BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS

1956 NOVEMBER 15 VOLUME XIII NUMBER 471

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN

A STUDY OF BRIGHT RIMS IN DIFFUSE NEBULAE

BY S. POTTASCH

The existence of bright rims in 34 emission nebulae is recorded. Their properties are studied in detail for seventeen nebulae whose distances are reasonably well known. In total, over one hundred such rims are listed along with their shape, size, thickness, distance from the exciting star, and orientation. An estimate of the density of the gas in these rims, usually between 100 and 2000 cm^{-3}, is obtained from these data.

The bright rims are in general located at the edge of dark un-ionized matter, and appear to be pointed in the direction of the exciting star. The emission complexes which contain bright rims are almost always excited by stars earlier than O9. The position of the rim in the complex appears to depend on the type of the exciting star, the rim being located more toward the centre of the complex for the stars of earlier type.

A distinct change in the shape of the rims with distance from the exciting star is observed. The form changes in a continuous manner from rather flat rims to trunk-shaped rims and roundish globules, which have no further connection with the dark matter. The flat rims are the least dense and largest rims, whereas the trunk-shaped rims and globules are smallest and densest.

For nine nebulae, the densities in the rims were compared with estimated average densities. Either density tends to be higher for small nebulae, but not in the same proportion. The ratio of rim density to nebula density varies from 7 to 23.

1. *Introduction.*

Bright rims at the edge of dark markings associated with diffuse nebulae have been noticed for well over thirty years. DUNCAN [1]) calls attention to several bright rims in his photographs of nebulae. STRUVE [2]) has compiled a list of bright rims and their associated nebulae. Ten nebulae are included in his list. ROZHKOVSKY [3]) also lists the bright rims associated with ten diffuse nebulae, five of which are the same as in STRUVE's list. THACKERAY [4]) has investigated spectroscopically the bright rims in three much studied diffuse nebulae, NGC 6611, 6514, 6523. Similarly, VAN DE HULST [5]) has taken slit spectra of the bright rims in NGC 6611.

STRUVE points out that the bright rims are always associated with diffuse emission nebulae, never with reflection nebulae; that the bright rims partly surround dark masses of nebular material; that the rims are sharply defined, especially on the dark side; that the brightest portion of each rim is in the direction of the exciting star. He concludes that there exists a connection between the diffuse nebula, the exciting star, and the bright rims.

In spite of the fact that the bright rims belong to emission nebulae, STRUVE attempted to explain the luminosity of the bright rims on the basis of scattering of nebular light by the dust grains in the dark cloud. This explanation of the luminosity is inconsistent with the emission character of the spectrum of the bright rims.

Another possible explanation of the luminosity of the bright rims was advanced by OORT [6]). Consider the expanding inner parts of a nebula coming in contact with interstellar matter surrounding it and essentially at rest. A shock front may be set up at the boundary, with a temperature, OORT estimates, three or more times higher than the ordinary region of ionized hydrogen. This would lead, according to OORT, to marked differences between the spectrum of the bright rim and that of the ordinary HII region; in particular, the forbidden oxygen lines would be considerably strengthened with respect to hydrogen lines. This difference has not been substantiated in the work of either VAN DE HULST or THACKERAY.

The luminosity of the bright rims is attributed in this paper to the same cause as the general brightness of the emission nebulae, namely absorption of light quanta below the Lyman limit ($\lambda = 912$ Å) and the subsequent reemission of a good part of this energy as visible light. STRÖMGREN [7]) computed that a hot star placed in a homogeneous gas will ionize a spherical region with a very sharp division between the bright ionized (HII) region and the surrounding un-ionized (HI) region. For a star surrounded by hydrogen of density $n = 1$ cm^{-3}, the radius of the HII region is:

[1]) J. DUNCAN, *Ap. J.* **51**, 4, 1920.
[2]) O. STRUVE, *Ap. J.* **85**, 208, 1937.
[3]) V. G. ROZHKOVSKY, *A. J. U.S.S.R.* **31**, 318, 1954.
[4]) A. D. THACKERAY, *M.N.* **110**, No. 4, 1950.
[5]) H. C. VAN DE HULST, unpublished.
[6]) J. H. OORT, *M.N.* **106**, 159, 1946.
[7]) B. STRÖMGREN, *Ap. J.* **89**, 530, 1939.

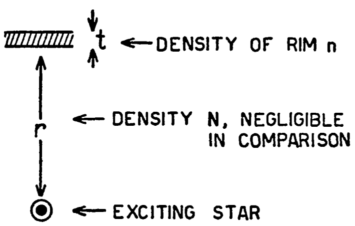
$$\log s_\circ = -0.47 + \tfrac{1}{6}\log\frac{T_e}{T_s} - 3.75\,\Theta + \tfrac{1}{2}\log T_s - 0.13\,M_v, \qquad (1)$$

where T_e = electron temperature,
T_s = temperature of exciting star,
M_v = absolute visible magnitude of exciting star,
$\Theta = \dfrac{5040}{T_s}$.

The radius of the HII region in a gas with uniform density n cm^{-3} is $s_\circ/n^{2/3}$ parsec, so the unit in which $s_\circ$ is expressed by STRÖMGREN's equation is parsecs/cm^2.

The bright rims will be interpreted in this paper as the ionized portions of a relatively dense hydrogen gas located at a distance r from an exciting star. An attempt will be made later in the paper to justify the assumption that the density between the star and the rim may be neglected. If spherical symmetry is assumed (Figure 1), the density n and the thickness t of the bright rim are related to $s_\circ$ and r in the following way[1]):

FIGURE 1



$$n^2 = \frac{s_\circ^{\,3}}{3r^2t}. \qquad (2)$$

This can be shown most simply by considering that the star can ionize a volume $\frac{4}{3}\pi s_\circ^{\,3} n^{-2}$, of density n. The volume included in the thin spherical rim is $4\pi r^2 t$.

Table 1 gives the values of T_s, M_v, and $s_\circ$ which were used throughout this paper. The values of temperature were taken from PETRIE[2]) and ALLER[3]).

TABLE 1

Spectrum	T_s	M_v	$s_\circ$
O5	43 600	−5.3	100
O6	40 000	−5.2	85
O7	37 000	−5.0	71
O8	34 700	−4.7	57
O9.5V	30 300	−4.1	41
O9.5Ib	30 300	−5.5	54
B0V	25 000	−3.8	25

The absolute magnitudes M_v are taken from V. G. FESENKOV[4]). They seem to agree well with the values used by MORGAN and his associates at Yerkes[5]).

[1]) B. STRÖMGREN, *Ap. J.* **108**, 259, 1948.
[2]) R. M. PETRIE, *Pub. Dom. Ap. Obs.* **7**, 321, 1948.
[3]) L. ALLER, "Astrophysics", Vol. II, p. 259, 1954.
[4]) V. G. FESENKOV, *A. J. U.S.S.R.* **31**, 314, 1954.
[5]) D. DUKE, *Ap. J.* **113**, 100, 1951.

TABLE 2
Diffuse nebulae showing bright rims

Designation of nebula	1900 Position		Distance (parsec)	Shape	Exciting star			Size of nebula (largest diameter)		Number of bright rims	Plate(s) used	Finest discernable detail (pc)	References	
	α δ	l b			Designation	Type	m_v	Angular (minutes)	Linear (pc)				Distances	Exciting star
S 278	0h 02m +67°20′	86.5 +5.0		I×						5				
vdH	0h 37m +51°48′	89.8 −10.0	960	I×	HD 3950	B0	6.93							
NGC 281	0h 47.4m +56°3′	91.0 −6.0	2460	I×	HD 5005	O6	7.7		13	5	60″MW	2″=.023	J	J
IC 1805	2h 24.5m +61°2′	102.3 +1.5	1000	I×	HD 15570 HD 15558	O5 O6	8.0 7.8		27	4	SH	8″=.039	D, SWH	MWC
IC 1848	2h 43.6m +60°1′	104.9 +1.6	1150	C E	HD 18326 HD 17505	O8 O7	7.91 7.11		12 15	3 2	SH	10″=.056	D, SWH	
NGC 1499	3h 56.9m +36°8′	128.5 −11.0	350	I	HD 24912	O7	4.05		7.5	4	48″	2″=.004	MWC	J
vdH	5h 7m +37°24′	136.9 +0.1	1150	C	HD 34656	O7	6.71			3	100″		MCW	
IC 405	5h 10m +34°12′	139.9 −1.1	530	I×	HD 34078	O9.5v	5.81		5.5	6	SH	10″=.021	BM	BM, J, SO
S 139	5h 26m +12°3′	159.9 −9.1		I										
NGC 1976	5h 30.4m −5°27′	176.6 −18.0	500		HD 37022 HD 37041	O7 O9	5.36 5.17						J	J
NGC 1977	5h 30.5m −4°54′	176.2 −17.5	500		HD 37018	B2III	4.65						J	S
IC 434	5h 36.0m −2°28′	174.6 −15.3	340	I	HD 37468 HD 37742	O9.5v O9.5Ib	3.78 2.05		4	7	100″	2″=.003	J, D	J

TABLE 2 *(continued)*

Designation of nebula	1900 Position α δ	l b	Distance (parsec)	Shape	Exciting star Designation	Type	m_v	Size of nebula (largest diameter) Angular (minutes)	Linear (pc)	Number of bright rims	Plate(s) used	Finest discernable detail (pc)	References Distance	References Exciting star
NGC 2244	$6^h 27^m$ $+5°$	174.2 —0.5	1350	C	HD 46223 HD 46150	O5 O6	7.14 6.80	80	31	6	48″	2.″5=.018	MWC	Mink.
NGC 2264	$6^h 35.5^m$ $+9°59'$	170.7 +3.8	700	E	HD 47839	O7	4.7	80×28	15×5	7	48″, 200″	2″=.007	J	J
NGC 2327	$7^h 1^m$ $-10°33'$	191.5 —0.2	1100		HD 53755	Bov	6.5						MCW	
NGC 3324	$10^h 34^m$ $-58°13'$	253.8 +0.0	3000	C	HD 92207		5.57	12	10.5	6	74″	1.″5=.022	C	C
NGC 3372	$10^h 41^m$ $-59°10'$	255.3 —0.5	1400	I	HD 93131	O8	8.2	81	33	8	74″, 60″ B 61″			C
NGC 3576-82	$11^h 7.9^m$ $-60°43'$	259.0 —0.8		C				16		4	60″B			
IC 2948	$11^h 34.1^m$ $-62°58'$	262.7 —2.4		$I_\times$				60		4	60″B			
NGC 6188	$16^h 33^m$ $-48°55'$	303.0 —2.6	1350	I	HD 150136		5.59	20	8	4	60″B	4″=.027		
NGC 6514	$17^h 56.6^m$ $-23°2'$	334.8 —1.8	1350	C	HD 164492 HD 164402	O8 BoIb	6.91 5.73	10	4	8	100″	0.6=.005	MWC	MWC
NGC 6523	$17^h 57.6^m$ $-24°23'$	333.7 —2.7	1300	C	HD 164794 HD 165052	O5 O7	5.9 6.8	31	12	9	100″, SH	0.6″=.004 8″=0.52	MWC	MWC
IC 1274	$18^h 3.7^m$ $-23°41'$	334.9 —3.6	1300	C	HD 165921	O7.5	7.4						SWH	S
NGC 6611	$18^h 13.2^m$ $-13°49'$	344.7 —0.6	2700	I	HD 168076 HD 168075	O5 O7	8.5 8.5	10	8.2	12	48″, 100″	0.7″=.010	SO, MWC	
NGC 6820	$19^h 37^m$ $+22°9'$	27.1 0.0	2100		+22°3782	O7	9.3						MCW	
NGC 7000	$20^h 50^m$ $+44°0'$	51.9 —0.1	900	$I_\times$	HD 199579	O6	6.01	165	43	7	48″	2″=.010	J, SO	J, SO
NGC 7023	$21^h 0.3^m$ $+67°46'$	70.6 +13.6												
IC 1396	$21^h 35.9^m$ $+57°0$	66.9 +3.4	900	C	HD 206267	O6	5.64	130	32	8	48″	2″=.008	SO, D	J, SO
vdH = McD 30	$22^h 15.2^m$ $+62°43'$	74.2 +5.1	1750	$I_\times$	HD 211880	Bo.5v	8.5	17						
vdH = McD 32	$22^h 53^m$ $+62°12'$	77.9 +2.7	1000	E	HD 217086 HD 216898	O6 O8	7.7 8.3	160×90					MWC	MWC
vdH = S 94	$22^h 8.1^m$ $+58°56'$	72.3 +1.6	630	E	HD 210839	O6	5.19	200×60					MWC, D	J
vdH	$22^h 40^m$ $+64°40'$	75.5 +5.5	580	$I_\times$	HD 216014	Bo	6.83	180					D	
NGC 7635	$23^h 16.3^m$ $+60°39'$	79.9 +0.2	3100	I	+60°2522	O7	8.2	10	9	7	200″	1″=.015	C, J	R
vdH	$23^h 48^m$ $+59°8'$	83.5 —1.5		C				4.3			100″			

J = JOHNSON, H. M., *Ap. J.* **118**, 372, 1953.
D = DUKE, D., *Ap. J.* **113**, 100, 1951.
SWH = STEBBINS, J., WHITFORD, A. E., HUFFER, C. M., *Ap. J.* **91**, 20, 1940.
Mink = MINKOWSKI, R., *P.A.S.P.* **61**, 151, 1949.
MWC = MORGAN, W. W., WHITFORD, A. E., CODE, A. D., *Ap. J.* **118**, 318, 1953.
MCW = MORGAN, W. W., CODE, A. D., WHITFORD, A. E., *Ap. J. Supp.* No. 14, 1955.
BM = BLAAUW, A., MORGAN, W. W., *B.A.N.* **12**, 76, 1953.
SO = SHARPLESS, S., OSTERBROCK, D., *Ap. J.* **115**, 89, 1952.
S = STRUVE, O., *Ap. J.* **85**, 208, 1937.
C = CEDERBLAD, S., Medd. Lund. Obs., Ser. II, No. 119, 1946.
R = ROSINO, L., *Publ. Bologna* VI, No. 3, 1953.

2. *Catalogue of bright-rim nebulae and bright rims.*

Table 2 is a list of all 34 diffuse nebulae that have been reported to have pronounced bright rims. Since most bright rims are visible only with a telescope whose aperture is larger than 48″, and because most of the photographs consulted were taken by northern instruments, more northern than southern nebulae are represented. The primary source of this list was photographs of the nebulae which were available to me. Two of the thirty-four nebulae listed (IC 1274, NGC 1977) were taken from STRUVE's [1]) list without personal check, one (S 278) from ROZHKOVSKY's [2]) list and five from VAN DE HULST's catalogue of emission

[1]) O. STRUVE, *op. cit.*
[2]) V. G. ROZHKOVSKY, *op. cit.*

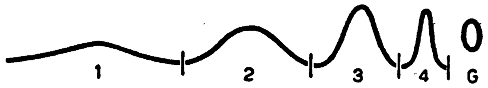
TABLE 3

Individual Bright Rims.

Key to table:

r = distance from exciting star to bright rim (parsecs).
t = thickness of bright rim (parsecs).
n = density of matter in bright rim (cm^{-3}).
l = length of bright rim (parsecs), or circumference in the case of globules.

Shape of rim:



IC 1396

Rim	r	l	t	r^2t	n	Shape
A	3.6	5.8	0.074	0.98	441	3
B	9.5	3.4	0.148	13.2	123	2
C	14.8	3.4	0.026	5.7	183	1
D	13.7	4.4	0.011	2.1	304	2
E	12.0	6.4	0.105	15.1	112	2
F	14.8	2.4	0.047	10.2	138	2
G	15.8	6.4	0.074	16.7	108	1
H	15.4	5.9	0.044	10.4	136	2

NGC 7000, North America Nebula, including the Pelican Nebula IC 5067 and IC 5068. The second star indicated in the drawing is 57 Cygni, B3, $m_v = 4.7$, probably not connected with the nebula. Note that rims E, F, and G do not point to the alleged exciting star.

Rim	r	l	t	r^2t	n	Shape
A	6.6	2.7	0.115	5.0	195	2
B	17	3.8	0.07	20	97	1
C	20	2.3	0.047	18.5	103	3
D	22	5.1	0.055	24	84	1
E	15.3	6.4	0.07	16	108	2
F	15.3	1.3	0.015	3.2	233	4
G	17	1.3	0.033	9.1	140	3

NGC 2244 (2237, 2238, 2246)

Rim	r	l	t	r^2t	n	Shape
A	8.8	1.95	0.055	4.26	357	2
B	5.8	3.5	0.110	3.7	385	1
C	13.4	2.9	0.102	18.4	174	1
D	7.4	1.15	0.034	1.9	535	3
E	6.6	0.9	0.041	1.8	545	3
F	6.4	1.0	0.027	1.1	706	G

IC 1805

Rim	r	l	t	r^2t	n	Shape
A	8.9	2.1	0.039	3.1	318	2
B	2.0	3.3	0.155	0.62	715	3
C	7.5	3.3	0.078	4.3	270	1
D	5.6	9.3	0.117	3.6	297	2

NGC 281

Rim	r	l	t	r^2t	n	Shape
A	1.6	2.9	0.096	0.24	890	G
B	4.5	1.0	0.072	1.4	368	4
C	6.8	1.6	0.047	2.2	294	3
D	7.2	1.2	0.060	3.1	248	3
E	8.3	1.0	0.060	4.1	216	2

NGC 3372, η Carinae. The bright rims in this nebula appear much thinner than most others measured. Errors in the measured thickness up to a factor 2, or more, would seem likely.

Rim	r	l	t	r^2t	n	Shape
A	11	2.8	0.02	2.5	154	1
B	5	3.2	0.014	0.34	417	1
C	6.9	1.4	0.014	0.63	306	2
D	3	0.9	0.014	0.11	715	2
E	10.5	2.8	0.007	0.86	261	1
F	1.6	0.35	0.014	0.035	1290	G
G	2.1	0.41	0.014	0.06	1100	G
H	7.3	0.83	0.014	0.72	320	G

IC 1848, Two separate Strömgren spheres.

Rim		r	l	t	r^2t	n	Shape
I	A	4.9	2.4	0.084	2.0	193	1
	B	3.9	2.0	0.100	1.5	208	2
	C	3.4	3.4	0.056	0.65	312	2
II	D	13.2	1.6	0.056	9.7	110	1
	E	7.8	1.2	0.123	7.6	125	?

NGC 1499, California Nebula. The bright edges are not very apparent. It is difficult to distinguish the bright edges from the diffuse brightness of the whole nebula. The surface brightness suggests that this nebula has greater density and less sharp density gradients than other nebulae.

Rim	r	l	t	r^2t	n	Shape
A	7.5	0.9	0.020	1.1	322	1
B	4.3	0.8	0.048	0.9	357	1
C	7.0	0.4	0.026	1.3	302	1
D	6.3	1.4	0.068	2.7	206	1

IC 405

Rim	r	l	t	r^2t	n	Shape
A	3.1	0.8	0.098	0.9	150	2
B	3.9	1.4	0.057	0.9	155	2
C	4.2	1.1	0.057	1.0	145	3
D	5.9	3.0	0.073	2.5	92	1
E	4.7	1.4	0.091	1.9	107	1
F	6.1	2.3	0.091	3.4	78	1

TABLE 3 *(continued)*

IC 434, Horsehead Nebula. There is some doubt as to which direction rims F and G are pointing.

Rim	r	l	t	r^2t	n	Shape
A	3.7	3.9	0.017	0.23	251	2
B	3.3	3.9	0.010	0.11	364	2
C	3.2	0.8	0.017	0.17	286	2
D	3.6	2.2	0.005	0.07	474	2
E	4.0	2.2	0.020	0.32	214	2
F	2.1	0.4	0.024	0.11	?	?
G	2.6	1.1	0.017	0.12	?	?

NGC 2264. The star shown near rim G is HD 47887, B3, $m_v = 6.8$. It lies in front of the nebula and has no connection with it. On a photograph rim G looks thicker than it actually is, because three small stars appear to be imbedded in it, though they probably have no connection with the rim.

Rim	r	l	t	r^2t	n	Shape
A	8.7	1.5				
B	3.6	1.5				
C	1.0	0.3	0.007	0.007	4100	3 ?
D	0.8	0.2	0.010	0.0064	4300	3 ?
E	3.5	0.5	0.012	0.15	885	2
F	5.1	0.4	0.017	0.44	510	3
G	4.9	1.2	0.048	1.15	314	3

NGC 3324. This has a continuous bright rim 16.5 parsecs long. The only other bright edges are very close to the star. The thickness at selected points is given. No densities are given as the spectral type of the exciting star is unknown.

Rim	r	t	r^2t	Shape
A	9.8	0.044	4.2	1
B	9.8	0.058	5.5	1
C	6.7	0.058	2.6	1
D	4.8	0.037	0.9	2
E	3.7	0.073	1.1	2
F	1.6	0.044	0.1	2

NGC 6188

Rim	r	l	t	r^2t	Shape
A	5.8	2.5	0.066	2.2	1
B	3.8	2.1	0.040	0.6	2
C	4.2	1.7	0.053	0.9	1
D	7.3	0.8	0.040	2.1	1

NGC 6514, Trifid Nebula, M 8. The whole nebula appears to extend, in diminished brightness, almost once again its distance to the north. Its extent to the east is probably greater than shown in the drawing. No distinct bright rims appear connected with these extensions.

Rim	r	l	t	r^2t	n	Shape
A	0.77	1.14	0.040	0.02	1710	4
B	1.0	0.38	0.020	0.02	1710	3
C	1.2	0.60	0.013	0.02	1740	3
D	1.1	0.25	0.013	0.017	1850	4
E	1.7	0.55	0.013	0.038	1230	4
F	2.2	0.60	0.013	0.063	964	3
G	2.2	0.70	0.013	0.063	964	3
J	1.45	0.18	0.007	0.015	1950	3

NGC 6523, M 20. There appears to be a brighter, roughly circular nebulosity at the west side. The star at the centre of this brightness is 3 magnitudes fainter than the exciting O5 star. The five thinner rims appear close to the brighter nebulosity.

Rim	r	l	t	r^2t	n	Shape
A	1.8	0.31	0.022	0.07	2100	4
B	2.0	0.28	0.019	0.08	2040	3
C	2.5	0.62	0.029	0.18	1320	3
D	3.5	0.56	0.013	0.16	1410	3
E	3.8	0.25	0.005	0.07	2230	4
F	5.7	1.9	0.104	3.4	303	2
G	9.5	3.6	0.100	9.0	189	2
H	5.4	2.5	0.068	2.0	397	2
J	7.6	2.6	0.100	5.8	235	2

NGC 6611, M 16

Rim	r	l	t	r^2t	n	Shape
A	3.9	0.83	0.083	0.6	740	G
B	5.4	1.1	0.034	1.0	563	3
C	5.7	4.5	0.034	1.1	535	4
D	4.9	1.4	0.022	0.54	768	3
E	6.2	0.6	0.022	0.85	610	3
F	3.2	0.8	0.038	0.39	900	4
G	2.8	1.5	0.075	0.59	738	4
H	3.8	0.8	0.034	0.49	802	4
J	2.6	0.9	0.177	1.2	515	4
K	6.0	1.1	0.059	2.1	388	3
L	9.6	3.0	0.031	2.7	342	1
M	9.6	2.3	0.031	2.7	342	1

NGC 7635. Surrounded by a thin shell of gas, not concentric with the exciting star. The luminous edges are located outside this shell, especially to the north.

Rim	r	l	t	r^2t	n	Shape	Rim	r	l	t	r^2t	n	Shape
A	0.74	0.6	0.023	0.013	2960	G	E	5.6	0.5	0.090	2.8	202	1
B	2.8	0.5	0.045	0.35	590	3	F	4.8	0.5	0.045	1.05	330	2
C	1.6	0.3	0.052	0.14	900	3	G	5.4	0.4	0.030	0.87	362	2
D	4.3	0.6	0.060	1.1	324	3							

nebulae [1]). In all cases the authors definitely stated the presence of bright rims.

The distances are taken from various sources, the principal source being Yerkes Observatory (DUKE [2])); JOHNSON [3]); MORGAN, WHITFORD and CODE [4]). These were complemented by data from STEBBINS, WHITFORD and HUFFER [5]). For one or two nebulae where little information was available, the 21-cm radio results from Leiden were used with the assumption that the diffuse nebulae are located in a spiral arm [6]).

The symbols used to designate the shape of the nebulae are: C = roughly circular; E = roughly elliptical; I = irregular; $I_{\times}$ = irregular with some suggestion of an overall or partially circular shape.

The exciting star is usually identified as being the early-type star to which the rim seems to be pointing. In many cases a tentative identification can be made even before the spectrum is known, and then the spectrum is used as a check. The identifications are fairly certain. If the only spectral type available is that given in the *Henry Draper Catalogue*, the spectral type is omitted from the table. M_v is the visual magnitude.

Photographic paper prints were used of originals taken by a large variety of instruments. The instruments are represented by the following symbols: SH = the photographs in the Shajn-Hase Atlas taken with the 26″ telescope at Simeis, Crimea; 48″ = 48″ Schmidt telescope at Mount Palomar; 60″ MW = 60″ reflector of Mount Wilson; 60″ B = 60″ reflector at Bloemfontein; 61″ = 61″ reflector at Cordoba, Argentina; 74″ = 74″ reflector at Pretoria; 100″ = telescope at Mount Wilson; 200″ = telescope at Mt Palomar. Each print was judged for its quality and a rough estimate of the finest discernable detail on each plate is given in the next column.

The last two columns indicate the references used for the exciting star and the distances of each nebula. There appears to be little dispute in the literature as to the identification of the exciting stars, but some dispute does arise as to the distances. Therefore it was necessary for me to choose among the several distances available, which was done with the help of available basic data (interstellar reddening, spectral type and visual magnitude).

The seventeen nebulae selected for further study are listed in Table 3 with the details of the bright rims in these nebulae. The nebulae selected were those whose distance and exciting star were fairly well determined and for which a good photograph was available. The quantities listed were measured and the density computed from the STRÖMGREN formula (equation 2).

Another method of obtaining the densities of the rims, and a check on the above method, is to compute the densities from values of the surface brightness. No calibration of the photographs used was in general available and so this method could not be used. A few measures of surface brightness or intensity are available and these check well with the results obtained from the application of STRÖMGREN's formula. MINKOWSKI [7]) from a measurement of surface brightness of NGC 2244, gives a value of 23 cm^{-3} for the density of the nebula, precisely the value obtained in Table 6. THACKERAY [8]) gives the relative intensities of two rims of NGC 6611 compared with the surrounding regions. These values (2.5 for rim J and 1.6 for rim G) may be converted into density ratios between the rims and the surrounding nebula if reasonable estimates of the depth of the rims are available. On the assumption of radial symmetry the depth of rim J was estimated to be 0.25 parsec at its brightest point and rim G to be 0.15 parsec. The extent of the nebula at these points is estimated to be 8 parsecs. The resulting density ratio of rim to nebula is 8.7 for rim J and 9.7 for rim G. This compares very well with the value 9.4 obtained by the use of STRÖMGREN's formula (see Table 6).

The lengths of the rims were not measured with the care taken in measuring the distances and the thicknesses (see next section). This was because there appeared no abrupt end to the rim, but a gradual fading of the rim into the background light. In a number of cases two rims appeared to be smoothly joined. These were treated as separate rims in the table, but the smoothness is indicated in the sketches.

The sketches (Figure 2) are intended as schematic pictures of the bright rims. The exciting star is shown as a dot surrounded by a circle. The rims are sketched accurately as regards orientation and distance from the exciting star. Their thickness is not represented in the sketches and the length shown in the sketches tends to be larger for clarity.

An attempt is made to represent their shape but the complexities could not be included.

The top seven diagrams have a scale in parsecs one half as large as the ten bottom sketches. The scale in minutes of arc subtended on the sky is noted on each sketch.

---

[1]) VAN DE HULST, unpublished, compiled from the Palomar 48″ Schmidt Sky Survey. Under the column "Designation of Nebula" in Table 2, the symbol vdH indicates that the nebula has been taken from VAN DE HULST's preliminary catalogue. No NGC or IC numbers correspond to these nebulae.

[2]) D. DUKE, *op. cit.*

[3]) H. JOHNSON, *Ap. J.* **118**, 372, 1953.

[4]) W. W. MORGAN, A. E. WHITFORD and A. D. CODE, *Ap. J.* **118**, 318, 1953.

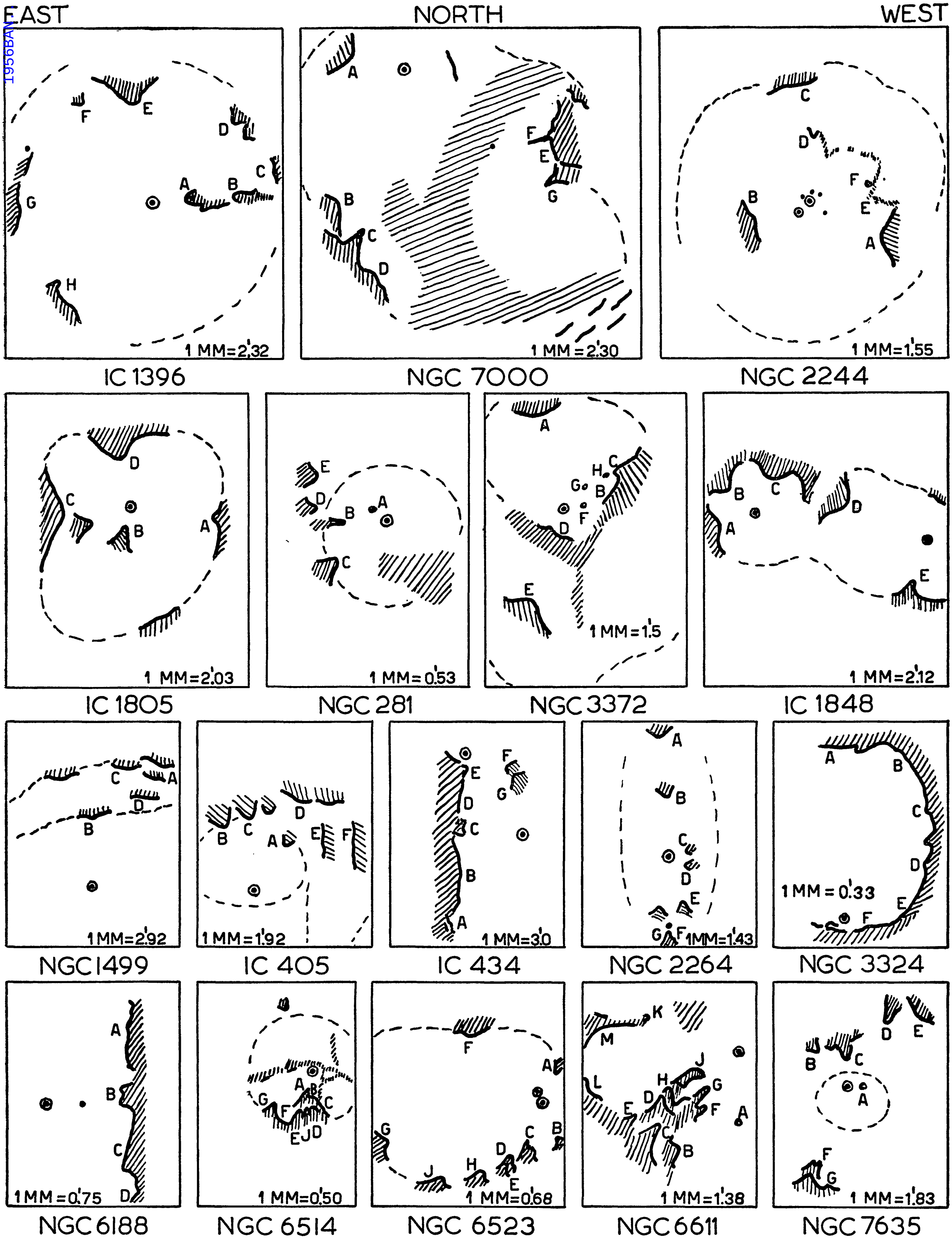
[5]) J. STEBBINS, A. E. WHITFORD and C. M. HUFFER, *Ap. J.* **91**, 20, 1940.

[6]) H. C. VAN DE HULST, C. A. MULLER and J. H. OORT, *B.A.N.* **12**, 117, (No. 452), 1954 and unpublished results.

[7]) R. MINKOWSKI, *P.A.S.P.* **61**, 151, 1949.

[8]) A. D. THACKERAY, *op. cit.*

FIGURE 2



Scale: top seven, 1 mm = 0.6 parsecs, bottom ten, 1 mm = 0.3 parsecs

3. *Discussion of observational errors.*

Before any conclusions based on the data of Table 3 can be accepted, the errors inherent in these data should be considered. They may roughly be discussed in four categories:

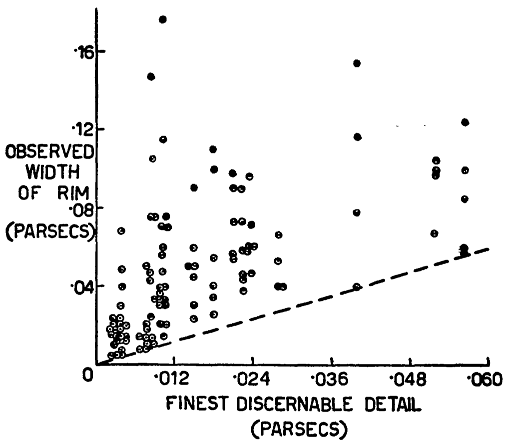
A. errors inherent in the photograph;
B. errors due to projection on a flat surface;
C. errors due to lack of accurate data regarding distances, identification of the exciting star and its spectral type, temperature and absolute magnitude, and to deviations from black-body radiation;
D. selection effects.

A. Two fundamental errors appear to be inherent in the photograph. The first of these is overexposure, which may cause two different types of errors. It may blot out all detail from the region of highest brightness, usually located around the central star, and thus eliminate bright rims close to the exciting star. Secondly, overexposure may increase the observed thickness of the bright rims.

A systematic check on overexposure, which would require measurements of each object on plates with various known exposures, was not possible. However, in those cases in which it was possible to compare the same object on plates taken at different observatories, the thicknesses measured were roughly the same, except for differences in plate definition as noted below.

The second cause of error was the fact that some of the nebulae were studied with large-aperture instruments (100″, 200″) and some with rather small-aperture instruments (26″). It would be expected that with the smaller instruments either the thin rims would not appear or would appear as thicker rims. A measure of the error introduced may be had from a plot of the observed width of the rim versus the 'smallest discernable detail' on the photograph. The latter quantity was judged independently for

FIGURE 3



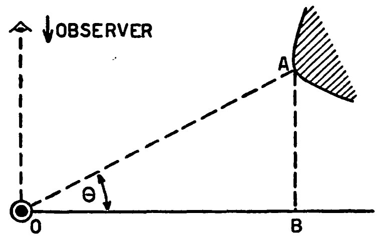
each photograph and the results in units of seconds of arc agree well for each single instrument (see Table 2). The results are shown in Figure 3. It would be expected that if the thin rims appear as thicker rims, there would be a great clustering of points near the dotted line in Figure 3. Since this is not the case it is assumed that the rims merely did not appear and they were not measured as thicker rims.

B. Errors due to projection of the nebulae on a flat surface may occur both in the measured thickness and in the measured distance from the exciting star.

The first error would appear to be very small, as two observers viewing the rim from two different directions will measure the same thickness of the rim, if the rim is uniformly thick, which is a good approximation in the measured region.

The distance between the exciting star and the bright rim appears smaller because of the projection. There is no way of discovering the error in an individual rim, but an estimate of the average error for a given type of shape can be made.

FIGURE 4



Consider, for example, a rim of shape 2 (as defined in Table 3). The chances are that a rim of this shape will not be observed if the line connecting the rim with the exciting star deviates more than 15° from the direction perpendicular to the line of sight (see Figure 4). If any angle less than 15° is equally probable, the ratio of the actual distance OA to the projected distance OB will be 1.01 on the average for a rim of shape 2. Table 4 gives corrections for rims of other shapes.

TABLE 4

rim shape	correction for projection (average)
1	1.00
2	1.01
3	1.03
4	1.26
G	1.12

C. Errors due to lack of accurate data concerning the temperatures of the exciting stars, their absolute magnitude, their distance from the observer, and deviations from black-body radiation all are relatively small. In any case they would not appear to introduce systematic changes that might affect the results significantly.

D. Selection effects would not seem to be serious. The quality of the photographs permitted the detection of approximately seven or eight rims on a nebula. However, when more were present they were duly noted, except in the case of η Carinae and in NGC 2244, where photographs of good quality showed many thin fuzzy rims. In the case of the 'continuous rim" nebulae about four or five well spaced places were chosen for measurement (refer to sketches, Figure 2).

4. *Statistical study of bright rims.*

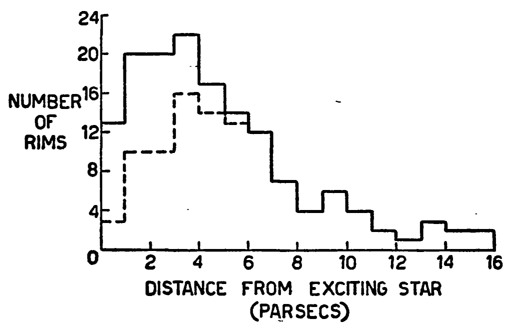
A. Number, position and orientation of the bright rims within the emission complexes.

a) Shape of emission complex: Twelve out of the seventeen emission complexes pictured in Figure 2 have a roughly circular shape. The bright rims usually lie within or near the edge of the bright region. In three cases (IC 434, NGC 1499, 6188) no clear-cut emission region is seen. In these cases the rims appear in a straight line or parallel and give the appearance of being 'continuous rims'. NGC 3324 is also a 'continuous rim' but shaped as a semicircle with the inside definitely filled with radiation. NGC 7635 has a conspicuous bright ring which has the appearance of a planetary nebula. All but one of the bright rims lie outside this ring and there appears no obvious connection between the two except that the northern part of the 'planetary nebula' is much brighter than the southern part and more of the pronounced bright rims are also to the north.

b) Orientation: In general, the bright rims are located at the edge of dark matter and the bright rims appear to be pointing directly at the exciting star, or nearly so. No real exception to this observation was found.

c) Number and position: A histogram showing the number of bright rims at each parsec interval from the exciting star is shown in Figure 5. The dotted

FIGURE 5



curve indicates the observations; the solid curve includes an estimated correction for the fact that rims may pass unnoticed in the inner, very bright part of the nebula. As nebulae of different sizes are involved, this histogram is not representative of the distribution of the rims in any one individual nebula, of which Figure 7 gives a better impression.

FIGURE 6

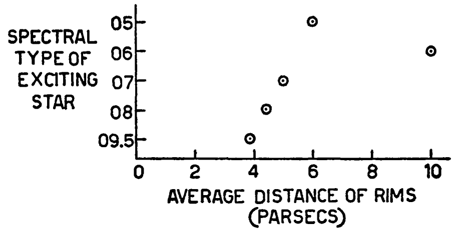
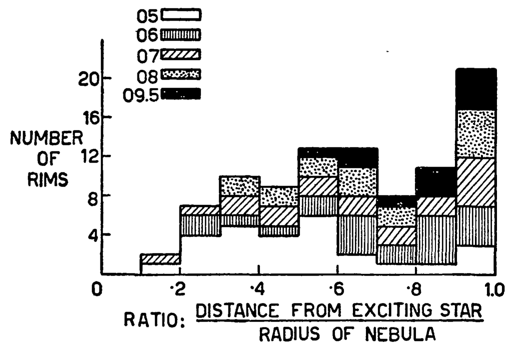


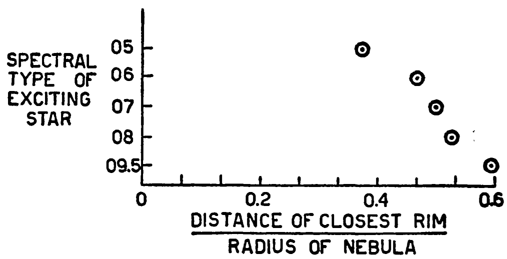
Figure 6 is a plot of the spectral type of the exciting star versus the average distance of the rim. The average distance of the rim is greater for hotter stars. However, this is mainly a manifestation of the larger size of the complex for earlier-type exciting stars. This is shown by Figure 7, in which the number of

FIGURE 7



bright rims is plotted against a ratio: the distance of the rim from the exciting star divided by a parameter indicative of the size of the nebula. This size was the radius of an emission complex wherever it was possible to indicate such a radius, and in other cases it was taken equal to the distance of the farthest rim. The plot is made separately for each spectral type. It shows that the rims are located more toward the centre of the emission complex for O5 stars, while for O9.5

FIGURE 8



stars the rims are more near the outer edge of the complex. A gradual change in rim position takes place through the stars of intermediate temperature. A similar systematic change with spectral type is observed if only the rims closest to the centre of each nebula are considered (Figure 8).

B. The thicknesses of the bright rims. The thickness measurement is the most inaccurate datum used in the derivation of density. More than the other data, it is subject to variations in quality of the plates.

FIGURE 9

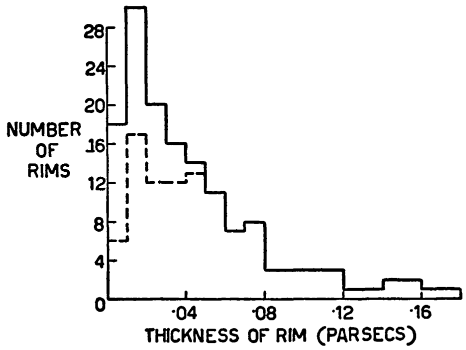


Figure 9 is a histogram showing the number of bright rims as a function of their thickness. The dotted line shows the observed distribution; the solid line above it is the corrected distribution to include rims that were too thin to be observed. The corrections have been estimated on the basis of Figure 3.

FIGURE 10

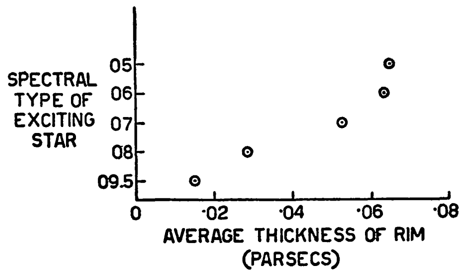


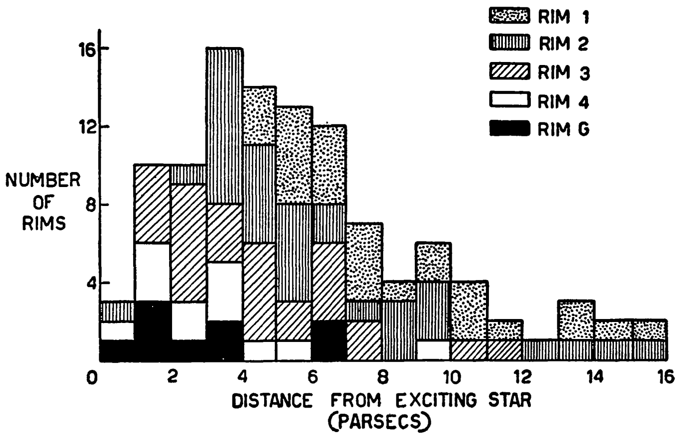
Figure 10 is a plot of the average thickness of the rims for each type of exciting star. There appears to be a general decrease in the thickness of the rims from O5 to O9.5.

There is a correlation between the thickness of the rim and the distance from the exciting star for the thin rims. For rims below about 0.035 parsecs in thickness, the correlation is strong, the thinner rims being located closer to the exciting star. Above the thickness of 0.040 parsecs the correlation completely disappears.

C. The shape of the bright rims. The bright rims were given a designation to indicate their shape. The key to the shape symbols is shown at the top of Table 3. Five shapes are distinguished, which, if given a reasonable amount of latitude, suffice to cover all of the observed shapes.

A more detailed histogram than Figure 5 showing the number of rims versus the distance from the exciting star is shown as Figure 11. Here the plot is

FIGURE 11



made separately for the rims of various shapes. It is clear that there is a distinct change in the form or shape of the rim with distance from the exciting star. Less rim 4's and globules G were recorded than other type rims as can be seen in Figure 11, but if the correction shown in Figure 5 is applied, the number of these rims rises so that it is about the same as the others. The data shown for rims of these two types will be less accurate than for the other rims, because of the smaller number. The uncorrected data are summarized in Table 5.

TABLE 5

shape	number observed	median distance from exciting star	average distance from exciting star	median thickness of rim	average density of rim	median length of arm
1	21	8.9 parsecs	8.5 parsecs	0.057 parsecs	206 cm^{-3}	2.85 parsecs
2	30	6.4	6.5	0.049	360	2.26
3	28	3.9	4.45	0.034	660	0.95
4	12	2.9	3.4	0.034	1190	0.85
G	7	2.6	3.4	0.023	1235	0.44

In initially recording the data, the globules were recorded merely because they showed bright rims. No connection was then suspected between them and the other rims.

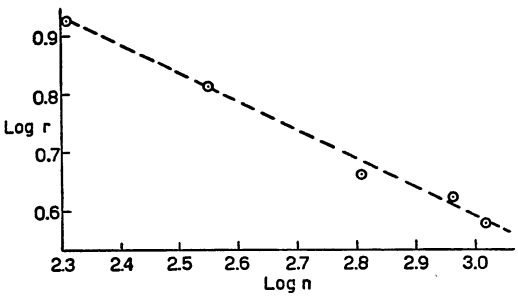
Although the similarity in shape between type G and the other types is not so marked, there do appear examples when it was difficult to classify the rim G or 4 or 3, or when a G rim appeared to be connected to a nearby bright rim. An excellent example of this appears in NGC 2244, where some of the inner rims seem to be composed of globules.

The physical properties of types 4 and G, listed in Table 5, suggest that type G belongs to the same sequence, slightly beyond type 4. The average distance and average density of each is about the same. Further the distances from the exciting star to the rim change smoothly from large distances for type 1 to small distances for types 4 and G. The densities derived from these data also change continuously. This seems adequate evidence to conclude that there is a real physical connection between the rims designated 1, 2, 3, 4 and G.

If these rims form an evolutionary sequence, the question arises: in which direction does the development of the rims proceed? All observations seem to point to a development beginning with type 1 and ending with types 4 and G. This is the direction of increasing distance from the exciting star, and of increasing density and decreasing size of the rim, and thus is the only logical direction if an evolution is assumed to be taking place in the nebulae with the bright rims as one of their visible consequences. All papers known to me on this subject indicate either explicitly or implicitly this direction, even without a knowledge of Table 5.

Figure 12 shows a logarithmic plot of the average distance from the exciting star for each type of rim against the average density. It should be borne in

FIGURE 12



mind that if the values of the density of rims were averaged for small intervals of distance, and then a plot of distance versus average density was made, the curve would have a greater slope than Figure 12. In this way the effect of averaging according to the type of rim can be seen.

D. The relative densities of rims and emission regions. It is important to investigate how the densities of the rims are related to the densities and sizes of the nebulae.

Before discussing this we may estimate the accuracy of the densities derived from equation 2 (page 78). The uncertainty in n^2 due to uncertainties in the numerical values of t and s_0 probably remains below a factor of 2. There might be some doubt, however, of the assumption made that matter between the exciting star and the rim may be neglected. This assumption is equivalent to assuming that most of the stellar radiation emitted in a small solid angle is used in ionizing the gases of the rim. The total number of recombinations to level 2 and higher per unit solid angle in a sphere of radius r is equal to $K N^2 r^3$, where N is the density of matter in the sphere, and the total number of recombinations to level 2 and higher per unit solid angle in a rim of thickness t is equal to $3 K n^2 r^2 t$ (assuming almost total ionization in both regions). Consequently the error made in neglecting the density N will be:

$$\frac{N^2 r}{3n^2 t},$$

which, if $n : N = 15 : 1$, $r = 5$ parsecs and $t = 0.05$ parsecs is 15%. These are probably typical values. The density ratio is uncertain and probably subject to change from one nebula to another. Some writers point to a density ratio of 100 : 1 between an HI and an HII region, but this would hold only under equilibrium conditions.

A curious question is raised by the conclusion just reached. If the matter between the star and the rim is negligible to the determination of the rim density, how is it possible to say in turn that we may eliminate the rims and use the STRÖMGREN method to determine the density of the whole nebula? The only correct answer seems that such a procedure cannot be justified in the solid angle subtended by the rims, but that this solid angle is really quite small. If this is true,

TABLE 6

nebula	N	n_{ave}	$\frac{n_{ave}}{N}$	diameter of nebula (parsecs)
NGC 7000	7.6	178	23.2	43
IC 1396	11.8	193	15.4	32
NGC 2244	23	433	18.7	31
IC 1848	28	234	8.4	12
IC 1805	32	400	12.8	26
NGC 281	46	403	8.9	13
NGC 6611	64	605	9.5	14
NGC 6514	148	1515	10.2	4
NGC 6523*	279	1820	6.6	4.5

* This refers only to the inner bright region.

the rims absorb little of the total radiation and the size of the sphere is still pretty well determined by the density of the diffuse nebula. This is supported by the observation that the nebulae extend beyond the bright rims. The computed densities may tend to be too high but should certainly be accurate within a factor of two.

Table 6 shows the average densities N of nine nebulae as well as the average densities, n_{ave}, of the rims in these nebulae. The ratio of the two, and the diameter of the nebulae are also given.

FIGURE 13

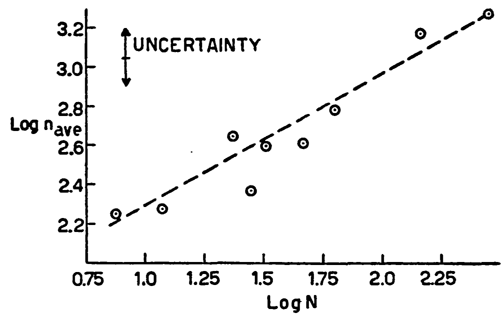


Figure 13 is a logarithmic plot of these data. The points fall around the straight line:

$$n_{ave} = 45\, N^{2/3}.$$

The smaller nebulae appear to have much higher average densities than the larger nebulae. Further, the ratio of rim density to average nebular density is lowest for the smallest nebulae.

5. *Summary of main observed characteristics of the bright rims.*

The bright rims are in general located at the edge of dark un-ionized matter. This dark matter is located in, or associated with, a diffuse emission nebula, which in turn is always associated with one or more early-type exciting stars. The shape of the emission complex is usually roughly circular. The bright rims may be distributed in this circle or may be slightly outside it. The bright rims are oriented so that they appear to be pointing almost exactly in the direction of the exciting star. In four cases no clear-cut emission region is seen and the rims have the form of 'continuous rims'.

In the emission complexes excited by the earliest type stars the rims are located more or less toward the centre of the emission region while for complexes excited by O9 or B0 stars the rims appear near the outer edge of the region. However, since the former emission regions are considerably larger than the latter, the average distance of the rim is larger for hotter stars.

The average thickness of the rim decreases with the decreasing temperature of the exciting star. There appears to be no correlation of the thickness of the rim with the distance of the rim from the exciting star, except for the thinner rims which lie closer to the exciting star.

There appears to be a distinct change in the form or shape of the rims with distance from the exciting star. The form seems to change in a continuous manner from rather flat rims in the direction of trunk-shaped rims and roundish globules, which seem to have no further connection with the dark matter. The flat rims appear to be larger and less dense than the trunk-shaped rims and the globules appear to have the smallest and densest of the rims.

The densities of the rims are 7 to 23 times the average densities in the emission region. The smaller regions tend toward the lower figure, while the larger regions show the higher figure.

This work was undertaken at the suggestion of Prof. H. C. VAN DE HULST, whose help and criticism during its preparation were invaluable.

The paper was prepared while the author was resident at the Observatory of Leiden, which was made possible by the hospitality of Prof. J. H. OORT and the staff of Leiden Observatory and the financial assistance of the United States Government through a Fulbright Fellowship.