Ref. (1)
HD 156385	RCW 114	WC7	Hα: f	s	73	1	...	...	...	
			[O III]: nd							
			[S II]: vvf	s	73					
St Sal	RCW 122	WP: r	Hα: vb	s	27	3	...	...	...	
			[O III]: nd							
			[S II]: vvf	d	27					
			Hα: vb	s	7.3	...	...	...	...	
			[O III]: nd							
			[S II]: vvf	d	7.3					
HD 157451	RCW 114	WC9	Hα: f	d	85	1	5.0	124	...	
			[O III]: vvf	d	85					
			[S II]: f	d	85					
HD 157504	NGC 6357	WC6	Hα: vvf	s	37	3	1.3	14	x	
			[O III]: f	s	37					
			[S II]: bf	s	37					
MR 74	...	WC9	Hα: vb	d	122	1	1.7	60	...	
			[O III]: f	d	85					
			[S II]: vvf	d	122					
LSS 4368	G2.4 + 1.4	WC4 pec	Hα: f	d	18	5	...	...	...	4
			[O III]: f	d	18					
			[S II]: f	d	18					
			Hα: bf	s	6.1	...	...	...	...	
			[O III]: vb	s	6.1					
			[S II]: nd							
HD 168206	S54	WC8 + O8 − 9	Hα: vb	d	122	2	...	...	...	
			[O III]: vf	d	85					
			[S II]: f	d	146					
			Hα: vb	s	12	...	...	...	...	
			[O III]: nd							
			[S II]: f	d	12					
MR 88	...	WC8	Hα: bf	d	49	2	...	...	x	
			[O III]: vvf	d	49 × 37					
			[S II]: vf	d	61 × 43					
HD 186943	S92	WN4 + O9	Hα: bf	d	27	3	...	...	...	
			[O III]: bf	d	27					
			[S II]: vf	d	27					
HD 187282	...	WN4	Hα: vvf	d	61 × 49	5	5.5	97 × 78	...	
			[O III]: f	s	61 × 49					
			[S II]: vvf	d	61 × 49					
			Hα: nd	s	20	5	...	32	...	
			[O III]: bf							
			[S II]: nd							
LS 16	S98	WN7	Hα: f	d	12	3	5.8	8.5	...	
			[O III]: nd							
			[S II]: nd							

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TABLE 1—*Continued*

Name (1)	H II Region (2)	Sp-Type (3)	Brightness (4)	Diffuse or sharp (5)	Diameter (arcmin) (6)	Credibility (7)	Distance (kpc) (8)	Diameter (*jc*) (9)	O Star (10)	Ref. (11)
			Hα: bf	s	12.2	3	0.7	2.5	...	5
MR 97	L69.80 + 1.74	WN7	[O III]: vvf	d	12.2					
			[S II]: vf	d	12.2					
			Hα: f	d	79 × 49	1	1.5	32 × 21	...	
HD 190002	Anon	WC6	[O III]: vf	d	73 × 39					
			[S II]: vf	d	73 × 49					
			Hα: vf	d	24	...	...	10.6	...	
			[O III]: vvf	d	24					
			[S II]: vvf	d	24					
			Hα: bf	d	17	5	1.6	8.0	...	5
HD 191765	S109	WN6	[O III]: vvf	s	17					
			[S II]: vf	d	17					
			Hα: vvf	s	12.2 × 17	5	1.2	4.3 × 6	...	1,2
HD 192163	NGC 6888	WN6	[O III]: vvf	s	12.2 × 17					
			[S II]: nd							
			Hα: vb	d	49	3	...	...	...	
HD 193576	S109	WN5 + O6	[O III]: vb	s	73					
			[S II]: bf	d	49					
		WC7 + abs	Hα: vb	s	73	3	...	...	...	
HD 193793	S109		[O III]: f	s	73					
			[S II]: bf	s	73					
			Hα: vf	s	7.3	1	...	...	...	
			[O III]: f	d	7.3					
			[S II]: vf	s	7.3					
		WN + WC	Hα: bf	s	18 × 37	1	...	...	...	
MR 111 = AS422	S108		[O III]: nd							
			[S II]: vvf	d	18 × 37					
		WN3	Hα: f	d	34	5	4.4	43	...	
HD 211564	S132		[O III]: vb	d	37					
			[S II]: vf	d	39					
			Hα: f	s	12.2	...	...	20	...	
			[O III]: vb	s	15.8					
			[S II]: nd							
		WN6 + O	Hα: vb	s	28	4	...	36	x	6
HD 211853	S132		[O III]: vb	s	21					
			[S II]: bf	d	21					
		WN4.5 + BO III	Hα: vb	s	31 × 51	3	...	...	x	7
HD 219460	S157		[O III]: b	s	31 × 51					
			[S II]: f		31 × 51					

REFERENCES.—(1) Smith 1967. (2) Johnson and Hogg 1965. (3) Lortet *et al.* 1980. (4) Johnson 1975. (5) Crampton 1971. (6) Harten *et al.* 1978. (7) Chopinet and Lortet-Zuckerman 1972.

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TABLE 2

RING NEBULAE ASSOCIATED WITH WOLF-RAYET STARS

Definite	Probable
HD 50896	HD 68273
HD 56925	HD 93131
HD 89358	HD 115473
HD 92740	(HD 155603B)
HD 92809	St Sa1
HD 96548	HD 157504
HD 113904	HD 186943
HD 117688	LS 16
HD 147419	MR 97
LSS 4368	HD 193576
HD 187282	HD 193793
HD 191765	HD 219460
HD 192163	
HD 211564	
HD 211853	

a) *θ Mus = HD 113904* (*WC 6+09.5I*)

The [O III] plate of this object, Figure 1 (Plate 3), reveals a prominent, arcuate structure approximately 33′ south of *θ* Mus. The feature has a scalloped appearance with three distinct, connected lobes and a total length of 67′. On the Hα plate, a sharp **J**-shaped filament is visible in approximately the same place as the [O III] shell, but *not* coincident with it. The Hα feature is smooth and thicker than the [O III] feature. No emission structure is visible either in [S II] or Hβ. *θ* Mus is an apparent member of Cen OB1.

b) *HD 92740* (*WN 7*)

HD 92740 lies within the Carina Nebula and therefore should be considered with caution. It is apparently located within a shell structure 30′ in diameter. The rim of the shell is quite sharp to the north but somewhat diffuse on the southern edge. The object is off-center to the north-east, toward the sharpest portion of the rim of the shell. On the [O III] plate, the rim is diffuse, and the ring is filled with emission in the eastern half. The Hα plate (Fig. 2 [Plate 4]) reveals the ring as sharp although clumpy and somewhat segmented. The interior of the eastern third of the shell is emission-filled.

c) *HD 211564* (*WN 3*)

HD 211564 and HD 211853, separated by 32′, appear to be embedded in a common diffuse H II region. However, each star has a very separate shell complex. The ring structure around HD 211564 is composed of two distinct shells, an outer one of diameter 36′ and an inner structure 17′ in diameter. On the [O III] plate (Fig. 3 [Plate 5]), this double ring structure is quite pronounced. The inner shell, as it appears on the original [O III] plates, is very sharp and complete, and the Wolf-Rayet star is displaced 3′.7 northeast of the center. The outer shell is diffuse. In Hα + [N II], the inner and outer ring structures are present. However, the inner ring appears more diffuse with no filamentary structure visible, in contrast to that revealed by [O III]. This double ring structure may be similar to the combined H II region-interstellar bubble around the peculiar Of star HD 148937 (Bruhweiler *et al.* 1981).

To the northeast of the double ring structure is a heavily saturated region (center of S132) on the Hα plate. Within this intense Hα emission region lies HD 211853. The emission region traced out by Hα is 20′.7 in diameter. Diffuse emission "fingers" extend from this structure to the southeast, and the nebulosity itself is elongated in the northeast to southwest direction. On the [O III] plate only a few knots of emission are visible: one centered on the Wolf-Rayet star and 6′ in diameter. Two other emission features appear to form two sides of a square around HD 211853 10′ to the east and south. Harten, Felli, and Tofani (1978) suggest that an O8.5 V star, located 1′ from HD 211853, is the dominant source of ionization of S132.

An intriguing feature seen most prominently on the Hα plate is an arclike filament 10′ directly north of HD 211564. This filament extends eastward 36′.5 from the nebulosity around HD 211853 and appears to be the southern edge of a sharp shell around a cavity. Image enhancement techniques have been applied to the Hα plate of this field and have shown the shell to be complete, and 34′ in diameter. However, no known Wolf-Rayet star or O star is within this cavity.

Our data imply that HD 211564 and HD 211853 share a common nebulosity. Distances currently determined for these two objects do not preclude a single nebulosity. The reddening of the two stars is about the same. Massey (1981) has shown that HD 211853 is not a member of Cep OB2, as believed earlier. The distance modulus of 13.2 for HD 211853 determined by Massey (1981) is in good agreement with the distance modulus of S132 (Crampton 1971). If HD 211564 is at the same distance, it should have $M_v \approx -3.0$. This result, although at least a magnitude fainter than generally adopted, can be reasonably consistent with current results as described by Massey (1981).

d) *HD 187282* (*WN 4*)

HD 187282 is located 24′ west of a diffuse emission region 60 × 49′ in size. This diffuse region is oblong and oriented north-west to south-east. On the [O III] plate, Figure 4 (Plate 6), several discrete structures can be identified within this nebulosity. One of these structures is a sharp, **S**-shaped filament 22′ long, directly east of HD 187282. The filament is undetected on Hα and [S III]. A very bright knot of emission, S84, lies 13.2′ northeast of HD 187282. This knot is 4.8′ long and appears arc-shaped with the center in the opposite direction from HD 187282. This emission arc is also detected more faintly on the Hα plate.

More importantly, the [O III] plate reveals a bow shock structure in the form of a sharp, hollow parabolic segment with the vertex again pointing east and 20′ in diameter. No hint of this sharp shell is seen on any of the other plates of this field, indicating a high degree of ionization for this inner nebulosity. The Wolf-Rayet star is 10′ south-southwest of the vertex of this [O III] shell structure.

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e) *HD 191765* (*WN 6*)

HD 191765[4] lies in the Cygnus region. On the Hα plate, this object is found in a field of bubble-like structures. It appears to lie 8'.8 east of a diffuse and hollow arc of emission. However, the number of interrelated filaments in this region precludes the detection of a complete shell. On the [O III] plate (Fig. 5*a* [Pl. 7]), the filamentary structure seen in Hα is only faintly, diffusely, and incompletely defined. However, there is a very bright, sharp, hollow arc of emission 11′ west of HD 191765. This arc is not coincident with the arc seen in Hα (Fig. 5*b* [Pl. 8]), but lies north of it. In [S II], the Hα structure is faintly traced; the emission arc present in [O III] is not detected.

V. ANALYSIS OF DATA

We have compared the relative brightness in Hα against [O III] for all nebulosities in Table 1 with a credibility rating of " 3 " or higher. The results for the WN star and the WC star nebulae are presented in Figure 6. It is apparent from Figure 6*a* that nebulosities associated with stars earlier than WN 6 tend to be brighter in [O III] than in Hα. Nebulosities associated with stars later than WN 6 tend to be brighter in Hα than in [O III]. While absolute calibration of the plate data is not available, it can be shown that if the relative brightness of [O III] is greater than that of Hα + [N II], then the [O III] line of λ5007 is stronger than that of an ordinary H II region of comparable Hα + N[II] intensity. Strong [O III] emission in comparison to Hα implies a high degree of ionization. We may conclude that the shells of earlier WN stars have a higher degree of ionization than the shells of later WN stars. For the WC nebulosities, our sample is quite small. Only nine nebulosities have a credibility rating of " 3 " or higher. The shells around WC stars do not show a correlation between [O III] brightness and Hα brightness. In this small sample, the majority of these shells are " faint " or less in [O III], regardless of the brightness in Hα. This suggests that WC shells generally exhibit a lower degree of ionization than the early WN shells.

[4] This object was noted by Crampton (1971) as being within an arc of nebulosity and possibly a ring nebula. The ring nebula seen on the [O III] plate is a definite shock structure, and we are basing our identification on this data, not on the structure seen on the POSS which Crampton used for his identification.

VI. CONCLUSIONS

We have discovered at least five previously unreported ring nebulae around Wolf-Rayet stars. Additionally, we have identified twelve " probable " ring nebulae. Most of the shell structures we have identified and given a credibility rating of " 3 " or higher are characterized by a cavity devoid of emission and a sharp, filamentary [O III] boundary. This description would be expected in the case of an explosive event or in the case of an interstellar bubble formed when a high velocity stellar wind interacted with the ambient interstellar medium and formed a shock front. The observational evidence collected here should lead to a better understanding of the origins of ring nebulae and more accurate determinations of net mass loss from Wolf-Rayet stars when coupled with spectrophotometric data and high resolution imagery, which we are presently acquiring.

The Wolf-Rayet stars in Table 1 associated with " probable " or " definite " shell structures cover a range of spectral types. Both WN and WC types are included, as well as a representative number of binaries. If we consider only the " definite " structures, we find three of the fifteen objects are WC stars (two of these three are WC 6). There are four WC stars among the twelve " probable " nebulosities. These statistics would indicate that nebulosities associated with WC stars tend to satisfy fewer of the criteria outlined in § III for assigning the credibility rating (i.e., WC nebulosities tend to be more diffuse; the

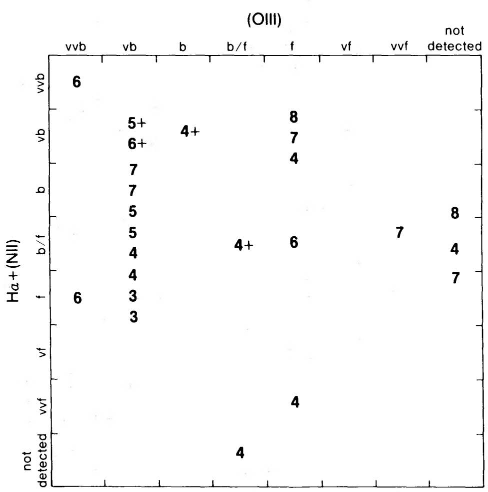

FIG. 6*a*

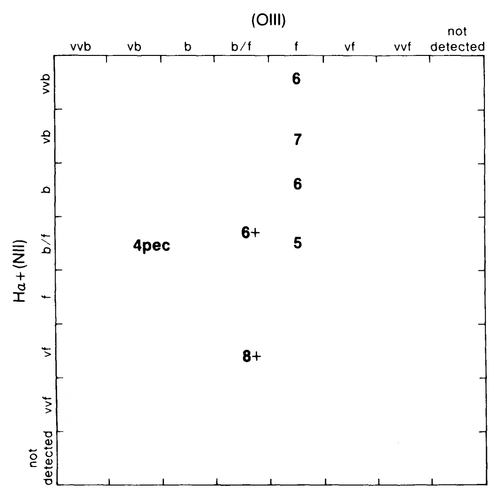

FIG. 6*b*

FIG. 6.—For all shell structures in Table 1 having a credibility rating of " 3 " or higher, the level of brightness in Hα + [N II] is compared to the level of brightness in [O III]. Fig. 6*a* shows values for WN stars, while Fig. 6*b* shows values for WC stars. The number on the graphs indicates the spectral class of the associated star. A cross indicates a binary.

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WC star tends to be off-center in a nonpreferred direction; and there is more likelihood that an O star or stars are within the nebulosity and possibly contributing to it). The mechanism of nebula formation must include the possibility that all types of Wolf-Rayet stars, WN and WC, single and binary, can be associated with ring nebulae.

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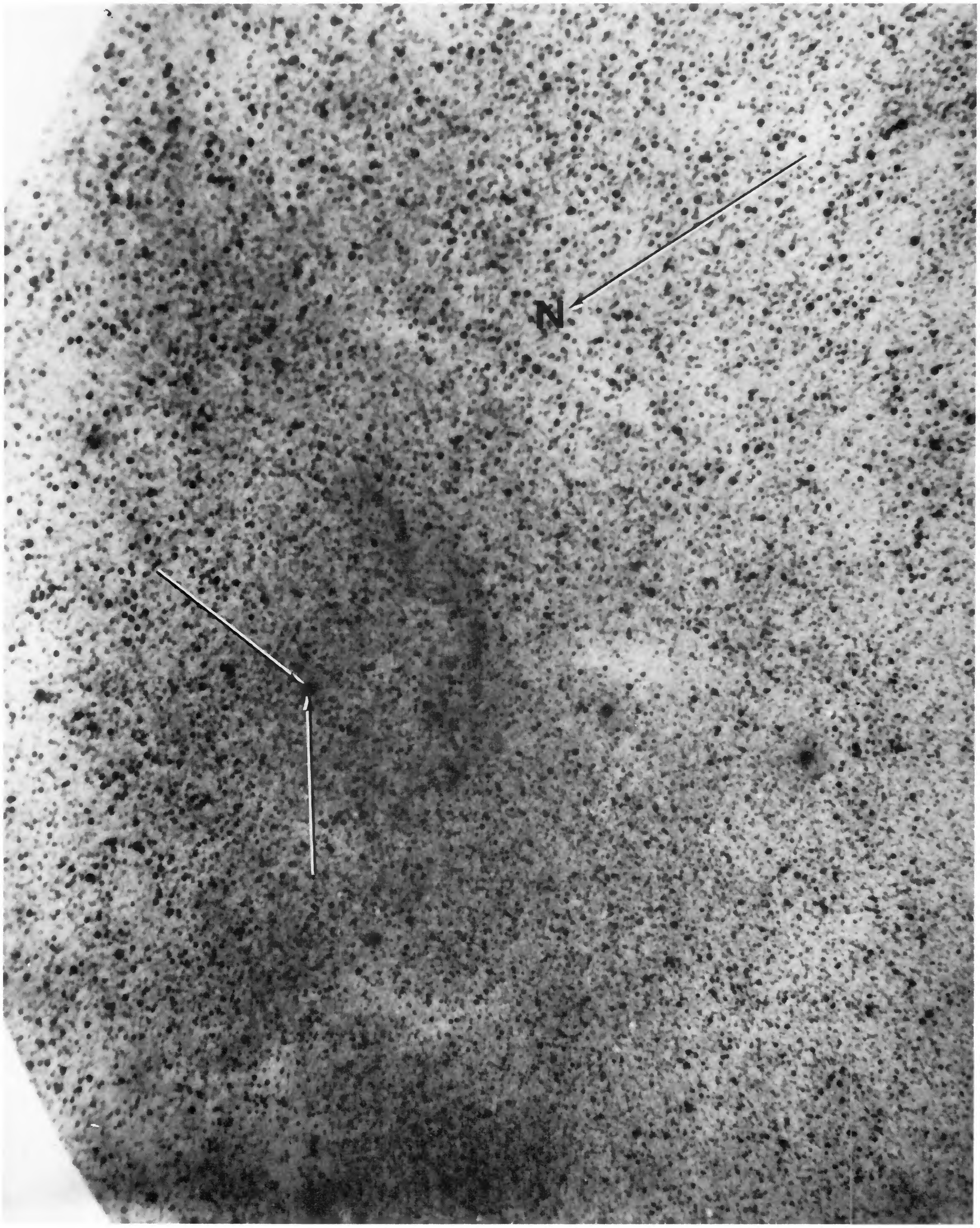

FIG. 1.—This [O III] plate shows the scalloped filament associated with θ Mus. The scale is 1:3 mm^{-1}. North is in the direction of the arrow.

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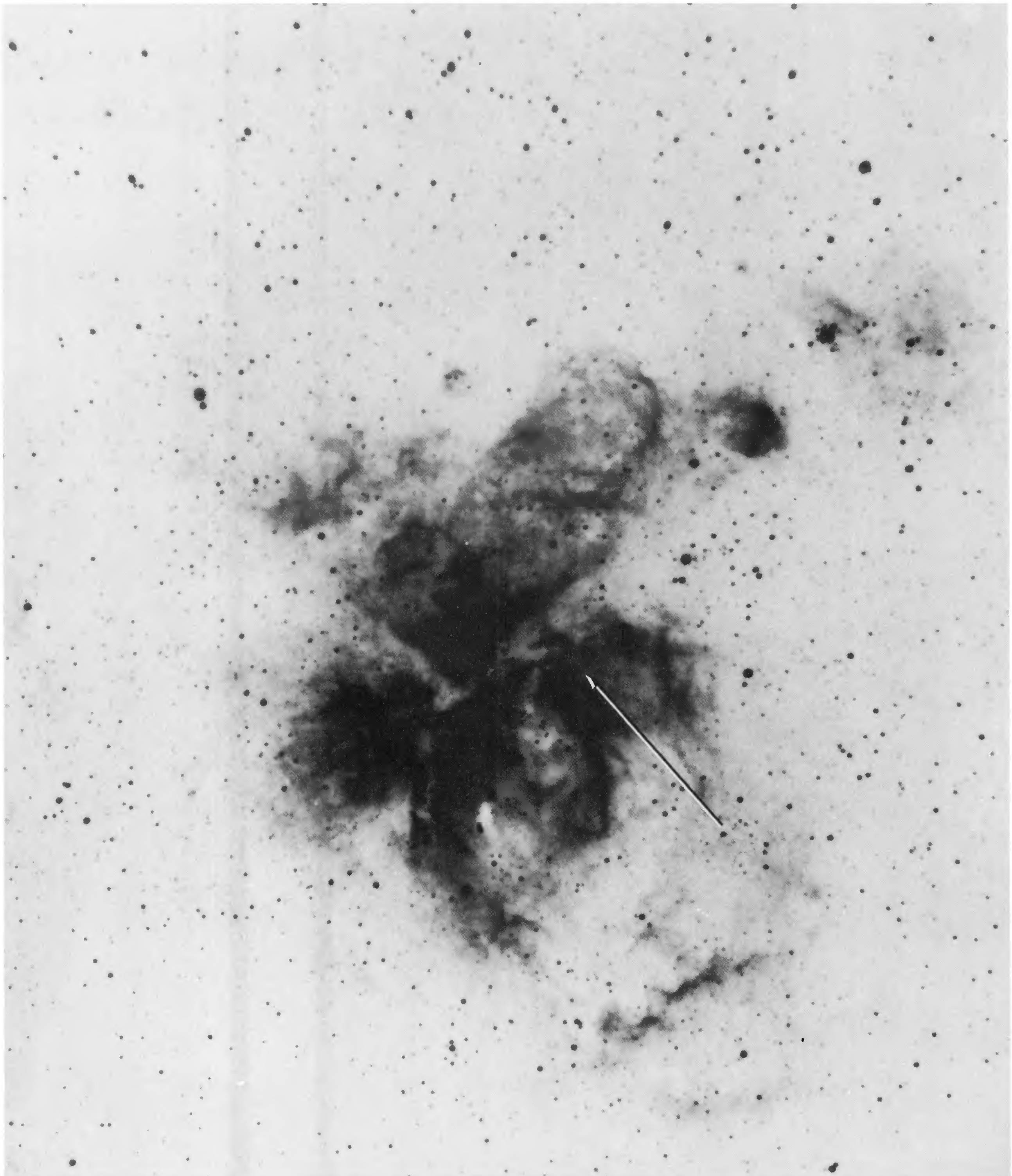

FIG. 2.—A ring-shaped nebula, 30′ in diameter, surrounds HD 92740. The star is off-center to the northeast, toward the brightest, sharpest portion of the ring. This is the Hα + [N II] plate with a scale of 1′.4 mm^{-1}. North is up.

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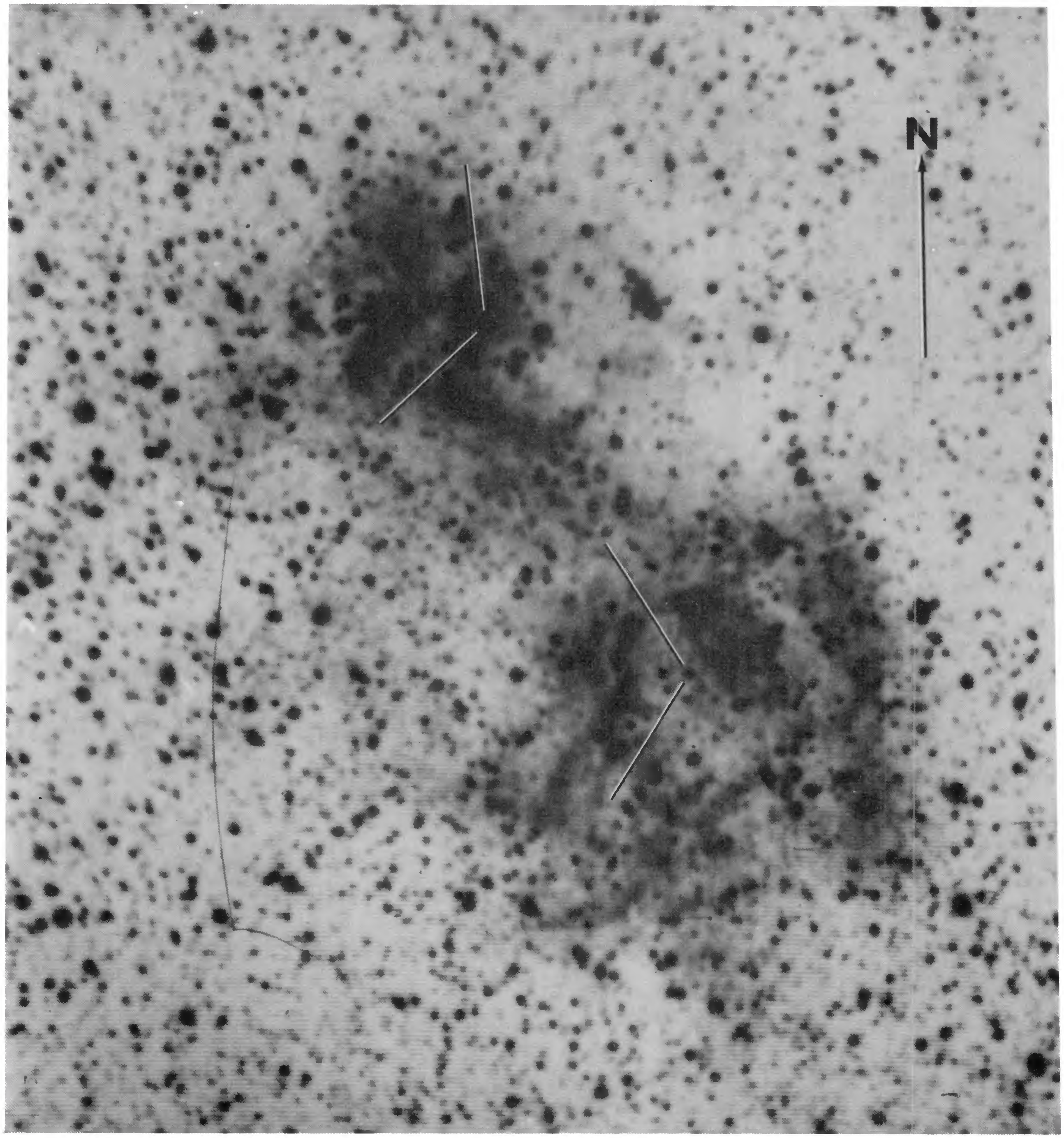

FIG. 3.—HD 211564 is surrounded by a complete, filamentary ring structure in [O III]. The ring is 16′ in diameter. HD 211853 is buried in the saturated emission region of S132. Scale on this print is 0′.58 mm^{-1}. North is up.

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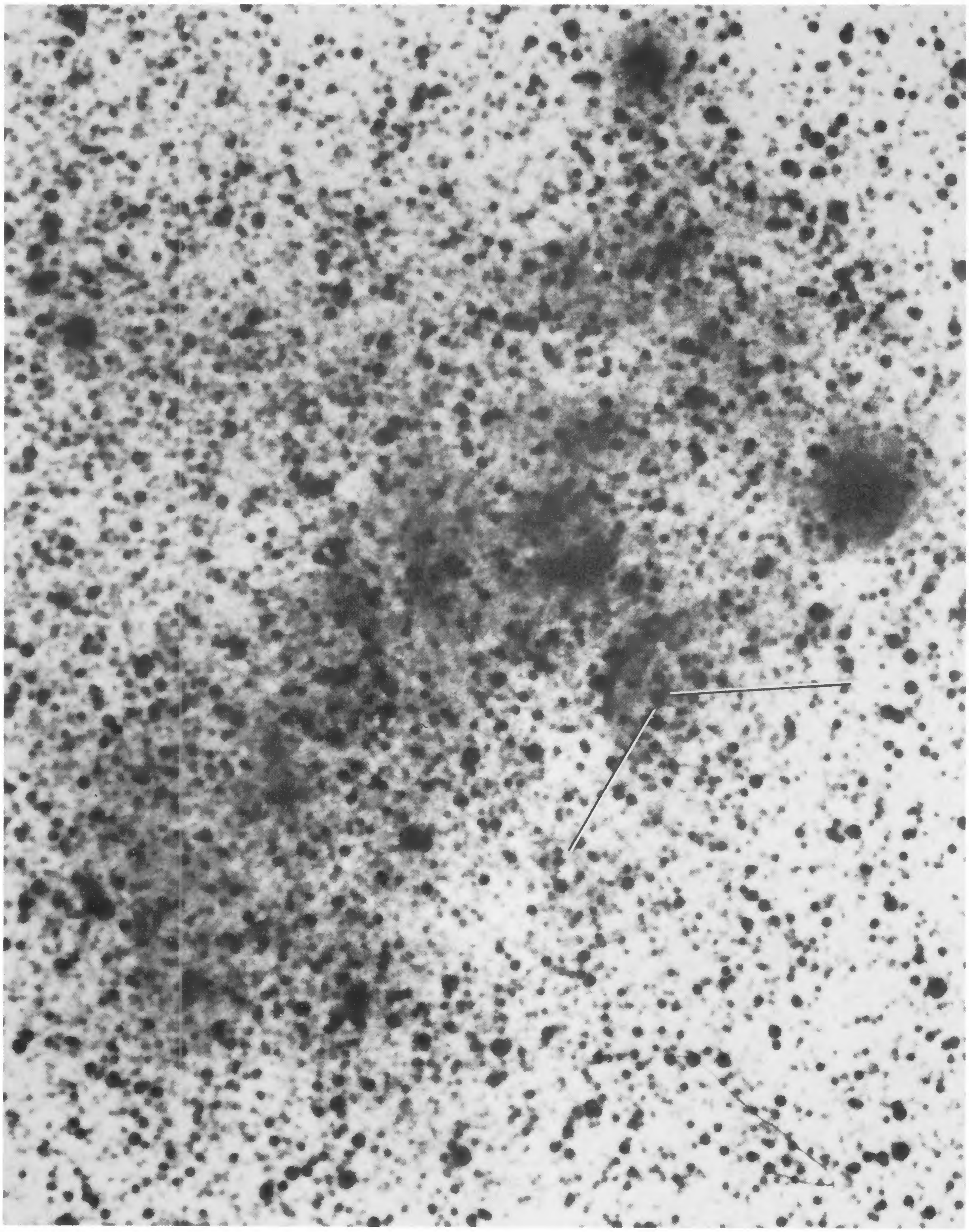

FIG. 4.—A sharp arc of emission around HD 187282 is seen only on this [O III] plate. Note the structure in the diffuse nebulosity to the northeast. Scale on this print is 0'.54 mm^{-1}. North is up.

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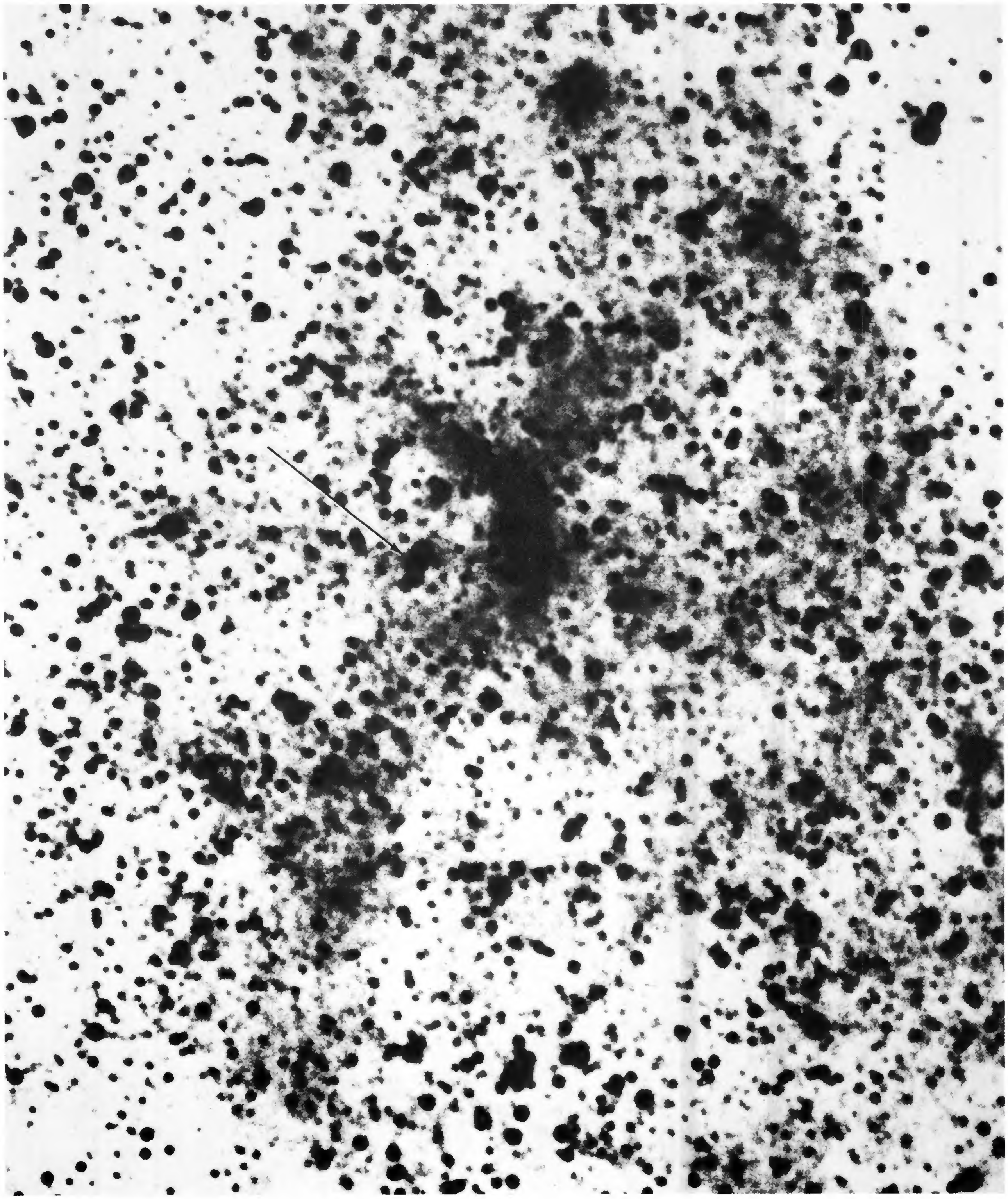

FIG. 5*a*

FIG. 5.—HD 191765 has a sharp arc of [O III] emission (Fig. 5*a*), not coincident with emission structure seen on the Hα + [N II] plate (Fig. 5*b*). Scale on these prints is 0.′52 mm^{-1}. North is up.

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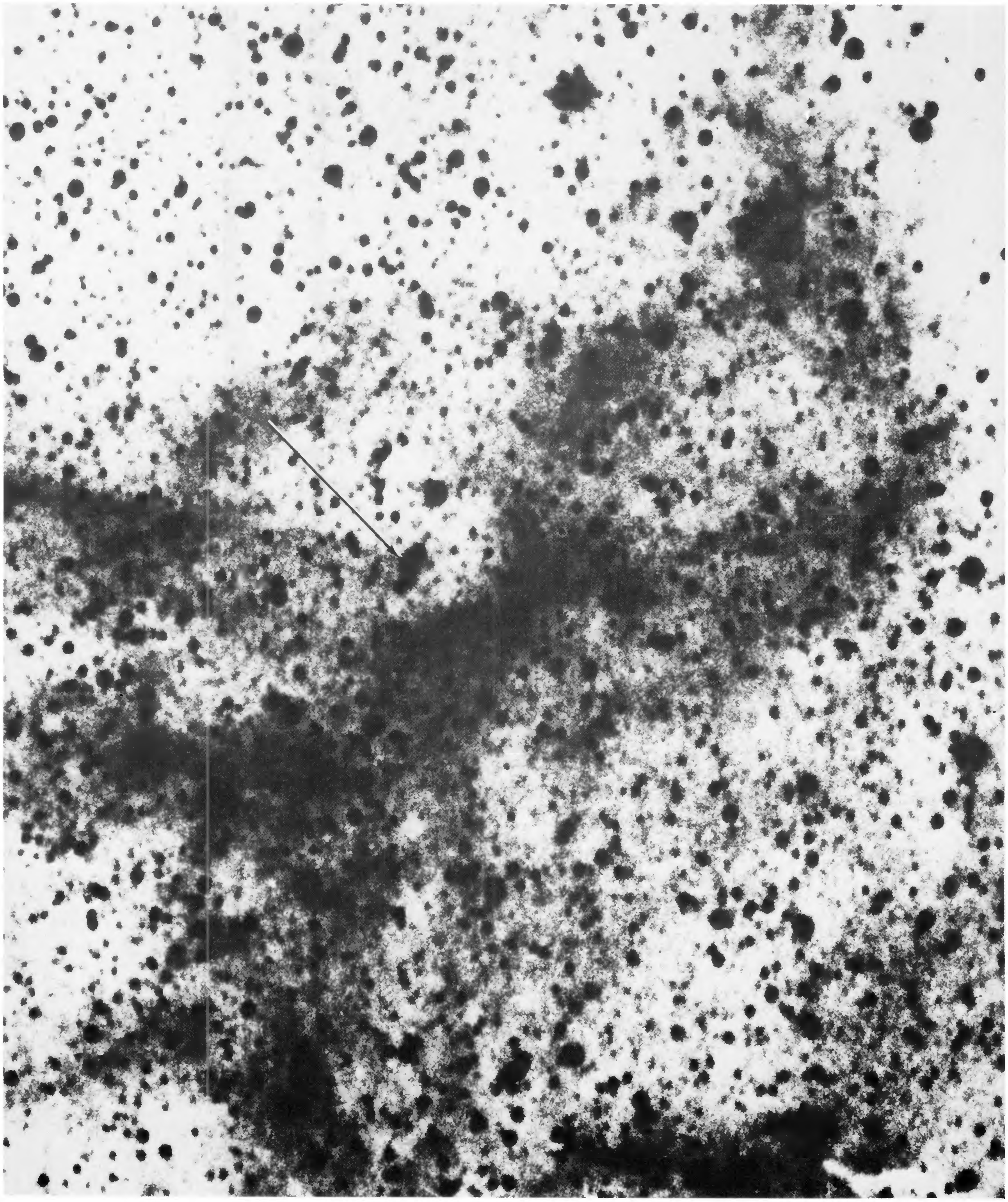

FIG. 5b

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