Part VI: Conditions at the Ionization and Shock Fronts in Collisions of Gas Clouds

Bright Rims in Diffuse Nebulae

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I. INTRODUCTION

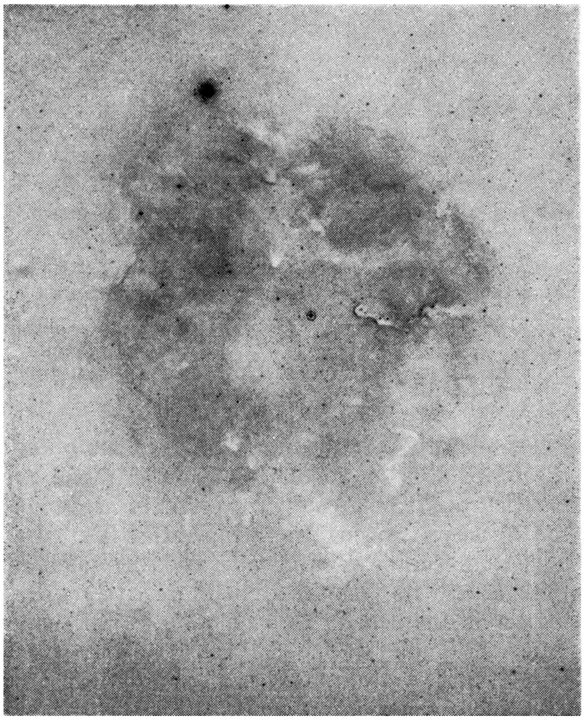
BRIGHT rims at the edge of dark markings associated with diffuse nebulae have been noticed for more than thirty years. An example is shown in Fig. 1, a photographic negative of the diffuse nebula IC 1396. Figure 1(a) shows the entire nebula, which is excited by an O6 star (circled). Figure 1(b) is an enlargement of one of the bright rims in this nebula. A number of general characteristics can be pointed out. The bright rim is always at the edge of what appears to be dark matter and always is bright on that side of the matter closest to the exciting star. If a line of symmetry is drawn through the dark material it is found in general to pass very near to the exciting star. Sometimes isolated matter similar to Bok's globules are present, and when present also show bright rims. These globules are included in the observational study.

I first describe the observations of more than 100 rims in 17 diffuse nebulae, all being excited by O stars. Measurements were made mainly of the distance of the rim from the exciting star, the thickness of the rims, and the length of the rims. Then I describe two different approaches to the study of the dynamics of the bright rim structures. I attempt to differentiate between the two dynamical theories by careful reference to the observations.

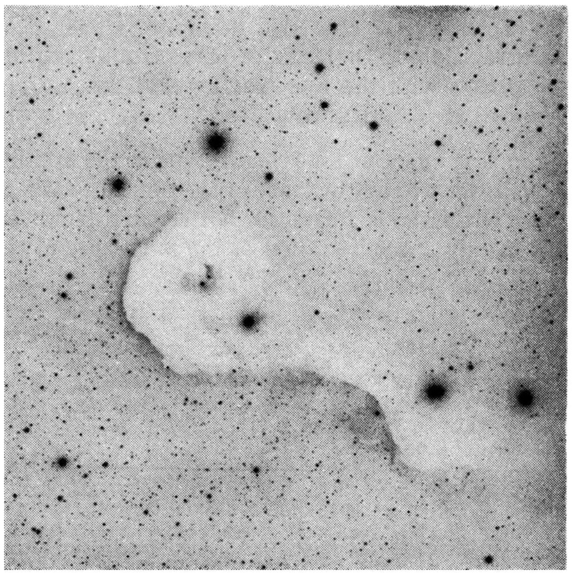
II. OBSERVATIONS

A. Directions of Bright Rims

As mentioned before it has been noted that a line of symmetry through the bright rim structure when extended passes very close to the exciting star. This effect can be measured by the angle between this line of symmetry and a line drawn between the rim and the



(a)



(b)

FIG. 1. (a) The diffuse nebula IC 1396 illustrating several examples of bright rim structures. The exciting star is circled. The photograph is a negative. (b) An enlargement of one of the bright rims in the nebula IC 1396. The photograph is a negative.

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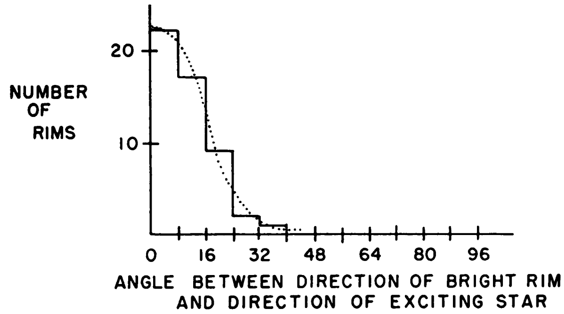

FIG. 2. The bright rims appear to "point" towards the source of exciting radiation. This is illustrated by plotting the number of rims against the angle between the direction of the bright rim and the direction of the exciting star from the bright rim.

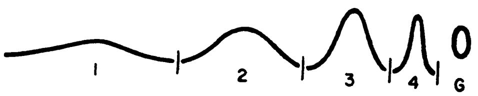

FIG. 3. A key to the classification of the shape of the bright rims used throughout this paper.

exciting star. The results are shown in Fig. 2. Over 70% of the observed rims "point" in a direction within 10° of the exciting star. This phenomenon has been noted by all observers and these measurements are due to Osterbrock.[1]

B. Shape of the Rims

Each rim observed was assigned a shape as shown in Fig. 3. Five different classes were distinguished and although some rims did not exactly fit into the classification there was never a great difference. The class numbers will be used to represent the shapes throughout the rest of this paper.

C. Correlation of Distance of Rims from Exciting Star with the Spectral Type of the Exciting Star

Figure 4 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

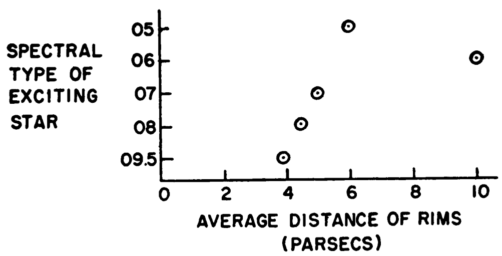

FIG. 4. The average distance of the bright rims from the exciting star is shown as a function of the spectral type (temperature) of the exciting star.

complex for earlier-type exciting stars. This is shown in Fig. 5 where the spectral type of the exciting star is plotted against the ratio "distance of closest rim/radius of nebula." A gradual change of rim position in the nebula is noted as a function of temperature. This is the first of several indications that the dynamics of the bright rims are closely connected with the dynamics of the diffuse nebula as a whole.

The choice of the "closest rim" is only a convenient one and the use of "average distance of rims" gives the same result.

D. Correlation of Average Thickness of Rim with Spectral Type of Exciting Star

The results are shown in Fig. 6. There appears to be a general decrease in the thickness of the rims with the decrease in temperature of the exciting star.

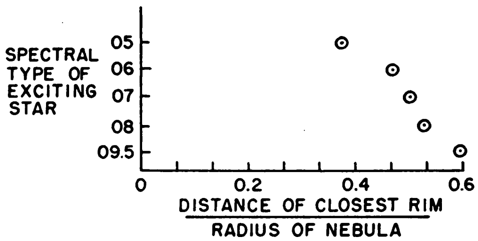

FIG. 5. The distance of the closest bright rim in a given nebula, divided by the radius of that nebula, is shown as a function of the spectral type of the exciting star.

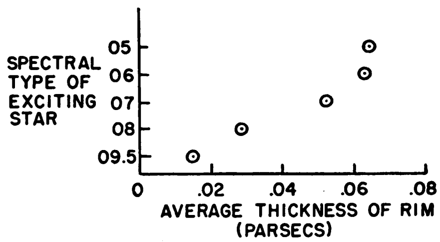

FIG. 6. The average thickness of the bright rims is plotted as a function of the spectral type of the exciting star in the nebula in which the bright rim is found.

E. Densities of the Rims and Discussion of Shape Variations

The densities were found from the assumption that the rim can be considered in effect a Strömgren shell and that the Strömgren[2,3] analysis can be used to obtain the density, knowing the temperature and absolute magnitude of the exciting star and the thickness of the rim and its distance from the exciting star. The results on the density as a function of rim shape are shown in Table I. The flat rims, type 1, have the lowest density, are located farthest from the exciting star, have the thickest rims, and have the largest length of the rims. There is a continuous change of

[1] D. Osterbrock, Astrophys. J. 125, 622 (1957).

[2] B. Strömgren, Astrophys. J. 89, 526 (1939).

[3] B. Strömgren, Astrophys. J. 108, 242 (1948).

each of these quantities as one proceeds from the flat rims to the more pointed rims.

F. Conclusion that Globules are Related to the Rims and Deductions as to the Densities of These Globules from This Relationship

An interesting feature of Table I is the relationship it indicates between the rims 1–4 and the globules *G*. The globules are apparently a direct extension of the sequence and presumably there is a close physical relationship between rims 1–4 and *G*. We conjecture from this table that an evolutionary sequence exists in the rims, and that their development proceeds in the direction from the flat rims through the pointed rims to the globules. This is in agreement with the assumption that the rims began their evolution when the ionizing radiation first reached the dark matter, since the type 4 and *G* rims are close to the exciting star and the flat rims farther away.

If we now say that the globules we have observed[4] are very similar to the globules of the same size observed by Bok (and there is no reason to assume otherwise)

TABLE I.

Shape	Number observed	Median distance from exciting star (pc)	Average distance from exciting star (pc)	Median thickness of rim (pc)	Average density or rim (cm^{-1})	Median length of arm (pc)
1	21	8.9	8.5	0.057	206	2.85
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

we can use Bok's[5] star count determination of the density of the dark matter in the globule as an approximation to the density of the dark matter behind the rims. Then we can approximately determine the pressures in the 3 regions: *A* in the diffuse nebulae, *B* in the bright rim, and *C*, the dark region behind the bright rim. This is shown in Table II. Notice that the pressures in the rim and behind the rim are about the same order of magnitude.

G. Relation of the Densities of the Rims to Those of the Nebulae in Which They Are Situated

Table III shows for 9 nebulae the average density of matter in the nebula, N (computed on the basis of a Strömgren sphere), the average rim density n_{Av}, the ratio of the two, and the diameter of the nebula. The values of both N and n_{Av} increase with decreasing diameter of nebulae but the ratio n_{Av} decreases with decreasing diameter of nebulae.

[4] S. Pottasch, Bull. Astron. Inst. Neth. **13**, 71 (No. 471) (1956); **14**, 29 (No. 482) (1958).
[5] B. J. Bok, Harvard Monographs No. 7, 53 (1948).

TABLE II.

	Temperature (°K)	Density (atoms/cm^3)	Pressure (dynes/cm^2)
Region *A*	10 000°	20	5×10^{-11}
Region *B*	20 000°	300	160×10^{-11}
Region *C*	100°	100 000	140×10^{-11}

III. DYNAMICS OF BRIGHT RIMS

A. The Bright Rims as Evidence for the Occurrence of Rayleigh-Taylor Instability

In the light of the preceding observations we intend to analyze the suggestion by Spitzer[6] that the Rayleigh-Taylor hydrodynamic instability causes the bright rim structures.

This instability results from a perturbation at the interface between two fluids of greatly differing densities in the presence of an acceleration field. The development of this instability is shown in Fig. 7, where the arrows in the center of the figure indicate that the acceleration field may be either a gravitational field or a greater pressure of the lighter gas. In the interstellar case, Spitzer proposed that the dark matter is the dense fluid, and the HII region the less dense fluid, while the pressure of the expanding HII region provides the accelerating force.

The major reason that the Rayleigh-Taylor instability is considered is the likeness in form between the shapes predicted by the theory and those seen in the experiments of Lewis,[7] and the shapes seen in diffuse nebulae.

Note, however, that the geometry differs between the gravitational and interstellar cases. The direction of the gravitational field is fixed, independent of structure. When the interstellar structure begins to form, the acceleration field acts perpendicular to the *local* surface of the rim, thus no longer resembles the gravitational configuration. Thus the resemblance to laboratory experiments and to theory loses significance.

The analogy also loses some of its force from an empirical standpoint when the Rayleigh-Taylor predictions of shape are plotted against the observations in a

TABLE III.

Nebula	N	n_{Av}	n_{Av}/N	Diameter of nebula (pc)
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

[6] L. Spitzer, Astrophys. J. **120**, 1 (1954).
[7] D. J. Lewis, Proc. Roy. Soc. (London) **A202**, 81 (1950).

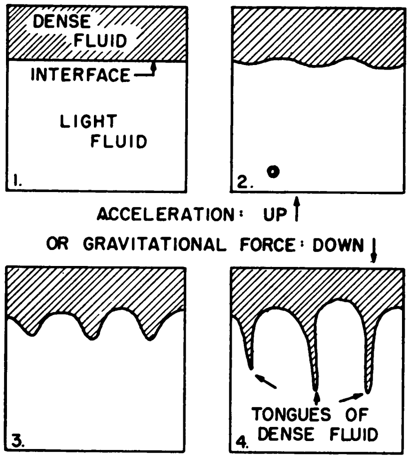

FIG. 7. The progress of the Rayleigh-Taylor instability as illustrated by Spitzer. The dense fluid forms tongues which penetrate into the light fluid.

diffuse nebula on a scale normalized so that the flat rims (type 1) are of equal size. Then for the Rayleigh-Taylor instability, shapes type 2 to 4 would have the same width (wavelength), but they would have increasingly greater heights, so that type 4 would be several orders of magnitude greater than type 1. This is not true, however, for the development of the bright rim structures. As can be seen from Table IV, the initial stages (the flat rims) are characterized by large widths, which become progressively smaller toward the more pointed rims. The heights or lengths of the bright rim structures remain constant during the development of the bright rim structures.

The final proof against Rayleigh-Taylor instability being the cause of the bright rims, however, comes from a consideration of the time required for the formation of the rims, which can be computed on the basis of D. Layzer's complete theory[8] of the R.T. instability, using the preceding observational data. The results of this computation are shown in Table IV. The first two columns are the observations. It is to be noticed that the height or length of the rim remains about constant, while the width or "wavelength" of the rim changes considerably between the flat and the pointed rims. This leads to the result that the type 4 or pointed rims are much younger than the flat rims, because on the basis of the R. T. theory the small wavelengths (widths) evolve much more quickly than the longer.

This result that the pointed rims are much younger than the flat rims contradicts the initial premise that

TABLE IV.

Shape	Height	Width	Height/Width	Time (years) for formation of rim with initial perturbation 10^{-4}	10^{-2}
1	0.43 pc	2.85	0.15	1.8×10^6	7.3×10^5
2	0.59	1.92	0.31	1.5	6.7
3	0.42	0.50	0.82	0.73	2.8
4	0.42	0.26	1.58	0.50	1.7

[8] D. Layzer, Astrophys. J. **122**, 1 (1955).

the instability begins when the HII region reaches the position where the rim will form. Since the unstable regions move toward the exciting star, the rims closest to the exciting star would be expected to be the oldest. But the type 4 rims are closest to the center and the type 1 farthest away, indicating in this way that the type 4 rims are older than the type 1. This contradiction is unavoidable on the basis of the observations and must lead to a rejection of the Rayleigh-Taylor instability as the cause of the bright rim structures.

B. Considerations on an Alternate Theory

1. Configuration of the Rim

The observations imply that the exciting star plays a very important part in the state and development of the bright rim structures. Thus to develop an understanding of the bright rims the first question to be asked is, "How does the ionizing radiation interact with the un-ionized gas?." The answer to this question

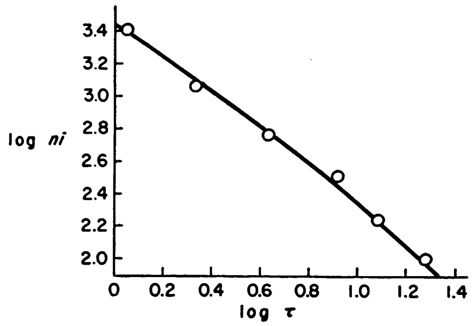

FIG. 8. A comparison of the predicted values of the electron density for an average amount of ionizing radiation (solid line) with the observed values of electron density N_i averaged in six distance intervals (open circles). The unit of distance is the parsec.

forms a basis for the discussion of the dynamics of bright rims.

A large amount of ionizing radiation incident on a gas of very low density quickly ionizes but imparts little momentum. Essentially, we treat each gas atom individually in its interaction with the radiation field. Following Kahn's notation, the gas in this state will be called R type. Decreasing the amount of ionizing radiation or increasing the density of the gas forces us to consider the behavior of the gas as a whole. The onset of ionization increases the gas pressure, a shock wave will develop and propagate into the gas and cause its motion away from the source of ionization. This case will be called M type, and the transition between M type and R type will be called R critical. If now the amount of ionizing radiation is decreased further, or the density further increased, then the ionizing radiation will be totally absorbed before it penetrates through a significant fraction of the gas, and any mechanical effect on the gas as a whole will be small, the chief result being that the gas on the inner border may expand toward the source of ionizing radiation. This case is called D type. The transition between D type and M type is called D critical.

An ionization front is always associated with the D-critical condition, if the ionization front is stable. Kahn[9] has predicted the relation between ionizing radiation and density for the D-critical condition in the one-dimensional case. We may attempt to check our presumption that the bright rim is an ionization front by comparing Kahn's predictions of density for the D-critical condition with the observations of density previously made. This comparison is shown in Fig. 8, where log density is plotted *vs* log distance. The solid line is the prediction assuming an average amount of ionizing radiation, while the open circles are the average values of the electron density observed in the distance interval under consideration. There are many sources of error, both random and systematic, in the plot and the results can be considered most encouraging.

With this rough success for the one-dimensional model, a transition to a three-dimensional model was attempted. The model simply consists of a part of a spherical surface with a given radius of curvature R_c.

TABLE V.

$T=38\,000°$		$R=10$ solar radii	
r	T_i	n_i	n
1	36 000°	2700	5.1×10^6
2	30 000	1320	2.1×10^8
4	24 000	620	8.0×10^5
8	19 000	320	3.2×10^5
12	16 500	170	1.5×10^5
20	13 000	80	5.7×10^4

The ionized matter is moving away from this surface (toward the exciting star) with a constant velocity of about 16 km/sec. The density at any point between the front and the exciting star is then proportional to r^{-2}. The temperature of this ionized matter is probably determined by the quality of the radiation at each point in the ionized matter. Cooling is probably not a significant effect close to the rim, since the time in which matter moving at this speed remains in a small region is probably short compared to the time required to reach equilibrium by cooling.

Table V shows how the temperature and density at the ionization front vary as a function of distance from the exciting star. The last column shows the predicted density behind the ionization front in atoms/cm^3.

If the temperature in the ionized gas is known, then the recombination coefficient is known, and the emission per cm^2 is the integral of the emission per cm^3 along the line of sight. Thus the brightness profile of the rim along a symmetric line through the rim, assuming the rim to be in a plane perpendicular to the line of sight, can be computed. The profile is a function of the tem-

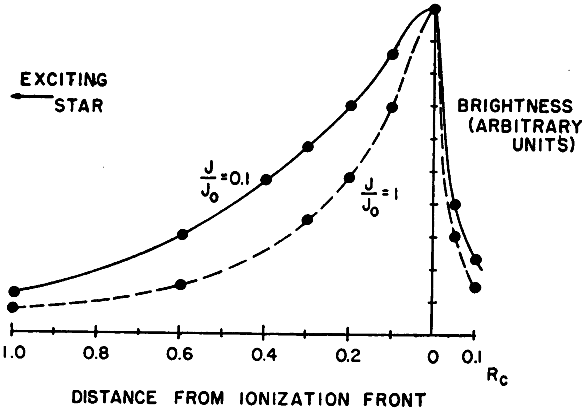

FIG. 9. The predicted brightness profile of a bright rim, as a function of the distance from the ionization front, in units of the radius of curvature of the bright rim. Two curves are shown, which differ in the ratio of the ionizing radiation reaching the ionization front, to the amount of ionizing radiation which would have reached this point in the absence of the bright rim.

perature of the exciting star, the distance of the rim from the exciting star, and the radius of curvature. Figure 9 shows the computed brightness profile; the solid line a rim close to the exciting star, and the dotted line for a rim further away. The abscissa is given in units of the radius of curvature.[10]

The brightness profile may be checked in a qualitative way. Figure 10 shows the observation by Osterbrock of a rim in 1C 1936 and the prediction, which is the same as the solid curve in Fig. 9. The similarity is striking. No quantitative comparison was made, however, since Osterbrock's brightness is given in arbitrary units, and the method of taking into account the background light of the nebula is rudimentary.

From the knowledge of how the brightness profile depends on the distance from the exciting star, and on the radius of curvature, it is possible to predict the thickness of the rim, assuming the edge to occur where the brightness falls to $\frac{2}{3}$ of its maximum value. The results are shown in Table VI. The agreement with

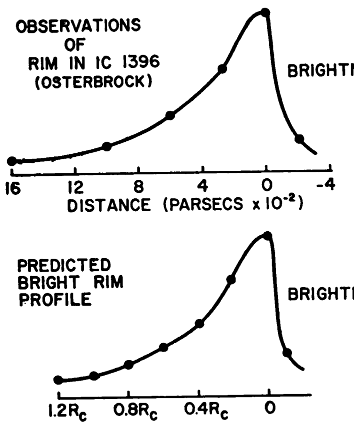

FIG. 10. A comparison of the brightness profile observed by Osterbrock in the nebula IC 1396 and the predicted brightness profile. The distance scales may be converted into the same units, but the brightness scales are arbitrary.

[9] F. Kahn, Bull. Astron. Inst. Neth. **12**, 187 (No. 456) (1954).

[10] The details of this computation are given by S. Pottasch, Bull. Astron. Inst. Neth. **14**, 29 (No. 482) (1958).

TABLE VI.

Rim shape	Observed R_e	Predicted thickness units of R_e	pc	Observed thickness
G	4×10^{17} cm	0.16 R_e	0.022	0.023
4	5	0.16	0.027	0.034
3	7.5	0.15	0.036	0.034
2	10.5	0.14	0.052	0.049
1	17.0	0.12	0.066	0.058

observation is good, particularly as regards the dependence of thickness on rim shape.

2. *Evolution of the Bright Rims*

In order to give a qualitative picture of the evolution it is necessary to assume that inhomogeneities exist in the initial medium, with the density decreasing from the center of the inhomogenity toward its outside. The mechanism of evolution must be one which will be capable of amplifying the initial density inhomogeneities and of producing the observed shapes.

When the ionizing radiation first is incident on this region, the size of the rim or visible boundary of the region will be determined by the density at which the R-critical condition is reached. Since the R-critical condition is not a stable one, and the conditions which follow the R-critical condition require a higher density (which is found closer to the center of the region), the initial stage of the evolution is short lived and associated with the largest size of rim.

Consider what happens on a line connecting the source of radiation with the center of the region. The matter on the outer edge of the region nearer the star will be compressed toward the center until a D-critical density is reached, after which there will be no further large-scale motions of the gas. But on a line connecting the exciting star with points to the side of the center, the density of matter will not easily become great enough to effect the D-critical condition. Certainly at some distance from the center of the region, the density will never become great enough to allow a stable D-critical condition, and the matter at these points will remain in motion, with respect to the center of the region. This action can be thought of as an etching effect of the radiation which will produce an elongated shape pointing in the direction of the exciting radiation.

This agrees at least qualitatively with the observations. The rim is larger at the beginning of its evolution and smaller and elongated toward the exciting star in the later stages. The more elongated rims would then be closer to the exciting star because they are the older rims.

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On the Stability of Ionization Fronts

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1. INTRODUCTION

THE boundaries between HII and HI regions often have shapes which suggest that the motion of the interstellar gas is unstable there. A characteristic shape of this kind is the so-called "elephant's trunk," a long tongue of dark material (presumably an HI region) seen superimposed on the luminous HII region, and outlined by a thin rim brighter than the luminous background. A detailed study of these shapes has recently been made by Pottasch[1]; earlier observations had been made by Duncan[2] and by Struve.[3]

Pottasch found that the bright rims always appear on the side facing towards the luminous star which is exciting the HII region, that these stars are almost always earlier in type than O9, and that the density of the ionized gas in the rims is of the order 100 to 200 ions and electrons/cm^3. This means that the density, and consequently the gas pressure, in a bright rim is 10 or more times greater than it is in the background HII region. It seems unlikely that any instability can arise at such an HII-HI boundary with the hot and light gas in the HII region pushing against the cool and dense gas in the HI region. Van de Hulst[4] and later Frieman[5] have made some suggestions of what might happen if the hot gas *were* at higher pressure, and the latter concluded that elephants' trunks might, indeed, be formed. However, the relation between the gas pressures in the rims and the background HII regions indicates that it is more probable that the ionized gas is streaming away from the ionization front at the

[1] S. Pottasch, Bull. Astron. Soc. Neth. **13**, 77 (No. 471) (1956).
[2] J. Duncan, Astrophys. J. **51**, 4 (1920).
[3] O. Struve, Astrophys. J. **85**, 208 (1937).
[4] H. C. van de Hulst, *Gas Dynamics of Cosmic Clouds*, edited by H. C. van de Hulst and J. M. Burgers (North-Holland Publishing Company, Amsterdam, the Netherlands, 1955), Chap. 19.
[5] E. A. Frieman, Astrophys. J. **120**, 18 (1954).