REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 3 JULY, 1958

Part I: Empirical Studies of Velocity Fields in, and Related Structure of, the Interstellar Medium

Density and Velocity Distribution of the Interstellar Gas

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1. INTRODUCTION

THE interstellar gas shows wide variations in density and in velocity. Common words to describe the existence of these variations are **cloudiness** for the density and **turbulence** for the velocity field. These terms have initially been introduced as vague descriptions and were not based on mathematical analysis or dynamical theory. The word **cloud** as used by astronomers did not always mean a region of large density with relatively sharp boundaries; nor did the word **turbulence** necessarily imply a velocity field with well-defined statistical regularities and energy dissipation by means of viscosity.

A question put in such terms may not have a definite answer. For instance, it may not be meaningful to ask for the number of clouds per unit volume. The schematic picture of discrete clouds is helpful in some problems, but in other respects misleading; the same holds true for the schematic picture of turbulence.

The meaningful question, of course, is how to understand and explain the beautiful phenomena laid before us by a large variety of observational methods. Evidently, schematic descriptions are indispensable in trying to gain this understanding. However, a description found helpful in one context may fail in another. We should not be surprised, therefore, to find different "sizes of interstellar clouds" determined from different sets of data.

Information on the structure and motions of the interstellar gas is very incomplete. We should like to have a full distribution function in three space coordinates and three velocity coordinates. Actually we never resolve more than one velocity coordinate (in the line of sight) and two space coordinates (across the line of sight) and very rarely a combination of these measurements on the same object is possible. A schematic survey of the resolution obtained by various methods is given in Table I.

Most of these data refer to relatively near regions of space. Reliable distance estimates for objects farther from the sun than 2 or 3 kpc still are exceptional. The region within 3 kpc, shown in Fig. 1, comprises parts of at least four spiral arms. The names Perseus arm, Orion arm, and Sagittarius arm were proposed by van de Hulst, Muller, and Oort[1] after their most prominent associations of O and B stars.[2] They have since been generally adopted. The coincidence between high hydrogen density and associations is fairly good in the northern sky, except near $l=40°–50°$, where the associations appear to fall in a region of very low hydrogen density. The more confused situation in the southern sky is not due solely to incompleteness of the observations. It is not certain whether the Orion arm really continues as suggested in Fig. 1, because a break at $r=2$ kpc, $l=210°–220°$, is suggested both by the Cepheids and by the hydrogen. Another arm, tentatively called the Carina arm is outlined both by the Cepheids and by the hydrogen data. The "inter-arm

Table I. Resolving power in the observable coordinates.

Object and method of observation	Quality of best data: Distribution on sky	Quality of best data: Distribution in velocity
1. Sizes and structural details of emission regions from photographs	fine	...
2. Studies of selected emission regions by means of interferometer, multislit technique, and nebular spectrograph	fair	fair
3. Multiple interstellar absorption lines	scanty data	fair
4. Studies of 21-cm line in emission and absorption	low resolution	fine
5. Studies of emission regions in cm waves	low resolution	...
6. Sizes and structural details of dark clouds from photographs	fine	...
7. Distribution of dark matter from fluctuations in apparent density of stars and/or galaxies	fair	...

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[1] van de Hulst, Muller, and Oort, Bull. Astron. Inst. Neth. **12**, 117 (No. 452) (1954).

[2] Morgan, Whitford, and Code, Astrophys. J. **118**, 318 (1953).

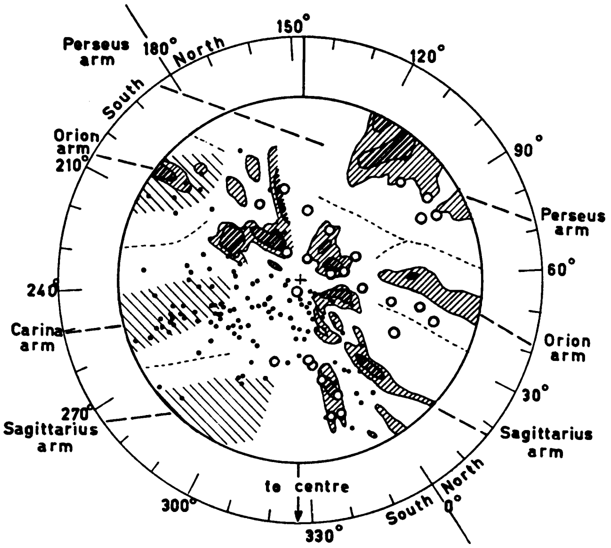

FIG. 1. Sketch of the spiral arms within 3 kpc of the sun. Circles: O-associations.[2] Dots: southern Cepheids.[7] Shaded parts: regions where atomic hydrogen is densest. In the northern part the shadings indicate $N > 1.6$ cm^{-3} and $0.8 < N < 1.6$ cm^{-3}.[6a, 8] The light shading in the southern part roughly indicates regions of high density.[4] Dotted lines: interarm valleys from the hydrogen data. Heavy dashed lines: tentative course of spiral arms (see text).

link" discovered by Gum[3] in the distribution of southern emission nebulae coincides with the Carina arm and may be identified with it. Kerr[4] tentatively linked this arm to the Orion arm, but the heavy concentration of hydrogen and Cepheids at $l = 330°$–$0°$, within 1 kpc, is the more likely continuation of the Carina arm. Finally the hydrogen near $l = 280°$, $r = 3$ kpc may quite well be the continuation of the Sagittarius arm outlined by associations and high hydrogen density near $l = 320°$; how this arm continues further north is again a problem. Thackeray's data[5] on multiple absorption lines in southern stars do not yet fit too well in this picture.

If the sketch given in Fig. 1 is basically correct, the sun is not really located in a spiral arm. It is about 0.4 kpc to the inside of the heaviest parts of the Orion arm, and about 0.6 kpc to the outside of the heaviest portions of the Carina arm. Moreover, it is about 25 pc north of the galactic plane.[6,7,*]

2. DISTRIBUTION OF INTERSTELLAR GAS ON A GALACTIC SCALE

The studies of the 21-cm line of atomic hydrogen during the past years have confirmed the general characteristics of the gas in our neighborhood: average density in plane, 0.7 atom per cm^3; i.e., about 20% of the stellar density; thickness of layer perpendicular to plane, measured between the points where the density is half the maximum density, 220 pc; deviations from circular velocity remain below 10 km/sec. These points I shall presently discuss in connection with the optical data.

Furthermore, the 21-cm studies have shown that other parts of the galactic system display gas motions of a different character. Some of these results are still provisional and have hardly any optical data for comparison. Yet they are of high importance for the topic of our Symposium.

A. The Galactic Disk; Density and Rotational Velocity

Let R be the distance from the galactic center. Schmidt[8] found the thickness of the hydrogen layer remarkably constant (220 pc). The density in the plane, averaged out over the spiral arms, reaches a maximum of 1 atom per cm^3 at $R = 6.5$ kpc and then falls gradually to zero at $R = 16$ kpc.[6a] The density in

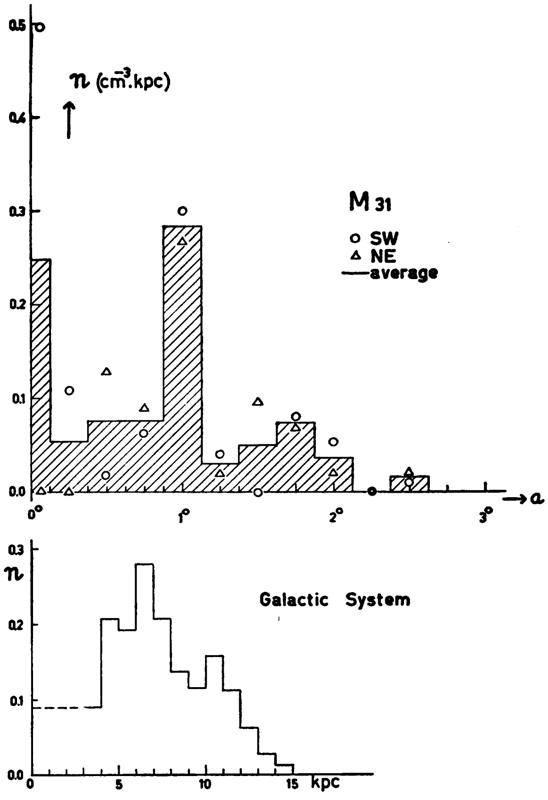

FIG. 2. Smoothed hydrogen densities in the Andromeda Nebula and in the galactic system. Ordinate: (number of atoms per cm^3) × (thickness in kpc perpendicular to the plane of symmetry). Abscissa: distance from the center, drawn on equal scales.

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[3] C. S. Gum, Mem. Roy. Astron. Soc. **67**, 156 (1955).

[4] Kerr, Hindman, and Carpenter, Nature **180**, 677 (1957).

[5] A. D. Thackeray, Mém. soc. roy. sci. Liège **15**, 437 (1955).

[6] G. Westerhout, (a) Bull Astron. Inst. Neth. **13**, 201 (No. 475) (1957); (b) "Radio astronomy." *I. A. U. Symposium No. 4* (Cambridge University Press, New York, 1957), p. 22.

[7] Walraven, Muller, and Oosterhoff, Bull. Astron. Inst. Neth. **14**, 81 (No. 484) (1958).

* *Note added in proof* (*June, 1958*).—Since this was written a map of the spiral structure in the galactic system based on a combined discussion of northern and southern data has been prepared for publication by Oort, Kerr, and Westerhout, Monthly Notices Roy. Astron. Soc. (to be published).

[8] M. Schmidt, Bull. Astron. Inst. Neth. **13**, 247 (No. 475) (1957).

the inner parts is about 0.4 cm^{-3}. The Andromeda Nebula[9] has densities quite comparable to those in the galactic system (Fig. 2). The maximum is near 1°, i.e., R about 10 kpc, and a gradual fall in density occurs beyond that distance.

The velocities of circular motion in the galactic system and the Andromeda Nebula are very similar. Figure 3 shows the best data available for both systems. If R and v are expressed in the units kpc and km/sec, the revolution period is

$$P = 6.12(R/v) \times 10^9 \text{ years.}$$

Mass distributions that would give rise to these rotation values have been derived for both systems by Schmidt.[10,11] Table II summarizes the main results. The adopted distance of the Andromeda Nebula is $500c$ kpc, where c is a scale factor to allow for the uncertainty in distance scale.

Table II. Comparison of galactic system and Andromeda Nebula.

	Mass, expressed in 10^9 solar masses		
	Atomic hydrogen	Grand total	Percentage of hydrogen
Andromeda Nebula	$2.5c^2$	$270c$	$1.0c$
Galactic system	1.5	100	1.5
Near sun			15

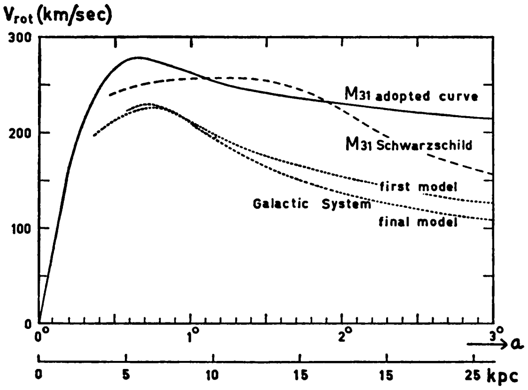

FIG. 3. Rotational velocity in the Andromeda Nebula and in the galactic system. Abscissa: distance from center.

B. High-Latitude Observations; Galactic Corona

The existence of an extended gas corona around the galactic system has been discussed by Pickelner,[12] by Spitzer,[13] and by Pickelner and Shklovsky.[14] Surveys of the continuum of radio waves in the meter range show convincingly that there is strong radio emission from a region in space that shows little flattening (axial ratio 0.7) and extends to about 15 kpc from the galactic center.[15]

The information contained in the observations of the 21-cm line is less conclusive. Figure 4 shows preliminary profiles measured in 4 high-latitude fields with a band width of 135 kcps = 28.5 km/sec between half-power points. The measured profiles are nearly twice as wide. This means an rms velocity component in the line of sight equal to 30 or more km/sec, somewhat wider than found in earlier results with a smaller telescope and a smaller band width.[6b] These velocities are higher than the ordinary gas velocities in the plane, but not nearly high enough to send the gas to very large distances from the galactic plane. The space distribution thus should be intermediate between "disk" and "halo." In three of the four fields a preponderance of negative velocities is seen, indicating that more atomic hydrogen rains down on the galactic plane than is moving away from it. The low maximum between −100 and −200 km/sec may still turn out to be an instrumental effect. Omitting this wing we find $\int T dv \approx 300\,°\mathrm{K}\cdot\mathrm{km/sec}$ from which follows $\int N dl = 6.0 \times 10^{-4} \times 300 = 0.2\ \mathrm{cm}^{-3}\cdot\mathrm{kpc}$. With an effective path length 2 kpc this gives a volume density of 0.1 atom per cm^3.†

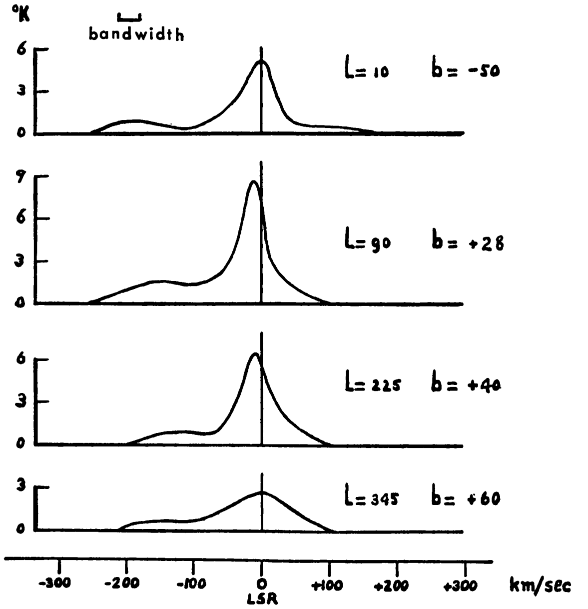

FIG. 4. Provisional 21-cm line profiles in high-latitude fields. Abscissa: velocity with respect to the local standard of rest.

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[9] van de Hulst, Raimond, and van Woerden, Bull. Astron. Inst. Neth. 14, 1 (No. 480) (1957).

[10] M. Schmidt, Bull. Astron. Inst. Neth. 13, 15 (No. 468) (1956).

[11] M. Schmidt, Bull. Astron. Inst. Neth. 14, 17 (No. 480) (1957).

[12] S. B. Pickelner, Izvest. Krymsk. Obs. 10, 74 (1953).

[13] L. Spitzer, Astrophys. J. 124, 20 (1956).

[14] S. B. Pickelner and I. S. Shklovsky, Astron. Zhur. 34, 145 (1957).

[15] J. E. Baldwin, Monthly Notices Roy. Astron. Soc. 115, 691 (1956); "Radio astronomy," *I. A. U. Symposium No. 4* (Cambridge University Press, New York, 1957), p. 233.

† *Note added in proof* (*June, 1958*).—Measurements with a band width of 10 kcps show at the north pole (second field in Fig. 4) a much narrower line with top 22°K, total half-width g km/sec, and wings extending to ±50 km/sec. Any wings at velocities >70 km/sec, if present at all, must be well below 1°K.

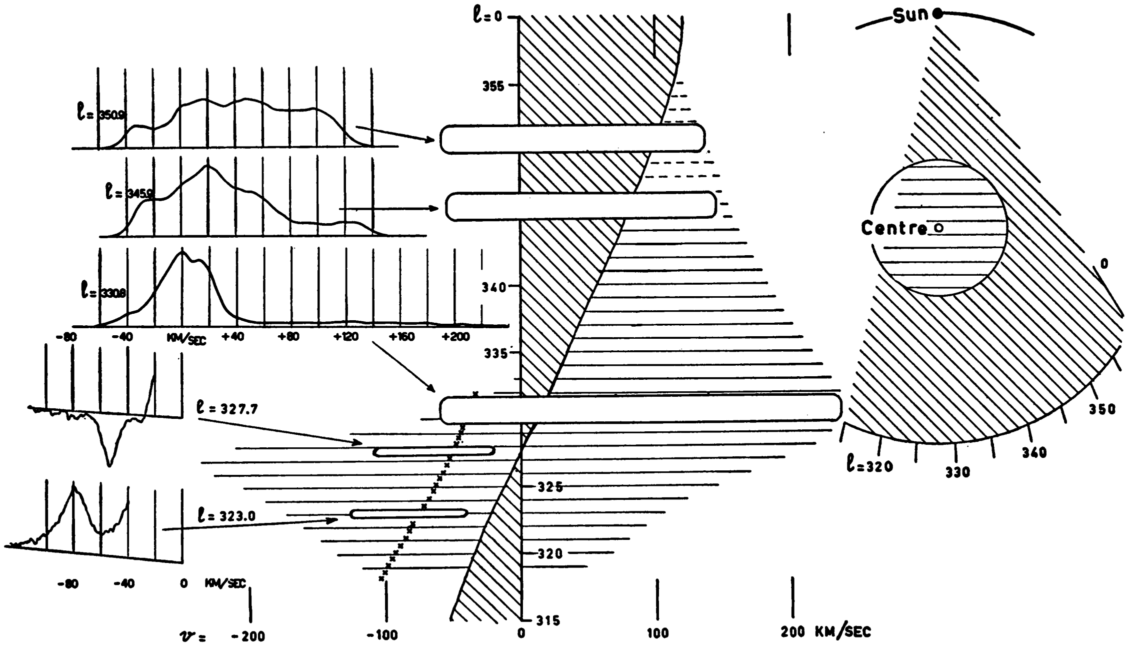

FIG. 5. High velocities and evidence for expansion in the central regions of the galactic system. Left: 5 measured profiles of the 21-cm line. The upper three with a 7-meter mirror,[6,25] the lower two with a 25-meter mirror.[16] Middle: A longitude-velocity diagram in which the shaded area indicates the velocities expected on the basis of differential rotation and the horizontal lines the additional wings due to gas near the center. The crosses indicate the expanding arm. Right: Geometrical situation in the galactic plane. Shadings corresponding to central graph indicate main region of origin of the radiation.

C. Expanding Motion near the Galactic Center

The 21-cm observations in and near the galactic plane indicate a fairly sudden change in the state of motion of the interstellar gas near $R=3$ kpc. The parts outside $R=3$ kpc (see *A*, above) give no problems of interpretation if we assume small random motions superposed on the general motion in circular orbits. Let us for a moment assume that the same description would hold true for the innermost parts of the galactic system. Omitting the radiation from regions beyond 8 kpc from the galactic center, we then should find the emission confined to the shaded area in Fig. 5. Instead, near 20° longitude from the center the line profile begins to develop long tails, which have very weak intensities but extend to maximum velocities of ±250 km/sec.

Initially, these tails were interpreted as a sign of turbulence of the gas with $R<3$ kpc. The structure in these tails has now been further explored with the much narrower beam of the 25-meter telescope at Dwingeloo.[16] It turns out that the arm causing the highest maximum in these tails can be traced from $l=331°$ to $l=319°$ (horizon) and is visible in absorption at $l=327°$. This means that the gas in this arm moves away from the center at a velocity of 50 km/sec, beside partaking probably in the general rotational motion. The density in this arm fits in quite well with the general density distribution discussed earlier. It might be 0.5 or 1 atom/cm^3 over a distance of 1 or 0.5 kpc. Even more extreme instances of such an expanding motion are suspected and are still being studied.

3. SPECTRAL STUDIES OF CLOUDS AND CLOUD MOTIONS

We now return to the local area and to the problem of the velocity field in the neighborhood of the sun. The most relevant data at the time of the earlier Symposia[17–19] were the observations of multiple absorption lines of Na and Ca$^+$ in the spectra of bright stars by Adams.[20] They have since been greatly extended by Münch[21] and the 21-cm observations, both in emission and absorption, may now be cited as an equally important source of information.

A striking property of the interstellar absorption lines is that they consist of a number (1–7) of separate components. This suggests at once that each component

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[16] van Woerden, Rougoor, and Oort, Compt. rend. **244**, 1691 (1957).

[17] B. Strömgren, "Problems of cosmical aerodynamics," Central Air Documents Office, Dayton, Ohio, 1951, p. 8.

[18] R. Minkowski, "Gas dynamics of cosmic clouds," *I. A. U. Symposium No. 2* (North-Holland Publishing Company, Amsterdam, the Netherlands, 1955), p. 3.

[19] J. H. Oort, "Gas dynamics of cosmic clouds," *I. A. U. Symposium No. 2* (North-Holland Publishing Company, Amsterdam, the Netherlands, 1955), p. 20.

[20] W. S. Adams, Astrophys. J. **109**, 354 (1949).

[21] G. Munch, (a) Publs. Astron. Soc. Pacific **65**, 179 (1953); (b) Astrophys. J. **125**, 42 (1957).

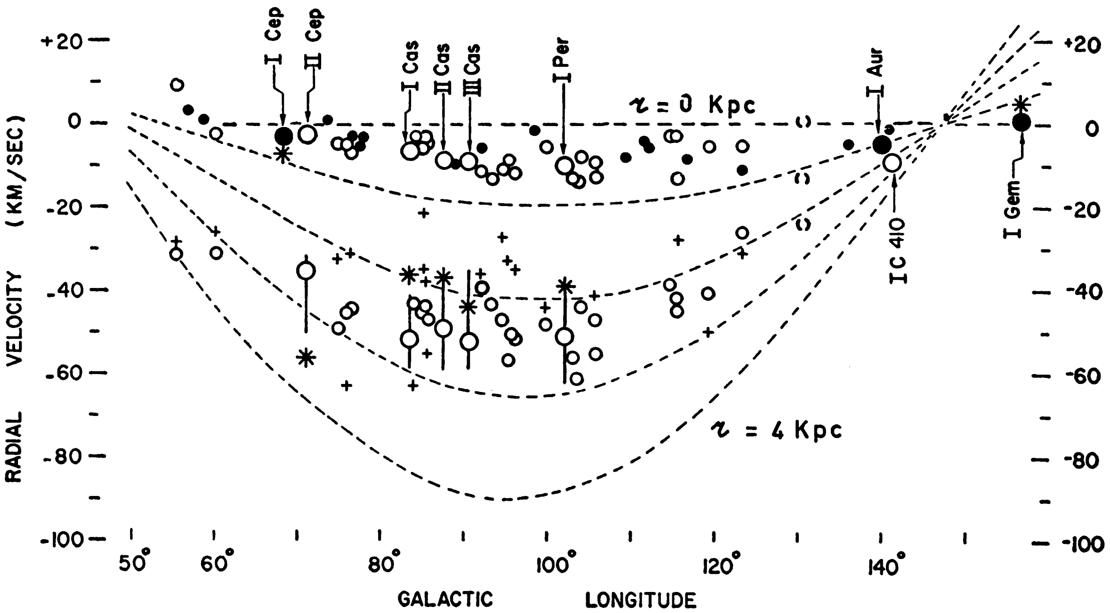

FIG. 6. Multiple interstellar absorption lines in the northern sky.[21b] The stars are all close to the galactic circle: galactic longitudes as abscissa, radial velocities of the measured components as ordinates. The open circles refer to interstellar lines observed in the spectra of stars and associations in the Perseus arm, whereas the solid dots are for interstellar lines observed for stars and associations in the Orion arm. The curved arcs show what galactic rotation shift in radial velocity might be expected at the indicated distances from the sun. The manner in which these curves represent the observed radial velocities suggest that the interstellar clouds are either in the Orion arm (400 pc) or in the Perseus arm (3 kpc) but not in between.

arises from a discrete cloud, moving with its own velocity.

A. Velocity Distribution

Let us, for a moment, adopt this schematic model of a gas consisting of many separate clouds. The radial velocities of the emitting or absorbing atoms then are sums of terms due to

a. differential galactic rotation on the basis of circular orbits;
b. systematic group motion of many clouds deviating from circular orbits;
c. random motions of individual clouds in the group;
d. gas streaming in one cloud;
e. thermal motions of individual atoms or ions.

A distinction in the terminology should be made. In the calcium and sodium line studies, a+b+c is called the cloud velocity, which shows up as a displacement, and d+e the velocity within a cloud, which shows up as a broadening effect. Münch has succeeded in separating b+c from a. The evidence for this separation and for the occurrence of absorption components in two separate spiral arms in the northern sky is presented in Fig. 6. The dotted lines represent velocity (a), and it is appropriate to call henceforth b+c the cloud velocity.

The situation in the 21-cm hydrogen line studies is different. Components that might be ascribed to separate clouds have so far shown up only in the absorption profiles, which refer to a small solid angle (5′ diameter in the case of the Cassiopeia source). In all other studies the beam width has been too large to resolve separate clouds. It thus became customary to refer to c+d+e as the random cloud motions. Some evidence for motions b was found from the parts of the line profiles that extend into the frequency ranges forbidden on the basis of regular galactic rotation. These motions usually have been ignored if they were large (10 or 20 km/sec) and taken into the random motions if they were small.

The numerical results have usually been expressed in one of two distribution functions, namely,

$$\text{exponential,}\quad \psi(v)=\frac{1}{2\eta}\exp(-|v-v_0|/\eta);$$

$$\text{Gaussian,}\quad \psi(v)=(1/b(\pi)^{\frac{1}{2}})\exp[-(v-v_0)^2/b^2].$$

The root-mean-square deviation, or standard deviation, of the velocity component in the line of sight is given by

$$\sigma=b/\sqrt{2}\quad\text{or}\quad\sigma=\eta\sqrt{2}.$$

Münch incorrectly calls b the standard deviation. Table III gives a compilation of the observational results. The following references and comments may be given.

1. Münch[21b] based his discussion on the ratios of the measured equivalent widths in the Na and Ca^+ doublets. This is a curve-of-growth method and, therefore,

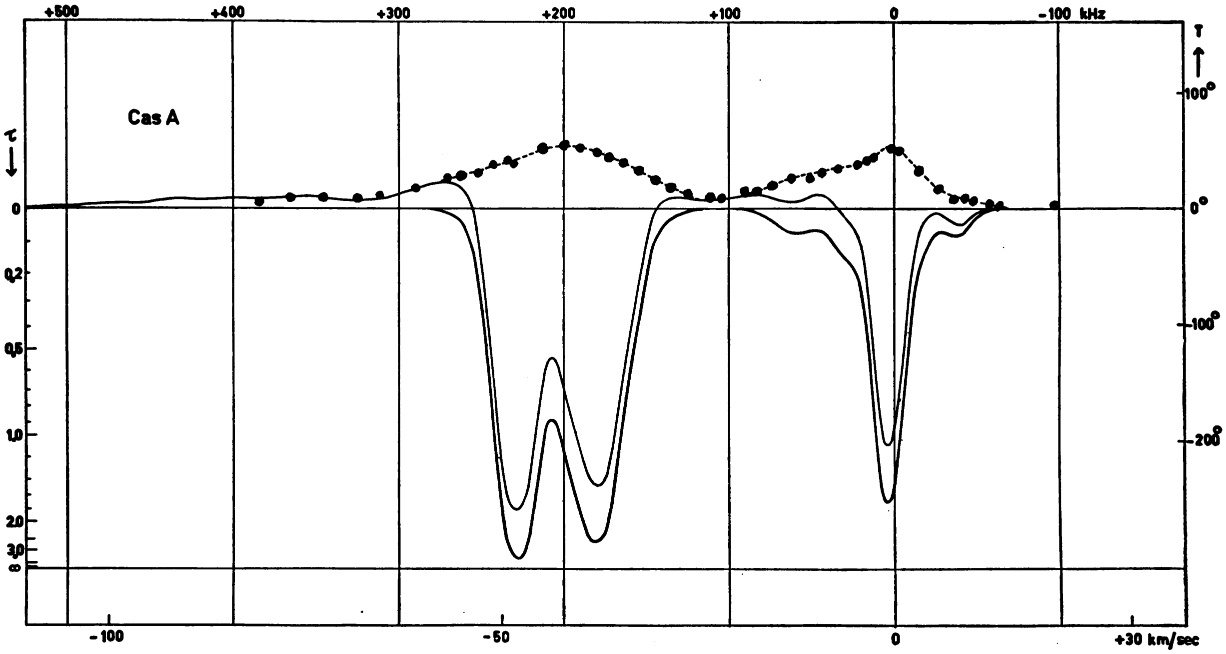

FIG. 7. The 21-cm line in absorption in the spectrum of the radio source Cas A.[25] Thin curve: measured profile. Dotted curve: expected profile if the source were absent. Thick curve: absorption profile to which only the solid angle of the source contributes.

independent of instrumental broadening. The exponential distribution fits much better than Gaussian distributions.

2. Blaauw[22] has discussed the statistics of the intensities and displacements of the line components in Adams' list. His result should be independent of instrumental broadening as he has taken account of the overlap of lines by limited resolving power.

3. Westerhout[6a] has discussed the best data available for the 21-cm line in emission. Instrumental broadening is small and has been eliminated. This determination should be regarded as an upper limit to the cloud velocities because a further dispersion in the distances will also increase the line width.

4. Spitzer and Skumanich[23] have measured the widths of well-isolated components of the Ca$^+$ lines and removed the instrumental broadening by computation. As the instrumental broadening was about the same as the resulting line width, this result should be regarded with caution. An alternative explanation of the discrepancy with (5) is that the fast-moving clouds studied by Spitzer and Skumanich (average $v=40$ km/sec) actually have higher internal motions than slow-moving clouds.

5. Following earlier work by Hagen, Lilley, and McClain,[24] Muller[25] has accurately measured the absorption line profiles of the 21-cm line in strong sources. Figure 7 shows the result for Cas A. The number given in Table III refers to the average width of the three heavy components after correction. Correction for instrumental broadening was quite small, but correction for saturation reduced the widths by factors 0.5 to 0.8, which form the weakest link in the velocity determination. The strongest absorption component in the spectrum of Tau A, observed with 5 kcps band width, gives the even lower value $\sigma=1.2$ km/sec (Muller, private communication).

TABLE III. Random velocities of clouds and in clouds.

Method	Mean velocity in km/sec
1. From doublet ratio, Orion arm	$\eta\sqrt{2}=5$ (Na) to 7 (Ca$^+$)
Perseus arm	$\eta\sqrt{2}=7$ (Na) to 8 (Ca$^+$)
2. From statistics of multiple absorption lines	$\eta\sqrt{2}=7$ (Ca$^+$)
3. From profiles of 21-cm line in emission	$b/\sqrt{2}=6$ (H) or $\eta\sqrt{2}=8$ (H)
4. From width of separate components	$b/\sqrt{2}=3.4$ (Ca$^+$)
5. From profiles of 21-cm line in absorption	$b/\sqrt{2}=1.9$ (H)

The results compiled in Table III are quite consistent and may be summarized thus.

1. The velocity distribution inside a cloud is Gaussian with σ (in one component) $=2$ km/sec, and possibly somewhat larger for clouds that have larger velocity as a whole.

2. The distribution of cloud velocities is exponential with $\sigma=\eta\sqrt{2}=7$ km/sec (again in one component).

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[22] A. Blaauw, Bull. Astron. Inst. Neth. **11**, 459 (No. 436) (1952).

[23] L. Spitzer and A. Skumanich, Astrophys. J. **116**, 452 (1952).

[24] Hagen, Lilley, and McClain, Astrophys. J. **122**, 361 (1955).

[25] C. A. Muller, Astrophys. J. **125**, 830 (1957).

If the rms velocity of 2 km/sec is interpreted as a thermal velocity of the atomic hydrogen gas, the temperature is $T=480°\text{K}$. However, it is more likely that part of it is due to internal fluid motion in the cloud. If the gas is assumed to have a homogeneous temperature, T is of the order of 125°K, as estimated from the 21-cm line studies.[6a] The real situation may be more complex. Kahn[26] has argued that the gradual cooling after a sudden heating by cloud collisions should lead to a wide range of gas temperatures simultaneously. The consequences of this suggestion for the observations of the 21-cm line and their interpretation have not been fully explored. A first tentative observation of local absorption by a particularly cool cloud has been described by Davies.[27]

B. Number and Sizes of Clouds

Blaauw[22] has analyzed Adams' data on the assumption of equal clouds, distributed at random. Each cloud in front of a star causes a separate absorption component, except for the fact that the least displaced components merge together into one wider absorption line. This model fits the data satisfactorily, if the line of sight cuts 8–12 clouds per kpc. The data are confined to nearby stars so that differential galactic rotation does not yet enter as a complication.

On the same model, the line of sight between the sun and the radio source Cas A ought to cut at least 20 such clouds. Muller's H absorption data,[25] however, give 3 strong absorption components and 5 weak ones. The strong lines do *not* have a contour as if they consist of several randomly displaced lines but are narrow and perfectly smooth. This observation furnishes a strong argument for the actual existence of a small number of relatively heavy clouds. Similar suggestions have beem made by Whipple[28] and Schatzman.[29] Typical optical depths in the 21-cm line are $\tau=2$ or 3 for the heavy clouds, $\tau=0.1$ for the light ones; the difference may be due to variations in density, size, and/or temperature.

In estimating the average size of a cloud we shall for a moment ignore the evidence for these variations. We assume that n spherical clouds per kpc³, each with radius a kpc, are randomly distributed in space. The average number seen per kpc then is $k=\pi a^2 n$, the fraction of space occupied by clouds, $f=\frac{4}{3}\pi a^3 n$. The number and size may be computed from k and f. Estimates in the literature[30–33] have ranged between the following extremes

$f=\frac{4}{3}\pi a^3 n=0.14$	0.07	$\cdots$
$k=\pi a^2 n\ =5$	10	kpc^{-1}
$2a=0.042$	0.010	kpc
$n=3600$	130 000	kpc^{-3}

This means that the diameter is somewhere between 10 and 40 pc and the n is extremely sensitive to changes in the assumptions.

An interesting extension of this method has become possible in the study of the 21-cm emission line with a narrow beam. If equal clouds are distributed at random in space, within the confines of a spiral arm, the fluctuations of intensity seen in scanning in angle and in frequency may give valuable information about the size, the internal motion, and the number of clouds. The only suitable data available so far are the scans made along a line of constant declination at eirher side of Cas A. These scans, made by Muller for the purpose of determining the "expected profile" (Fig. 7 of this paper), were kindly put at my disposal for a preliminary investigation. Because of the differential rotation, the random distribution in distance (τ) works out as a random distribution in velocity v, so that the clouds may be treated as randomly distributed in the (α,v) plane ($\alpha=$ right ascension). The following tentative results for the Orion and Perseus arms were obtained.

1. The velocity-width of a cloud is 5 km/sec in both arms. This corresponds quite well with the value $\sigma=2$ km/sec estimated in Table III from entirely independent data.

2. The angular size of the cloud, determined from the intensity correlation in right ascension, is

for the Orion arm: 1.8°, which gives $2a=18$ pc
for the Perseus arm: 0.6°, which gives $2a=35$ pc.

The latter result has been reduced for beam width. These sizes agree well with those cited above.

3. The number of clouds per unit volume, determined from the depth of the intensity fluctuations, came out

for the Orion arm: $n=500\,000$ kpc^{-3}
for the Perseus arm: $n=40\,000$ kpc^{-3}.

These numbers are larger than those cited above. The corresponding occupied fraction of space, f, is about 1. The density of one cloud following from these data is $N=1.5$ cm^{-3}, which is indeed the same value as found in reducing the 21-cm data without any reference to the cloudiness of the distribution. But, mathematically, $f=1$ means that the clouds overlap in space and not only in the spectrum. The density distribution would follow a Poisson law, in which 37% of space is empty, 37% has the normal density, and, for instance, 2% would have four or more times the normal density, i.e., $N=6$ cm^{-3}.

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[26] F. D. Kahn, Mém. soc. roy. sci. Liège **15**, 578 (1955).

[27] R. D. Davies, Monthly Notices Roy. Astron. Soc. **116**, 443 (1956).

[28] F. L. Whipple, Harvard Obs. Monographs No. **7**, 109 (1948).

[29] E. Schatzman, Ann. astrophys. **13**, 367 (1950).

[30] J. H. Oort and H. C. van de Hulst, Bull. Astron. Inst. Neth. **10**, 187 (No. 376) (1948).

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

[32] D. ter Haar, Z. Astrophys. **32**, 251 (1953).

[33] J. H. Oort, Bull. Astron. Inst. Neth. **12**, 177 (No. 455) (1954).

For comparison, we wish to estimate the hydrogen density and 21-cm optical depth of the clouds inferred from the studies of the Ca$^+$ lines. Unfortunately, these estimates involve assumptions about the abundance ratios and the ionization formula. From Strömgren,[31] choosing $T=125°$ for an HI region, we find that an ordinary cloud has $N=6$ cm^{-3}, $2a=20$ pc. On the assumption of a total internal velocity range of 4 km/sec this gives $\tau=0.4$ for the 21-cm line. The mass of such a cloud is 600 solar masses. Oort[33] takes a slightly lower size and 130 solar masses for a single cloud. Strömgren also discusses the particularly heavy cloud seen in front of χ^2 Ori. The estimates are $N=60$ cm^{-3}, $2a=15$ pc, $\tau=3$ with a velocity range of 4 km/sec, and mass$=$2600 solar masses.

A clear conclusion cannot yet be reached. Nevertheless there are some points of striking agreement. The heavy clouds discussed by Strömgren might be similar to the heavy clouds in the Cas A absorption spectrum. The ordinary clouds in Strömgren's analysis may not differ much from those causing the weak components in the Cas A spectrum.

On the other hand, the fluctuations in the emission intensity of the 21-cm line indicate a more even distribution of atomic hydrogen; for a medium consisting of individual clouds with $\tau=0.3$, or even 0.1, would give stronger intensity variations with position and frequency than observed. Several remedies may be sought. For instance, we might think the clouds embedded in a substratum that contains a good part of the total mass. Or, we might use the picture of a Poisson distribution in density with $f=1$. The clouds with $N=6$ cm^{-3} then would be just numerous enough to count as Strömgren's "normal" clouds, but it remains to be investigated whether the larger total mass contained in the less dense regions can have escaped attention in the Ca$^+$ investigations.

A further point that needs investigation is the statistics of the "heavy" clouds. The heavy clouds in the Cas A spectrum cannot fill the entire beam, unless they are extremely cool, for otherwise they would contribute more strongly to the emission profile. It seems somewhat strange that these clouds are seen in almost equal numbers as the lighter and more normal clouds.

Finally, we should recall the existence of huge cloud complexes, that are bigger than any cloud we have mentioned so far. By Oort's estimates[33] they would have a 2–4 times larger density and a 3–30 times larger volume than Strömgren's normal clouds and have total masses of the order of 30 000 solar masses.

4. INFERENCE FROM DIRECT PHOTOGRAPHS

No other type of astronomical observation gives such rich information as a good photograph. If we did not have this opportunity and had to be content with radio astronomy and spectra of bright stars, we might have thought forever that the interstellar clouds actually had sizes of 30 pc, or perhaps 3 pc, without any finer structure. Both the ordinary photographs in various wide wavelength regions, and those taken with special $H\alpha$ filters, reveal details almost beyond hope of ever explaining. No motion can be seen, but the momentary picture contains plenty of suggestions of motion. For a thorough description and fine illustrations we refer to Minkowski.[18] In this paper I try to summarize only the data relevant to the sizes of clouds and of striking details inside clouds.

A first distinction is between nebulae or clouds seen in emission and those seen in absorption. Both types of data are discussed separately.

A. Sizes and Structural Details of Emission Regions

The galactic belt between $b=10°$ and $-10°$ contains a great many emission regions. As their main emission line, $H\alpha$, is formed by recombination, the surface brightness is proportional to

$$E=\int N_eN_pdl\approx\int N_e^2dl,$$

where N_e, N_p are the numbers of electrons and protons per cm^3, dl is the element of the line of sight expressed in parsec. The quantity E, expressed in cm$^{-6}\times$pc is called the emission measure.[17,31] On present $H\alpha$ photographs, objects with $E=400$ are just visible. The best quantitative data on the emission measures in many regions have emerged from the nebular spectrograph observations of Johnson.[34] The brightest emission regions, or the brightest patches in faint regions, were formerly called diffuse emission nebulae.

Several hundreds of emission regions or nebulae may be unambiguously cataloged as discrete objects. Most of them are within 5° from the galactic equator. Only few have $|b|>10°$; among these are some conspicuous objects like the Orion complex, the California nebula, and the region of γ Velorum and ζ Puppis. A similar total area is covered by emission regions that cannot be unravelled as individual objects, either because objects at widely different distances overlap, or because a faint emission filament or patch is evidently connected with neighboring emission regions. Both difficulties occur in the Cygnus region. The general status of cataloging efforts as of spring 1955 was reviewed in the Report of I.A.U. Subcommission 34A at Dublin.[35] Later lists have been drawn up by Gum[3,36]; by Johnson[37]; by Morgan, Strömgren, and Johnson,[38] and by L. Münch.[39]

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[34] H. M. Johnson, Astrophys. J. **117**, 235 (1953).
[35] G. Shajn, Trans. Intern. Astron. Union **9**, 504 (1957).
[36] C. S. Gum, Observatory **76**, 150 (1956).
[37] H. M. Johnson, Astrophys. J. **121**, 604 (1955).
[38] Morgan, Strömgren, and Johnson, Astrophys. J. **121**, 611 (1955).
[39] L. Münch, Bol. Tonanzintla y Tacubaya No. **13**, 28 (1955).

The red plates of the Palomar Sky Survey furnish excellent material for the study of these regions. In 1953 I carefully inspected all plates and/or prints then available at Pasadena between longitudes 42° and 138° and latitudes 10° and +10°. Excluding as well as possible the planetaries, reflection nebulae, and reddened galaxies I listed about 120 emission regions with diameters <1° and 17 regions with diameters >1°. A sketch map and a brief description of each object was made, noting in particular the presence of dark lanes, or bright edges, wisps, or patches. The size of the smallest detail, e.g., the width of the narrowest wisp, in each nebula was also noted. This size ranged from 20 μ (as sharp as the plate will render) to several mm. On the scale of these plates 1 mm=1′. Emission regions without any detail were fairly rare. The vast majority showed finest details between 1/20 and 1/200 of their own size, while some went to 1/1000. A full search for the exciting stars of these objects has not been made, so the distances of most are unknown. Those with known distances have linear sizes between 2 and 50 pc with 10 pc as the median value; 10 pc is also noted by Pottasch[40] as the size of a typical emission region. Both the densities and the dimensions are of the order of those of the normal clouds discussed in the previous sections. The largest emission regions, of which the Rosette nebula is a fine example, are more comparable in size and mass to the cloud complexes.[33]

The finest details may perhaps serve, in combination with other characteristics, for a distinction between intrinsically different types of emission regions. The statistics indeed suggest a division. On one hand there are lots of objects with details of the order 0′.05. Their estimated distances are of the order of 1 kpc, which means internal structure as small as 0.02 pc or 4000 astronomical units. Some even have wisps as narrow as 1000 astronomical units. Most of these objects show striking dark lanes superposed on the emission and make the impression of discrete objects. Tentatively we might put them in a class with the well-known brighter nebulae like M 16.

On the other hand the list showed 11 objects with definite absence of visible details <1 mm. The majority of them are faint and extend over areas of 3° or more, or are connected with dark lanes extending over such an area. Hardly any of these entries stands out as a convincing discrete object. From the latitude distribution we infer that they must be near; we tentatively adopt a distance 300 pc. It may be surmised that this class of objects has no separate physical existence but consists of random regions of interstellar space that happen to be faintly excited by nearby stars. The finest details in these regions are 0.2 pc, which is ten times that found in the class of objects mentioned above. This quantity may give a foothold for a dynamical theory.

Only one object with finest details of 2 mm seems to be of a different type. It is the nebula at $l=72.3$, $b=+4.3$. If it is excited by HD 210352, its distance is 1.5 kpc. Its size is 30′=15 pc and it consists of faint streaks, each wide 2′=1 pc.

A question of prime importance in the interpretation of the emission regions is whether or not the mass of gas is larger than the visible nebula. All early studies tacitly assumed that a nebula was as large as it seemed. Strömgren[41] showed, however, that a hot star placed in a homogeneous gas would keep the hydrogen of a limited spherical region ionized. This HII-region would look like a faint, spherical emission nebula, while HI gas of the same density could extend beyond it indefinitely. Since then it has become customary to interpret all emission regions by the theory of the Strömgren spheres or its modifications.[17,31] The absence of serious contradictions in the results is a point in favor of this assumption. Other points in favor are the appearance of dark clouds at the outer edges of emission regions and the observation of 21-cm radiation from atomic hydrogen in neighboring regions.

Yet the answer is not nearly so convincing as for planetary nebulae, where it now seems possible, on the basis of photometric data, to decide for any nebula whether it is mass-limited or radiation-limited. Already the size, comparable to the "clouds" inferred from the absorption line studies, should warn us. against adopting the picture of a Strömgren sphere too hastily. Further, the roundish shapes of many emission regions might be explained more easily as an aerodynamic phenomenon than (in view of the highly erratic density distribution) by Strömgren's theory. Finally, many nebulae are known to be much brighter at the periphery than inside.[42,38,43] If they are shells, the inner edges of the shells have to be explained by a deficiency of the gas density in the center; the outer edges do not look so strongly different to justify the assumption that they represent only the limit of the available radiation. If these nebulae are rings, the need for an aerodynamic explanation is even stronger.

In two circumstances the answer seems clear. First, the filamentary nebulae like the well-known Cygnus veils cannot be radiation-limited. We must even keep in mind the possibility that they are not excited by stellar radiation at all but derive their energy from friction with the interstellar gas.[44–46] Secondly, the bright rims of dark clouds projected in front of an emission nebula are almost certainly radiation-limited

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[40] S. Pottasch, Bull. Astron. Soc. Neth. **13**, 77 (No. 471) (1956).

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

[42] G. A. Shajn and V. F. Hase, Astron. Zhur. **30**, 135 (1953).

[43] H. M. Johnson, Astrophys. J. **124**, 90 (1956).

[44] J. H. Oort, Monthly Notices Roy. Astron. Soc. **106**, 159 (1946).

[45] Reference 18, p. 106.

[46] R. Minkowski, Revs. Modern Phys. **30**, 1048 (1958), this issue.

TABLE IV. Representative sizes of structural details of the interstellar medium.

	pc
Diameter of spiral arm in plane	500–1000
⊥ plane	200
Condensations in spiral arm	100
Large emission region	60
Average emission region	10
Typical cloud, Ca^+ absorption	30
Typical cloud, 21-cm emission	20–70
Heavy cloud, 21-cm absorption	3
Globules	0.1–0.5
Dark veins in Ophiuchus	0.1
Dark veins in Cygnus	0.02
Width of bright rims and other details in emission region	0.02
Reflection filaments in Pleiades	0.005
Filaments in Cygnus veils	0.001
Cometary condensations in Aquila nebula	0.001

at the side that is turned away from the star and towards the dark cloud. This side of the bright rim is distinctly sharper than the side turned to the star. The shapes of these dark clouds with their rims form fascinating examples of aerodynamic phenomena[40,47,48] which are discussed in other papers in this Symposium.

B. Sizes of Dark Clouds

The dark clouds and lanes suggest an enormous variety of structural details. They range from the very large complexes, like the Taurus and Ophiuchus complexes, to the smallest clouds known as globules. Even finer details are seen by reflected light in the Pleiades nebulosity. Typical sizes of miscellaneous objects in the entire range from large to small are summarized in Table IV.

At one time there were hopes of obtaining useful information on the sizes of dark clouds from statistical studies of interstellar extinction or reddening. When applied to the nearer stars this method shows mainly the presence of the large complexes of dark clouds. When applied to very faint stars and/or galaxies, its use depends on the intrinsic smoothness of the distributions of these objects. Present indications[49] are that the intrinsic irregularities in the distribution of these objects are so strong that they mask the fluctuations arising from the cloudiness of the interstellar extinction. For the earlier literature see, for instance, Agekian.[50]

I should like to add a word about the globules. Bok and Reilly[51] and Bok[52] have first called attention to small dark clouds called globules, size 0.5 pc, which would be best visible against the even background of an emission nebula. In the later work of Osterbrock and of Pottasch, globules have been considered as the final stage of the areodynamical evolution of the elephant's trunks. This would mean that they are intrinsically connected with the emission regions and are not a feature of the general distribution of interstellar dust. I think that this is correct.

Fleischer and Conti,[53] on the other hand, have described globules seen against the background of resolved and unresolved stars in a rich star field. After discussing these data with Fleischer, I believe that these objects are identical to the ones beautifully illustrated in Fig. 1 of Minkowski's paper in the earlier Symposium volume.[54] This mottling has a typical size of 1′, which is 0.1 pc at a distance of 300 pc but has the structure of veins in marble rather than that of separate globules.

Finally, the peculiar dark clouds discovered by Thackeray[5,55] may be mentioned. Their sizes are of the same order as those of globules but they have much more erratic forms with surprisingly sharp boundaries. The fact that they were found in a faint emission region and seem to have some relation to the exciting star, suggests that they may be more akin to globules than would seem at first sight.

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[47] S. Pottasch, Bull. Astron. Inst. Neth. **14**, 29 (No. 482) (1958).

[48] D. E. Osterbrock, Astrophys. J. **125**, 622 (1957).

[49] A. Poveda, Bol. Tonanzintla y Tacubaya No. 15 (1956).

[50] T. A. Agekian, Astron. Zhur. **32**, 416 (1955).

[51] B. J. Bok and E. F. Reilly, Astrophys. J. **105**, 255 (1947).

[52] B. J. Bok, Harvard Obs. Monographs No. **7**, Centennial Symposia, 53 (1948).

[53] R. Fleischer and P. S. Conti, Astrophys. J. **61**, 4 (1956).

[54] Reference 18, p. 18.

[55] A. D. Thackeray, Monthly Notices Roy. Astron. Soc. **110**, 524 (1950).

DISCUSSION

M. P. SAVEDOFF, *Department of Astronomy, University of Rochester, Rochester, New York:* I am intrigued by what van de Hulst said about the material near the center of the galaxy moving out at 50 km sec; I estimate that in 20 million years this material will move about a thousand parsecs. We are not very much farther away. Do you have anything to say about this? It sounds like a very interesting phenomena.

H. C. VAN DE HULST, *Leiden University, Leiden, the Netherlands:* No, I do not have anything to say, but I hope that somebody else will think up an answer during the Symposium.

V. A. AMBARTSUMIAN, *Burakan Astrophysical Observatory, Academy of Sciences of the Armenian S.S.R.,* *Erevan, U.S.S.R.:* van de Hulst has made a very important statement about the cloud in the central part of the galaxy which is approaching us and in which we can observe both emission and absorption. Are there also indications about clouds which are receding, i.e., having positive velocities?

H. C. VAN DE HULST: Long wings of the line profiles near the center extend also to the side of positive velocities. Very preliminary observations showed that at least one arm seen at that side did *not* show up in absorption at the longitude of the center. This would mean it would be behind the center and also receding from the center.