A MODERN LOOK AT 'INTERSTELLAR CLOUDS'

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Abstract. We compare past and present modes of investigation of the structure of the interstellar gas. Many aspects of the interstellar cloud model are invalid.

Interstellar optical absorption lines and H I 21-cm emission lines show a number of very large aggregates with properties similar to those of 'cloud complexes'. At nonzero velocities especially for $b<0°$, exist optical lines which have no H I counterparts. These are almost certainly produced in low-density gas clouds; perhaps the intercloud medium is itself cloudy.

Maps of H I column density taken over large velocity ranges do not reveal much small-scale structure. This fact cannot easily be reconciled with the statistical analyses of interstellar reddening. The maps do reveal large, coherent gas structures which are often filamentary in shape and at least sometimes aligned parallel to the interstellar magnetic field.

Maps of H I column density over small velocity ranges show much small-scale structure, often filamentary in shape. The filaments are almost universally oriented parallel to the interstellar magnetic field and have Doppler velocity gradients along their lengths. In one area the geometry of the field and gas almost exclusively suggests Alfvén-type motions.

I. Introduction

The 'cloud model' of the interstellar medium (see, for example, Spitzer, 1968a, b) pictures the gas as distributed in two components: regions of high density (the clouds), and the intercloud region where the density is much smaller. The clouds are pictured to be of random sizes (within certain limits), shapes, distribution in space, and velocity. For purposes of simplification, the whole range of cloud sizes is often replaced by a single one, the 'standard cloud.' Much of the observational work concerning the interstellar medium has been directed toward the determination of the spectrum of cloud sizes, and much of the theoretical work has used the cloud model.

The origin of the cloud model appears to lie mainly in old statistical studies. The average reddening per unit length in the Galactic plane must arise from both the uniformly-distributed dust and that portion which is concentrated into clouds. The latter will, in addition, provide a spatially fluctuating component. The classic studies of this by Chandrasekhar and Münch (1952) and Münch (1952) indicate two types of cloud, with reddenings of about 0.07 and 0.4 mag and line-of-sight intersection frequencies of 6.5 and 0.6 per kpc, respectively. These frequencies, combined with the statistical estimates of number of clouds per kpc^3 by Ambartsumian and Gordeladse (1938), imply cloud radii of 5 and 50 pc, respectively. The reddenings imply corresponding H I column densities of 3.5×10^{20} and 20×10^{20} cm^{-2} (cf. Savage and Jenkins, 1972), volume densities of about 10 cm^{-3}, and thus masses of 90 and 80000 $M_\odot$ respectively. The larger of these are often called 'cloud complexes' after Oort (1953), with the implication that they contain smaller clouds within. Similar results (but with somewhat smaller radii and larger volume densities) are derived from more modern data by Scheffler (1967a). The larger of these two types of clouds is not in-

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consistent with results derived from completely independent data (see Section II).

A more modern analysis by Scheffler (1967b) shows that the picture of two types of clouds must be replaced by one of a continuous distribution of cloud parameters. He derives a mass spectrum for clouds which varies as $(\text{mass})^{-\beta}$ with $\beta = 1$ to 2 for different mass ranges. The upper mass limit is about the same as for a cloud complex, discussed above. His spectrum fits quite well with the existing, but very sparse, H I data on cloud masses (Field and Hutchins, 1968).

These data have, until recently, seemed fully consistent with existing interpretations of H I data and optical line data, although the exact quantitative results were never certain. However, the cloud model does not fully describe the situation. In particular, how good are the fundamental tenets concerning randomness? Where do the dense and massive dust clouds, which contain nearly half of the total mass of the interstellar gas, fit in? Authors, when carefully describing the observational situation in review articles such as this one, have generally been careful to point out many of these uncertainties. But many other authors, both theoretical and observational, go right ahead and ignore them. After enough repetition the standard assumptions have come to be regarded as being observational fact. The purpose of the present paper is to critically discuss these uncertainties.

Until recently, insufficient data have been available to make such a discussion. We will find that some aspects of the cloud model remain valid. Other aspects, especially the assumptions concerning randomness, are incorrect. Much of the observable gas is affected by the interstellar magnetic field and/or huge explosions. Many large aggregates contain hierarchical structure with non-random shapes and velocities. Outside these aggregates, the gas is often distributed in long, delicate, interconnected filaments rather than clouds.

II. Comparison of Optical (Na I and Ca II) and Radio (H I) Studies

Although mechanisms governing the strengths of Na I and Ca II interstellar lines are ill-understood (see, for example, Pottasch, 1972), much can be learned from the study of these lines. Most of the following discussion, which emphasizes the comparison of optical and radio results, is concerned only with stars having $|b| > 10°$. The line observations in these directions delineate individual interstellar gas structures and avoid confusion with H I beyond the star which occurs to such a large degree near $b = 0°$.

(a) THE GENERAL PICTURE: GOOD CORRELATION AT LOW VELOCITIES

(i) *Velocities*

The early definitive study by Howard *et al.* (1963) compared Adams' (1949) and Münch and Zirin's (1961) interstellar Ca II lines with 21-cm H I lines and showed that there is in general a good correlation for both velocity and intensity. Disagreements were always ascribable to distance effects, with some nearby stars showing no optical absorption lines.

This single general and important conclusion – that interstellar optical lines are similar to the 21-cm line of H I – has remained unchanged, with one exception. These authors restricted themselves to stars showing single interstellar lines, which nearly always appear at the same velocity as the 21-cm line peak. For $|b| > 10°$, this is always near 0 km s^{-1} (LSR). New studies by other workers, however, have included spectra which show more than one velocity component. These include the relatively small studies by Takakubo (1967) and van Woerden (1967) and the large studies by Goldstein and Macdonald (1969) and Habing (1969), all in the Northern Hemisphere; and the large study by Goniadzki (1972) in the South. It has become apparent from these studies that interstellar optical lines may occur at nonzero velocities which have no obvious corresponding H I lines. Here and below the word 'nonzero' means $|v_{LSR}| > 10$ to 20 km s^{-1}. We discuss these 'noncoincident' components in the next section (IIb).

The more recent optical interstellar Na I line data of Hobbs (1969a, 1971) and Ca II data of Marschall and Hobbs (1972) and to some extent Rickard (1972), obtained by scanning with a series of Fabry-Pérot interferometers, carries the comparison of Ca II, Na I, and H I to new heights in terms of precision and detail because of the much higher velocity resolution. Many of the older optical data were almost marginal in this regard. At present the comparisons with Hobbs' newer, higher quality data have yielded more precise quantitative information and increased confidence in the abovementioned correlations.

The line widths in the interstellar medium are almost *never* determined purely by thermal broadening. The 21-cm line usually has a full halfwidth of more than 5 km s^{-1}, which would imply temperatures of many hundreds of degrees in the absence of turbulent broadening. H I absorption studies (Radhakrishnan *et al.*, 1972; Hughes *et al.*, 1971) show that temperatures are more often lower. Furthermore, if thermal broadening were predominant the Na I and Ca II linewidths would be smaller than the H I values by factors of 5 to 6. Instead the optical lines are usually more than half as broad and often nearly as broad as the radio lines. As perhaps extreme examples, the three stars, ζ Oph, ζ Per, and 32 Peg have optical lines which essentially mirror the 21-cm lines (Hobbs, 1971; Marschall and Hobbs, 1972) as shown in Figure 1. The solid angle sampled by radio telescopes looking at H I in emission is usually a factor of some 10^{14} larger than that sampled by optical telescopes looking at absorption against a star, which by itself can only make the radio lines appear broader. Hence, line width differences cannot be regarded as significant and the widths must be determined almost exclusively by turbulence, as concluded by Hobbs (1969a).

(ii) *H I in Absorption*

Comparison of optical lines with H I seen in *absorption* against bright radio sources would reduce effects caused by solid angle differences, and provide unique information on the temperature and ionization as well. Both the optical and radio absorption measurements are biased towards cold gas, while the optical measurements are in addition biased toward regions of high recombination rate of the prevalent ions (Na II and Ca III) and thus also to regions of high electron density (see Habing (1969)

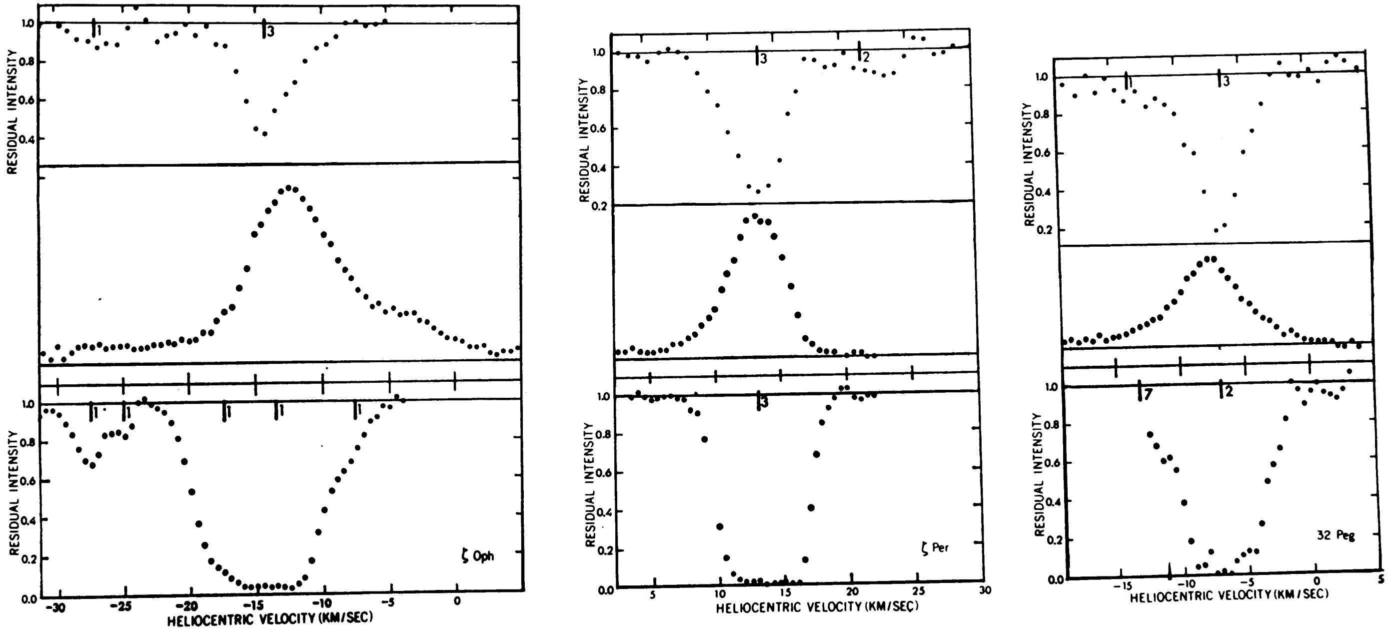


Fig. 1. Comparison of Na I (top), H I (middle), and Ca II (bottom) lines for 3 stars for which the lines have components which are nearly identical in shape. For ζ Oph, much of the difference in shape undoubtedly occurs because the star is in front of most of the H I. From Hobbs (1971) and Marschall and Hobbs (1972).

for a recent discussion of the ionization balance of Na and Ca). If the optical spectra are of high enough quality to provide line shapes, comparison of the velocity dispersions of H I, Na I, and Ca II can be used to separate thermal and turbulent broadening due to the differences in molecular weight. The resultant temperature could then be used in determining the recombination rate, and hence the electron density in the cloud. Both the Na I and Ca II lines are more easily detected, for a given column density of H I, than the corresponding H I absorption lines. Even without good velocity resolution in the optical spectra comparisons can provide information on electron density, although less complete. The only objects for which such data exist are extragalactic radio sources. Such data must certainly exist in profusion; unfortunately, it all remains unanalyzed in the plate files of the great optical observatories.

Although the comparison of optical and radio lines in absorption is potentially very interesting, it is most useful if in fact the lines are all produced in the same region. This might not be the case. Histograms of ($1/e$) line widths in absorption (Clark, 1965; Radhakrishnan and Goss, 1972) show peaks at 1.5 to 1.8 km s^{-1}, usually somewhat smaller than H I widths in emission. Since H I widths in emission seem to be close to the optical line widths, the optical lines might not compare well with H I in absorption. Another indication that they might not be produced in the same region is the comparison of the number of line components seen per kpc in the line of sight for the two types of observation. Blaauw (1952) finds 8 to 12 optical components per kpc for Ca II. This is much larger than the 2.5 per kpc derived by Radhakrishnan and Goss (1972) for H I in absorption. One contributory cause to the large number seen by Blaauw is the association of high-velocity optical lines with low-density ionized regions (see Section IIb). Another is his correction for instrumental blending which is based on the assumption of complete randomness of the clouds in space and velocity. This assumption is unjustified (see Section IV), and he has therefore overestimated the correction for instrumental broadening. Nevertheless, the discrepancy between the absorption results obtained in the radio and optical probably remains real.

It is therefore our impression that H I absorption probably correlates with optical absorption less well than does H I emission. If so, this would seem contrary to theoretical expectation. Comparative studies of optical and H I absorption against the same background source is a potentially rich and rewarding field, presently unexploited.

(iii) *Line Strengths*

In his comparison of H I and Na I, Hobbs (1971) found that the average apparent ratio $Q = [\text{Na I}]/[\text{H I}] = 3.2 \times 10^{-9}$. However, velocity components in five stars were found to have ratios which are larger by factors ranging from 4 to 20. One of these is in κ Ori and is a nonzero velocity component; given the large number of early-type stars in the vicinity of the Orion complex, ionization of H I would not be unexpected and would account for the large value of Q. The remaining three cases are more interesting.

One occurs in ζ Oph; in a large region in this direction, Heiles and Jenkins (1974) show that the apparent H I/dust ratio is lower than usual. This is probably due to saturation of the 21-cm line. Although this would give an above-average value of Q, the value of $Q = 20$ for this star is even higher than expected from saturation effects alone. Perhaps this O9.5V star, distance 170 pc, is ionizing enough gas to enhance the Na I line (which will always appear stronger in H II than H I regions, see Hobbs, 1969). Can this hypothesized H II region be detected by other observational techniques?

Two other stars, 35 Ari and ζ Per, are located in the general region of Perseus. ζ Per ($l = 162°$, $b = -17°$) is very close to the small region (about 10° diameter) in Perseus where the extinction is so large that it merits classification as a separate 'island' in the zone of avoidance (Shane and Wirtanen, 1967). Heiles and Jenkins (1973) have shown that an H I deficiency exists in part of this region, which is most straightforwardly interpreted as a result of conversion of H I to H_2. The large value of Q for the star then simply shows that this chemical transformation has not significantly affected the Na I abundance. Comparison by eye of the Ca II line profile (Marschall and Hobbs, 1972) with the Na I profile indicates the usual low-velocity abundance ratio; however, this estimate must be done again with much care to reach a definite conclusion due to the saturation in the Na I profile. If the ratio is in fact the same as for other low-velocity interstellar line components, it argues against depletion of Ca by dust as being responsible for the usually observed underabundance of Ca II relative to Na I. This is because the region is very dense and very dusty. 35 Ari ($l = 151°$, $b = -29°$) is about 10° away from the apparent edge of this dark region in Perseus. A combination of 21-cm line saturation and H I conversion to H_2 may be responsible for its large value of Q. Due to its large value of Q we can surmise that all the H I seen in this direction is closer than the star, whose distance is 170 pc.

There are, of course, stars which show absolutely no indication of H I at velocities seen in Na I and/or Ca II. At least two of these appear in Habing's (1969) list discussed in Section IIb. It seems most sensible to ascribe these to circumstellar matter which is invisible with the large telescope beamwidths employed for studies of the 21-cm line. However, proof of this hypothesis would be comforting. If it is instead H II, we are missing a most interesting, though undoubtedly relatively insignificant in mass, portion of the interstellar medium!

(b) DEVIATIONS FROM THE GENERAL PICTURE: H I→H II, A CLOUDY INTERCLOUD MEDIUM?

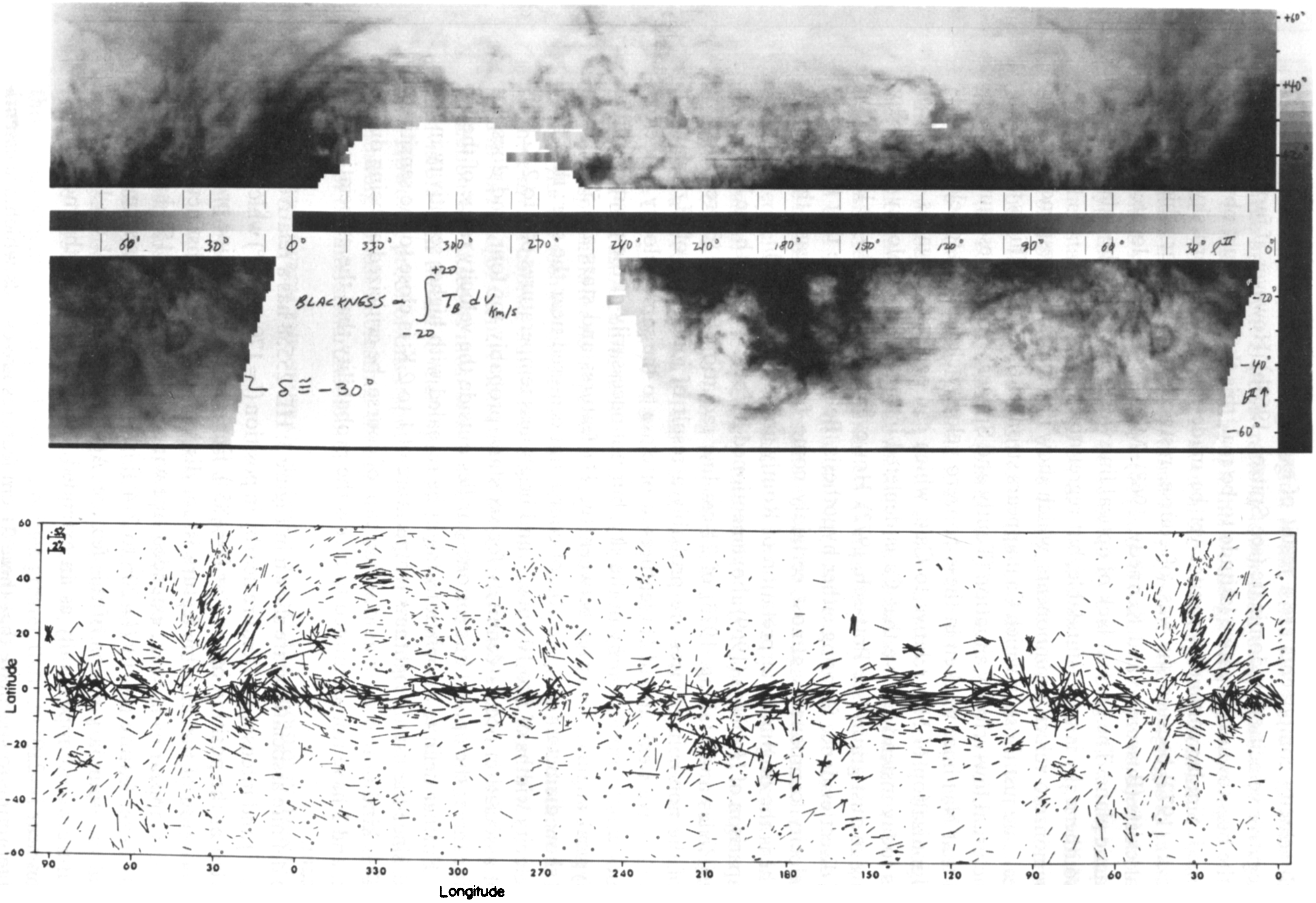
It was mentioned above that optical components at nonzero velocity, i.e., $|v_{LSR}| > 10$ to 20 km s^{-1}, often have no associated H I line component. Habing (1969) makes this velocity distinction particularly clear by presenting a list of 17 stars (14 of which have $|b| > 10°$) showing this 'noncoincidence.' All but one of these 14 stars are located at negative galactic latitudes! This discovery caused the author to look at the interstellar line velocities relative to the star velocities, given by Adams (1949); again, those components showing relative velocities greater than 20 km s^{-1} preponderate for negative latitudes if stars having $|b| \leqslant 10°$ are excluded. It has been thought that the high velocity components are a result of expansion of matter around the star, since negative velocities predominate (see Spitzer, 1969b). However, if further study shows the bias towards negative latitude to be real, this thought must obviously be abandoned. Similar comments cannot yet be made for the southern sky work by Goniadzki (1972) because she was, of course, restricted to stars for which optical material exists (Buscombe and Kennedy, 1968). Most of these are located close to the galactic plane. The general lack of optical line work outside of the galactic plane in the southern sky is understandable, but regrettable.

These nonzero velocity components, which show no H I peak corresponding to the Ca II peak, are just those in which Ca II appears stronger than Na I. This is the reverse from the usual low-velocity situation (Toutly and Spitzer, 1952). These authors postulated that Na I lines weaken in these nonzero velocity clouds due to selective collisional ionization of Na I relative to Ca II, which can occur if the gas is hot. Most authors today instead believe that Ca is depleted in normal low velocity clouds by adhering to dust grains (see Pottasch, 1972). However, there seems to be little in the way of direct evidence favoring either hypothesis. Below we will see that these nonzero velocity components almost certainly come from ionized gas; this greatly strengthens the original interpretation of Routly and Spitzer (1952).

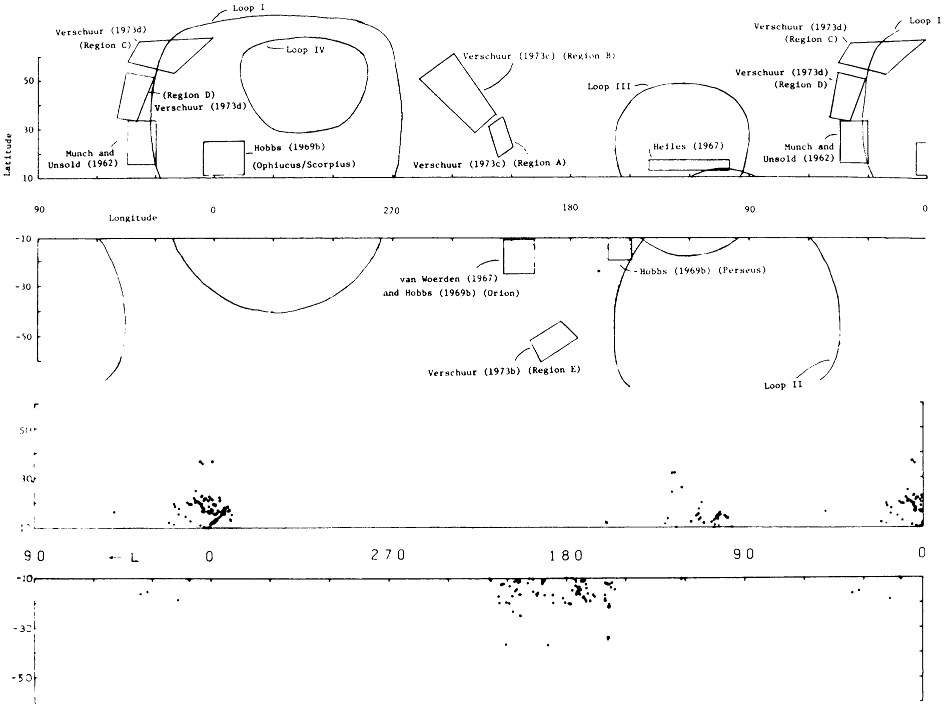
Comparison of Habing's (1969) abovementioned list of 14 stars with the Hat Creek Survey (Heiles and Habing, 1973) of 21-cm line radiation for $b \geqslant 10°$ reveals that some of the non-coincidences are probably a result of ionization of H I. Many of these stars have weak, broad H I features at or close to the same velocity as the optical lines which appear *nearby* in the sky, but not necessarily *at* the position of the star. Typical angular distances between the H I features and stars are 5°. The H I clouds show diameters of up to 10°, of course not centered near the star; they have total velocity widths of 5 to 10 km s^{-1} and brightness temperatures of 1 to 2 K. This kind of association occurs definitely for six stars, probably for four, and does not occur for three; the optical line for one star lies outside the velocity range of the H I survey. Further definite associations might be revealed with higher sensitivity in the H I line, since the usual brightness temperature of 1 to 2 K is close to the sensitivity limit. This kind of uncertain association can, of course, be criticized as being due to chance, and I have not attempted to assess the probability that the associations are significant.

Two definite associations are shown in Figure 3. HD 25558 has a relatively narrow (4 km s^{-1}) and intense (3 K) feature nearby in position ($l = 170$ to 180°) which weakens somewhat at the position of the star ($l = 185°$). For a single 21-cm line profile taken at the position of the star this feature is not distinguishable as a distinct peak and would only appear as a weak, extended line wing. HD 34816 ($l = 215°$) has a weak, large diameter feature nearby ($l = 206$ to 214°); in Figure 3a the star seems to be located in the boundary region of this feature. Again, for a single 21-cm line profile this feature would appear only as an extended line wing, even at the most intense position near $l = 210°$.

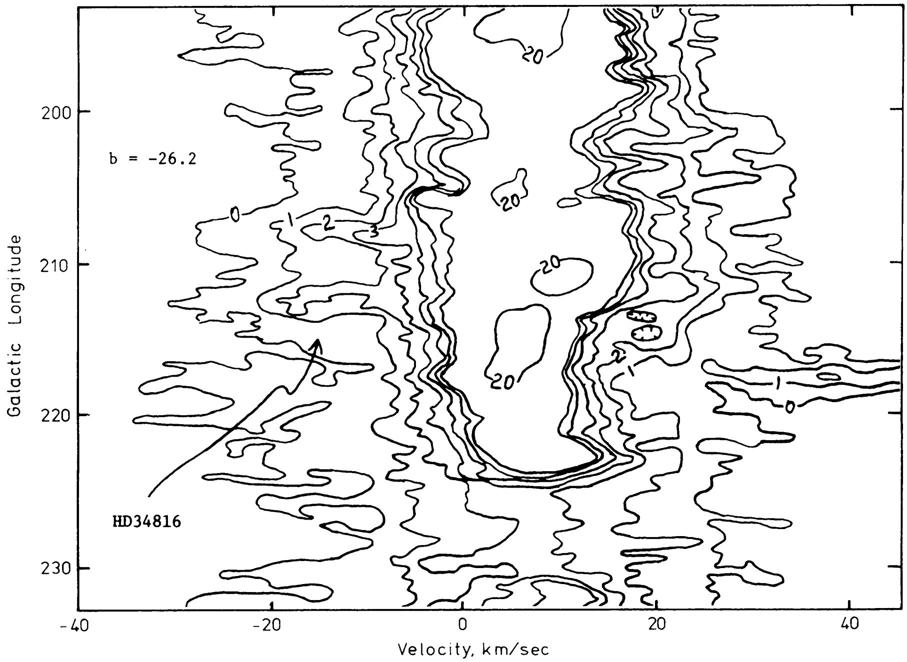
It is tempting to speculate that these 21-cm features are clouds which are essenti-



Figs. 2a–b. (a) A photographic presentation of the distribution of H I column density in the sky over the velocity range −20 to +20 km s^{-1} (LSR). From Heiles and Jenkins (1974). (b) The directions of polarization of optical starlight, and hence presumably the direction of the interstellar magnetic field. From Mathewson and Ford (1970).



Figs. 2c–d. (c) Regions referred to in the text. (d) The locations of dust clouds catalogued by Lynds (1962). Made from computer cards recently generated by Lynds.



Figs. 3a–b. Contour maps of antenna temperature vs. galactic longitude and velocity, for fixed galactic latitude. Each covers a star showing an interstellar Ca II line with no corresponding H I line. The position of the star and the velocity of the line are located at the tip of the arrow. Note that H I emission occurs nearby in angle. From Heiles and Habing (1973).

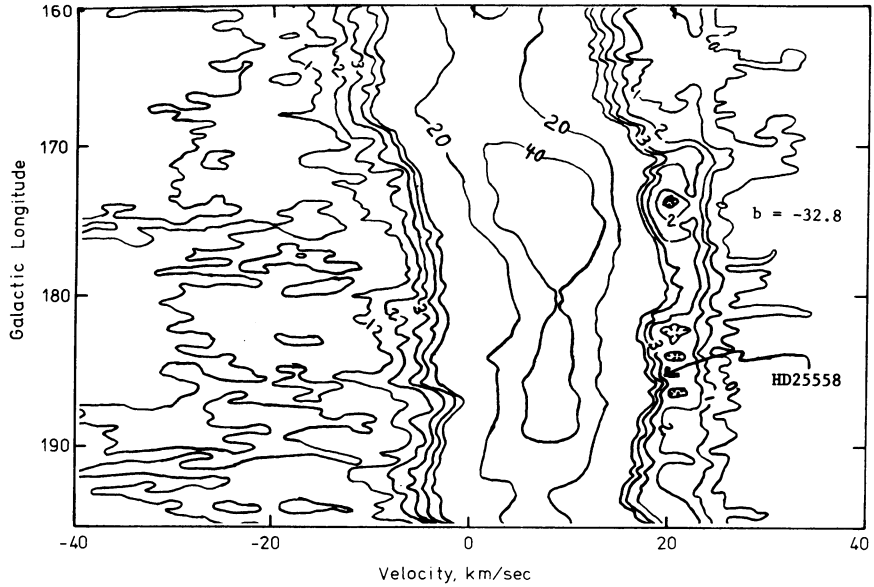


Fig. 3b.

ally completely ionized at the position of the star, either by random chance or perhaps even by the star itself. Values for the physical parameters of these clouds can be estimated. Typical equivalent widths for the Ca II components are only a few hundredths of an ångstrom unit. Using the ionization equilibria and Ca/H abundance ratio given by Habing (1969) and a temperature of 3000 K, one can derive the emission measure, about 0.1 cm^{-6} pc, by assuming the gas is fully ionized. The distance can be no more than that of the star, typically 300 pc; if the distance is 100 pc, the angular size of about 10° implies a diameter of 10 pc and a density of about 0.1 cm^{-3}. This density reminds us of the intercloud medium. However, the intercloud medium is supposed to be distributed smoothly in space instead of in clouds moving at specific velocities.

An emission measure of 0.1 is far below the limit of detectability for any type of emission observation. These clouds are therefore impossible to observe by any means other than optical absorption lines. The observation of these lines in more than one object in the same region, showing the same velocity, would constitute irrefutable proof that these clouds are interstellar rather than circumstellar and that the above picture is correct in its fundamentals. Much suitable observational material presumably already exists in the form of spectra of globular clusters, external galaxies, and quasars.

(c) ATTEMPTS TO DERIVE SPATIAL STRUCTURE FROM OPTICAL LINES ALONE: USUALLY UNSUCCESSFUL

The number of detailed studies of angular structure using optical interstellar lines is small. All deal with low-velocity lines, so it is no surprise that conclusions drawn from optical and radio data are consistent. One of the earliest studies (Schluter *et al.*,

1953) grouped Adams' (1949) stars by position and showed that groups of stars contained in small areas show low-velocity lines which all have about the same velocity. Thus interstellar clouds are larger than these areas. More recent and accurate data for these regions, and others, has been obtained by Hobbs (1969b); in the discussion below, the regions are shown on Figure 2c, and the physical parameters of the associated clouds are summarized in Table I.

TABLE I

Gross properties of Hobbs' (1969b) clouds
For other cloud parameters, see Section IVa

Region	Size[a]		$10^{-11} N_{\mathrm{Na\,I}}$[b]	$10^{-20} N_{\mathrm{H\,I}}$[c]	$n_{\mathrm{H\,I}}$	Mass
	(deg)	(pc)	(cm^{-2})	(cm^{-2})	(cm^{-3})	($M_{\odot}$)
Perseus	17	>45 <100 (72)	53	4[d]	1.8	2200
Pleiades	15	<30 (30)	3 to 10	1	1.1	390
Scorpius	34	>46 <80 (63)	8	8	4.0	13600
Orion	21	$>47?$[e] <160 (103)	–	14	4.3	65000

[a] Geometrical mean of orthogonal diameters.
[b] From Hobbs (1971).
[c] From H I alone (Heiles and Habing, 1973).
[d] See discussion of ζ Per in Section IIa (iii).
[e] See text.

In *Perseus* Hobbs (1969b) finds coherence over the whole area sampled, which is 15° in angular extent. The distance of the gas is approximately 150 pc, implying clouds of size at least 40 pc. Examination of the 21-cm line contour maps (Heiles and Habing, 1973) show that the true size of this feature is larger. At $b = -18°$ the high-longitude end is cut off by what is probably a large, dense cloud of H_2 (Heiles and Jenkins, 1974) which appears as a white area in Figure 2a. Closer to the galactic plane, e.g., at $b = -12°$, there is no obvious boundary until $l \cong 235°$. A boundary may be rendered indistinct by blending of H I at different distances; alternatively, there really might be no boundary! Further from the galactic plane, e.g., $b = -30°$, a distinct velocity change appears near $l = 170°$ which should perhaps be taken as the high longitude boundary at all latitudes. The velocity structure of the feature appears to change character between $b = -30°$ and $-40°$; thus, the extent of the features in latitude is probably about 25°. Gross properties of this cloud are summarized in Table I under these assumptions, using the H I line data.

Six stars were observed in the *Pleiades* cluster, all in an area of about 1 deg^2. Here the 21 cm data show two peaks, one at $-4\ \mathrm{km\ s}^{-1}$ and another at $+10\ \mathrm{km\ s}^{-1}$ (both LSR). It is this latter peak which is seen in Na I. The former, which is the more intense, must therefore be more distant than the cluster. (This situation, in which the more-negative-velocity gas is the more distant, also occurs 30° to 50° lower in longitude, see Ames and Heiles, 1970.) In contrast to the situation in Perseus, the Na I seems to show considerable spatial structure. This implies angular structure on the scale of 1°, or about 2 pc for this cloud. H I data shows that this cloud extends about 12° in longitude at $b = 23°$, and about 20° in latitude. There is apparent rotation with $dv/dl = 0.5$ to 1 (km s^{-1}) per degree. However, there are a number of sub-condensations within the cloud. The Pleiades cluster lies near an internal boundary where the H I changes particularly rapidly with position. Thus the optical data show the structure within the cloud rather than the angular extent of the cloud as a whole, and an interpretation based on the latter assumption is misleading. Gross physical properties of this cloud are given in Table I.

In *Scorpius* Hobbs (1969b) finds an intense line near 0 km s^{-1} covering all stars sampled within an area bounded by $l \cong 346°$ to 6°, $b \cong 15°$ to 24°. The lines are all well-correlated with H I (Hobbs, 1971). Again, the sample of stars does not cover enough area to fully cover the cloud. Examination of the H I 21-cm emission line data shows the profile looks similar for the 50° interval $l \cong 342°$ to 30° at $b = 24°$. This large concentration is visible in Figure 2a and is at positive galactic latitudes where Gould's belt rises highest above the galactic plane. This distance lies between 100 pc (from star counts; Bok, 1956) and 170 pc, the distance of the stars (which of course, may well be imbedded in the gas rather than located behind all of it). The angular extent of nearly 50° in longitude corresponds to a linear size of some 80 to 140 parsec. Gross properties of this cloud are summarized in Table I.

In *Orion* the situation is more complex, with three velocity peaks in Na I located at -10, -7, and $+7$ km s^{-1} (LSR). Although Hobbs suspects the -10 km s^{-1} component to be circumstellar since it is seen in only one of his 10 stars, it is in fact interstellar and is associated with a spectacularly large and intense H I feature. This feature has relatively sharp boundaries and extends from $l \cong 203°$ to 210° and $b \cong -19°$ to $-26°$, reappearing again below $b \cong -29°$ at somewhat different longitudes. The -7 km s^{-1} line appears obvious only in four stars near NGC 2024 (Orion B) where there is a corresponding H I feature with a small angular size. If this small feature has been accelerated by the H II region, the 22 km s^{-1} velocity of Orion B (Mezger and Höglund, 1967) implies an ejection velocity of about 15 km s^{-1}. Finally, the $+7$ km s^{-1} Na I line coincides with the main H I peak and appears in the spectra of all the stars. Again, the feature is so large that its boundaries fall outside the regions sampled by the stars. It is the large concentration surrounding the Orion region shown in Figure 2a. This concentration has large linear velocity gradients in parts amounting to $|dv/dl| = 1$ (km s^{-1}) per degree, but restricted in angular extent so that the total velocity change is no more than 10 km s^{-1} or so. One of these gradients is responsible for the shift in velocity of the Na I line for the star κ Ori as compared to the other stars. All of the stars observed are located in the Orion association, 450 parsec distant. There is therefore no lower bound to the distance to the interstellar gas. One star, λ Ori, is closer (130 pc) and was observed by Hobbs to have no Na I for velocities less than -3 km s^{-1} (LSR), but unfortunately he did not obtain complete data for this star. For the purposes of expediency we assume in Table I that this star also lies in front of the $+7$ km s^{-1} (LSR) component feature; this assumption is not unreasonable since this gas is probably physically associated with that in the nearby Perseus region.

Münch and Unsöld (1962) examined 13 stars in a region in which the gas is probably affected by the North Polar Spur, as revealed by both continuum and H I radio astronomical studies (see Section IVb). They found the usual low-velocity association of Ca II and H I at -2 km s^{-1} (LSR) for seven of the stars. More interesting was a second component at -8 to -11 km s^{-1} (LSR) in three of the six stars not showing the -2 km s^{-1} component; all of these stars are at small distances. One of these, α Oph (distance $= 18$ pc), is surrounded by a number of other more distant stars which did not show the -8 to -11 km s^{-1} component. The angular extent of this component is thereby strictly limited to a few degrees. For one of these stars there is no corresponding H I component. For two of these stars there exist very weak H I components which are discernable only as very small bumps on a contour map of antenna temperature versus position and velocity; on a single profile they are too weak to be easily distinguished as separate components and would normally be considered part of the 21-cm line wing. They are small in angle and the strength varies rapidly with position. (The contour maps of Heiles and Habing (1973) are currently at the printers; in examining these stars I was forced to use my personal set of copies of maps, which is incomplete. The above statements are made on the basis of the map at $b = 23.2°$, which is 0.6° to 1.2° away from the stars of interest. I am therefore unable to state with absolute confidence that my statements about H I apply at the particular positions of these stars; they may instead apply only at nearby positions). The distance of these clouds is limited by the distance of α Oph, 18 parsec. On this basis Münch and Unsöld assign a diameter of 1 pc. However, as mentioned above, there must be considerable angular structure in this cloud on much smaller length scales. This cloud is strange in showing a large Ca II/Na I line intensity ratio which normally occurs only for nonzero velocity components. The velocity of this component is definitely different from that of the H I main peak, however, so the high ratio is perhaps not surprising. It is tempting to speculate that the North Polar Spur is somehow responsible for this feature.

We summarize Habing's (1969) work here even though strictly speaking it fits in a slightly different category. He found high-velocity components in Ca II data for three stars of Adams (1949) and Münch and Zirin (1961) which he then mapped in the 21-cm line. One of these was associated with a negative intermediate-velocity cloud which was so large in angular extent that he abandoned the job of mapping it. The second had a velocity dispersion of 5 km s^{-1}, central velocity from 20 to 30 km s^{-1} (LSR) depending on position, $\langle N_{\mathrm{H\,I}} \rangle = 0.6 \times 10^{20}$ cm^{-2}, and an angular diameter of 15°. Its distance lies between 140 and 3400 pc. Assuming a distance of 1000 pc, its diameter is 260 pc; its density, 0.08 cm^{-3}; its mass, 24000 $M_{\odot}$. The density is not inconsistent with that of the noncoincident, probably ionized components discussed above in Section IIb; since both are at intermediate nonzero velocities, they may be similar. The third cloud often showed two velocity peaks with similar angular structure. The H I velocities vary from -40 to -60 km s^{-1} and the feature measures 12° by 3° in angular extent. If its distance is 1000 pc, its mass is 8000 $M_\odot$ and its density about 0.5 cm^{-3}. As Habing points out, the double-peaked velocity structure may indicate the presence of a strong shock front.

To summarize, thirty years of effort in studying optical absorption lines has not been particularly profitable for the purpose of mapping the angular extents of interstellar gas structures. Boundaries have been located only for one small cloud, (Münch and Zirin, 1961), which is itself much smaller than clouds which are normally responsible for optical lines. However, due to the coincidence of the radio and optical data, at least for the main body of gas, the radio results are expected to give the same results as would be obtained from a closely-sampled field of stars in the optical lines. The optical results which do exist are usually in full accord with the known radio results.

We note, however, that those statements refer to comparisons only of equivalent widths and central velocities of the optical and H I lines. If, for example, both sets of lines were subject to the scrutiny of van Woerden's (1967) Gaussian procedure, they might compare less closely. Such comparisons will always be subject to additional uncertainties due to the different beamwidths; however, given the close comparison existing for some objects (see Figure 1), it is most reasonable to assume that the structural details shown would in fact be identical.

(d) SUMMARY

In the main, the optical interstellar absorption lines arise mainly from gas which is *inter*stellar rather than *circum*stellar. The line width of low velocity gas is always much too large to result from thermal broadening and is therefore determined by macroscopic gas motions. The 8 to 12 optical components per kpc is an overestimate, but the true number is probably larger than the 1 or 2 found from H I absorption, even when accounting for the various velocity components which are seen in optical absorption but not in H I emission.

These noncoincident components occur at nonzero velocities and are almost certainly formed in H II regions. The high temperature may be responsible for the enhanced Ca II/Na I line intensity ratios in these objects, instead of the usually assumed depletion of Ca in low velocity clouds. These nonzero velocity features have low emission measures and are detectable only with the Na I and Ca II lines themselves. A large amount of suitable observational material presumably already exists in the form of spectra of external galaxies, quasars, and even globular clusters. Optical spectra of extragalactic radio sources would also permit the comparison of optical and radio absorption, which should be fruitful.

III. The Magnetic Field

Parker (1969) has pointed out that the correlation lengths of the gas and magnetic field in interstellar space should be the same if the magnetic energy density is smaller than that of the gas; the field which is frozen into the gas is randomized by the gas motions. Some of this random field component lies in the z direction. This z component is necessary, in the picture of Jokipii and Parker (1969), to enable cosmic rays to travel to high z distances and, ultimately, escape the Galaxy altogether by inflation of the magnetic tubes by cosmic ray pressure (Parker, 1966). (Cosmic ray particles are known to traverse less than a few g cm^{-2} of interstellar matter because of the absence of substantial quantities of nuclei heavier than H^1). This general picture has generated a series of papers attempting to derive the correlation length for the magnetic field (as opposed to the interstellar gas).

(a) THE CORRELATION LENGTH OF THE FIELD

Jokipii and Parker (1969) used the rms deflections of direction of starlight polarization in the galactic plane as determined by Hiltner (1956). The result was a correlation length of 100 to 300 pc.

Jokipii *et al.* (1969) have analyzed more recent starlight polarization data (Behr, 1959) in more detail and found similar results. However, the functional form used to match the data was such that equally good fits to the observational data could have been obtained with much different values of the correlation length simply by changing the required mean square value of the magnetic field. We therefore do not regard their quantitative results as being very reliable and hope that they will repeat the analysis with a more extensive set of data, for example the compilation of 7000 stars by Mathewson and Ford (1970). Jokipii and Lerche (1969) analyzed the dispersions of Faraday rotation measure for polarized extragalactic radio sources within a number of bins of galactic latitude and again obtained similar results. We regard this procedure with suspicion because they used a statistical approach which by its very nature requires a large number of independent samples. However, the derived correlation length, about 250 pc (equal to the total thickness of the galactic disk), is so large that the observational data in fact refer to only two or three samples (in this context, a sample is an individual magnetic bulge) over the whole area of sky ($|b| > 10°$) used in their analysis. Their 'dispersions' therefore simply represent differences between the small total number of independent samples visible from the Earth, and the dependence of dispersion on galactic latitude which they found simply reflects the fact that the average rotation measures become bigger in absolute value near the galactic plane because the average magnetic field is directed parallel to the galactic plane. All of this is self-evident in global plots of rotation measure, e.g., Wright (1973), or starlight polarization (Mathewson and Ford, 1970; see Figure 2b). That their derived correlation length is comparable to the thickness of the galactic disk is almost inevitable, given the nature of these global plots and their analysis technique. While it therefore follows that their numerical result is roughly correct, it does not necessarily follow that the result applies anywhere except immediately locally, or that the field really is randomly distributed as they assumed.

(b) THE CORRELATION LENGTHS OF THE FIELD AND GAS: DIFFERENT?

We regard the first determination by Jokipii and Parker (1969) as reasonably reliable.

It has the additional advantage that it refers to a substantial volume of space and is not restricted to the volume within a few hundred parsecs of the Sun. The correlation length for the magnetic field derived by Jokipii and Parker (1969) is larger than the 70-parsec correlation length for the gas derived by Kaplan (1966). Although one would hesitate to take the quantitative difference seriously, there are other data which indicate a scale difference between field and gas. These are the starlight polarization maps of Mathewson and Ford (1970) and the H I photographs of Heiles and Jenkins (1974) (see Figure 2). Although H I filaments arch out from the tops of some of the large cloud complexes, it is clear that at least in some regions (e.g., $l \cong 0°$, $b > 0°$) the large clouds (which would make the largest contribution to the correlation length) appear to be physically smaller than the loops of magnetic field. This difference in angular scale is almost certainly equivalent to a difference in linear scale, since the similarity of the directions of H I filaments and magnetic field strongly suggests a close physical association.

We should not forget that there certainly exist structural features in both the gas and the field on much smaller length scales than those discussed in the above paragraph. This is evident from looking at Figure 2. The large correlation lengths discussed above are those that are, or would be, derived by smoothing out all the small-scale irregularities. If these are not smoothed one will derive a whole spectrum instead of a single correlation length. At some stage it will probably be of theoretical interest whether this spectrum is more intense at small or large length scales. At present neither theory nor observation has really reached that stage of sophistication.

(c) SUMMARY

We believe that the difference in angular scale is real, in which case the z component of the field cannot be produced exclusively by gas motions as pictured by Parker (1969). The general picture of a field being produced exclusively by the gas motions would then also be incorrect. It is not clear to us that the cosmic ray problem actually requires a random field of the sort explicitly envisioned by Jokipii and Parker (1969); one can easily imagine that the cosmic ray particles could still reach substantial z distances and leave the Galaxy by magnetic tube inflation in a more organized (helical? – see Mathewson and Nichols, 1968) field which is not necessarily produced exclusively by random gas motions. It is less easy to imagine that the cosmic ray velocities will be made isotropic by such a more organized field.

The 21-cm data sheds more light on this relationship between gas and field, and strongly suggests the field is controlling the motion of the gas. These data are discussed in Section IV.

IV. H I 21-cm Line Observations

H I 21-cm line studies have the unique advantage over all others that the interstellar gas can be sampled in emission. Hence, the selection of positions to be observed is not limited by the availability of background sources. This very fact, which is of definite advantage in mapping individual features, has one disadvantage: individual features too near the galactic plane cannot be easily observed because of blending with hydrogen at other distances in the line of sight. The majority of work done in H I has been in the galactic plane, related to problems of galactic structure. In this paper we usually restrict our attention to studies at higher latitudes, since we are concerned with the spatial and velocity distribution of interstellar matter on a scale small compared to that of the Galaxy. Furthermore, in the main we consider only low-velocity gas. Much discussion has been aired on the subject of intermediate and high velocity gas in recent years, and the picture is still not clear. We doubt it will become so without high quality surveys of the southern sky. Thus, we avoid this material – which is itself sufficient for another whole symposium, anyway.

A number of H I studies have derived structural properties using statistical arguments applied to profiles taken at positions widely separated compared to the telescope beamwidth. These studies discard the fundamental advantage of emission studies – the ability to directly map structural features – and, in addition, always make some assumptions about the nature of interstellar gas structures in order to do the statistical analyses. This seems to us improper, since the goal is to derive the nature of the structural features in an unbiased manner. Accordingly, we omit such studies from consideration and restrict ourselves in the main to studies in which the gas has been directly mapped by 21-cm line emission, small-scale features noted, and their properties discussed.

The number of extensive mapping programs away from the galactic plane has burgeoned in recent years. This is because, by their very nature, emission studies require the acquisition of many profiles because structures exist on angular scales ranging from less than 10′ to about 60° or so, a range of about 10^5 in solid angle. Much smaller features exist, down to the smallest scale resolved by aperture synthesis techniques in the absorption spectra of some bright radio continuum sources (Greisen, 1973; Elliot *et al.*, 1973); we exclude these from present consideration. Studying the small structures to the exclusion of the large ones not only provides a biased view of the size scales in the interstellar medium, but also fails to show how the various size scales are related. Receivers and automatic data-taking and data-handling equipment of the quality required for really large survey programs became available only in the mid 1960's.

The first definitive emission study showing structural features of the interstellar H I was performed by Helfer and Tatel (1959) in the regions of Perseus and the Pleiades. This early study is remarkable in several respects. It used the first multichannel line spectrometer, of the same type as the one now being used at the IAR in Argentina, but without the aid of automatic digital data recording and analysis equipment. The authors presented data in the now standard formats of contour maps of antenna temperature vs one position coordinate and velocity, and contour maps of column density in certain velocity ranges vs both position coordinates. Their conclusions concerning the structure of the interstellar gas were prophetic. Six gas aggregates were found, none of which fell completely inside the area surveyed, a total of 225 deg^2. Some of the aggregates were definitely noncircular in shape. Unfortunately, the direction of polarization of interstellar starlight (hereafter referred to simply as 'optical polarization') is confused in this region so no comparisons can be made with the directions of elongation. They noticed that the map of column density for a velocity range of about 20 km s^{-1} showed much less structure than would be seen for a smaller velocity range. Thus they suggested that "many of the fine details in the line profile result from local turbulence rather than from the existence of sizable discrete gas clouds". Although the use of the word 'turbulence' may be incorrect and misleading, this suggestion is fully substantiated by the more extensive and recent studies by Verschuur (see below). If gas and dust are well mixed, as we suspect, there would then be no angular structure of interstellar reddening on small length scales, as has apparently been found (see Section I). This is a discrepancy which is not easily resolved. The reddening data used in those studies are usually confined to the galactic plane which, from our rather uninformed radio astronomical vantage point, makes the results suspect.

Since this early study, structural features have been seen in several forms which are easily classified. Some are definite *clouds*: structures which appear roughly circular on the sky, and are thus most likely roughly spherical in shape. They have diameters ranging from one to perhaps 100 pc with a corresponding range in mass. A surprising number of authors find structures which are distinctly different from clouds: *filaments and sheets*. Within these are sometimes imbedded cloud-like structures. The clouds are sub-condensations within the filaments or sheets, which themselves are single, coherent structures. Sometimes the 'clouds' are instead filamentary and are associated with the interstellar magnetic field. Finally, some of the gas is in a temporary state, having been affected by some (presumably) external process such as a supernova explosion: below we refer to this as *active* interstellar gas, because it definitely shows significant kinematic effects whereas the clouds, sheets, and filaments often show little obvious kinematic structure apart from relative motions of up to about 10 km s^{-1}. Discussion of this active gas violates, to some extent, our avowed intention to avoid the subject of intermediate velocity gas; however, we will restrict ourselves exclusively to studies of gas whose velocities are obviously not (even to Verschuur, 1973a) a result of galactic structure.

(a) CLOUDS

Raimond (1966) found 10 clouds with random shapes in the direction of the stellar associations I Mon and II Mon. Half of these seem to be related to the stellar associations themselves, and the others to dark clouds. Those associated with dark clouds are not dissimilar to that observed in the 21-cm line by Simonson (1973), who derives $M = 3400\ M_\odot$ and $n_H = 2.2$ cm^{-3} for the dark cloud Kh 713 (Khavtassi, 1960). The clouds associated with I Mon have masses ranging up to 90000 $M_\odot$ and diameters to 115 pc; those associated with II Mon are less massive by a factor of 10 or so. The densities are the usual 5 to 15 cm^{-3} found for most interstellar gas aggregates when seen in the 21-cm line. In addition to clouds, Raimond found an expanding shell around the Rosette nebula which is discussed below as 'active' gas.

Heiles (1967) studied the region $l = 100°$ to $140°$, $b = 13°$ to $17°$, and found a host of cloud-like structures. He divided these into two classes, large clouds and 'cloudlets'. Large clouds typically have mass $\cong 3000\ M_{\odot}$, density $\cong 5\ \mathrm{cm}^{-3}$, and diameter $\cong 30$ pc. These values contrast with those of the cloudlets, which typically have mass $\cong 4\ M_{\odot}$, density $\cong 2\ \mathrm{cm}^{-3}$, and diameter $\cong 5$ pc. Field and Hutchins (1968) point out that the large clouds and the cloudlets fit roughly onto the mass spectrum of interstellar clouds derived from the interstellar reddening data by Scheffler (1967a, b) but that there is an absence of objects in the mass range 24 to 280 $M_{\odot}$. This absence may simply reflect Heiles' bias in selecting objects for study, but it also may be real. All of the large clouds and cloudlets were found to exist in two huge sheet-like structures extending tens of degrees in angle and thus having characteristic dimensions of perhaps 100 pc; the material within each sheet moves coherently, apart from small random motions whose dispersion amounts to about 2.1 and 3.4 km s^{-1} for the two sheets.

Another huge aggregate was studied in detail by Riegel and Crutcher (1972). This object is distinguished by its self-absorption dip, seen in all profiles over an area 30° in longitude by 12° in latitude centered near $l = 15°$, $b = 3°$. The object is seen at three distinct velocities and has $N_H \leqslant 1.2 \times 10^{20}$. It contains much small-scale structure. Mass estimates are rendered very uncertain due to its completely uncertain distance, which is probably in the range of a few dozen to 1000 pc. The authors derive densities of 0.1 to 0.5 by assuming the gas is spread out uniformly over the line of sight to the upper distance limit of 900 pc. In fact we argue that the structure is much more compressed along the line of sight simply because it has a characteristic angular size of about 20° and contains a profusion of small-scale structure. If the distance is what we consider more reasonable, 100 pc, the density would probably be about 30 times larger, i.e., 3 to 15 atoms cm^{-3}, comparable with most other H I concentrations seen in the 21-cm line. Given its low temperature, one would a priori expect a density at least this large, but probably not excessively larger due to the absence of dust and molecules which always seem to appear in detectable amounts in dense concentrations.

A similar feature, but at a somewhat higher temperature, has been found by Baker (1973a) near $l = 180°$, $b = -15°$ to $-40°$. Such objects cannot appear in simple self-absorption at intermediate galactic latitudes because of the absence of a bright background temperature in the 21-cm line. Baker has invented a new analysis technique, the 'deviation defect method', to detect such objects; use of this technique should provide a new look at the colder portions of the interstellar gas in the coming years.

Van Woerden (1967) mapped 140 deg^2 of the Orion region, distinguishing 31 clouds by careful Gaussian analysis of all the profiles. He mapped the clouds by mapping the Gaussian parameters and found that the clouds are not dissimilar from the 'standard' interstellar cloud (Spitzer, 1968b). Both the velocities and shapes appear randomly distributed, in accord with the standard cloud model. Assuming a distance of 280 pc as used in Table I rather than the 480 pc used by van Woerden, cloud diameters are typically 25 pc, densities a few atoms cm^{-3}, and masses about 1000 $M_{\odot}$. (These values were estimated only very crudely from information given in van Woerden's paper.) The character of his results seems different from all the others quoted above. There are probably two reasons for this. First of all, the Orion region is a very special region in the sky. Examination of the contour maps of Heiles and Habing (1973) shows that the 21-cm line is stronger and contains more structure with larger, more extensive velocity gradients than for the typical region of interstellar space. The Orion nebula itself could not be responsible for this kinematical behavior because it is so young. Although older star associations exist in the same region, any old H II regions produced by them could not be responsible because the total extent of the disturbed region is huge, extending almost 30° in angle. We believe instead that the conditions which enable stars to form – presumably the preponderance of self-gravitation over disruptive forces – are themselves generated by, or are themselves responsible for, the kinematical structure. That is, we feel that the cause of the kinematical structure lies in gas-dynamical processes residing within the gas itself, rather than in any external influence such as hot stars. This feeling is based on little evidence, however. We state the above partially to justify the distance estimates for the gas used in Table I, which (for lack of definite evidence one way or the other) differ from the distance to the Orion nebula and the older stellar associations in its vicinity.

The second reason why van Woerden's results differ from those of others might be his extensive and thorough use of the technique of Gaussian analysis of individual profiles. Other observers usually discern structural features directly from contour maps. It would be extremely useful to see what van Woerden's data would look like if presented in the more usual form of contour maps of antenna temperature vs one position coordinate and velocity, or of contour maps of column density vs. both position coordinates for specific velocity ranges. We hope that the conclusions drawn are independent of the details of the analysis process; however, only a thorough comparative investigation will provide a definitive answer to this urgent question.

Finally, we come to the extensive high-resolution studies of Verschuur and his collaborators, made with the NRAO 300-ft telescope, the largest used for this type of work. Knapp and Verschuur (1972) analyze the properties of cold (temperature $\cong 25$ K) clouds near $l \cong 230°$, $b \cong 45°$. Physical properties are derived by assuming pressure equilibrium with the intercloud medium ($n_H T$ taken as 2000 K cm^{-3}); distance $\cong 19$ pc, mass $\cong 0.2\,M_\odot$, $n_H \cong 50$ cm^{-3}, and diameter $\cong 0.5$ pc for one and similar values for the other cloud.

Verschuur (1973c, d) has surveyed more than 500 deg^2 in two large regions, designated A and B, centered near $l = 235°$, $b = 44°$, and $l = 215°$, $b = 27°$, respectively. He (1973b) also observed the large filament, and its internal cloudy structure, which arches out of the Perseus-Orion gas aggregate near $l = 180°$, $b = -55°$, visible clearly in Figure 2a and here called region E (this nomenclature is not used by Verschuur).

In all of these regions he finds many small clouds of mass $\cong 10\,M_\odot$, diameter 3 pc, and density 40 cm^{-3}. Many of these clouds are really elongated filaments, parallel to the magnetic field; they are discussed more fully in Section IVb. Heiles's cloudlets, which are smaller and less dense, seem to be similar to these in qualitative aspects (except perhaps with regard to orientation of the magnetic field). Verschuur finds higher velocity dispersion, however: 4 to 5 km s^{-1} in regions A and B and the major

H I filament, with somewhat higher values in two minor filaments associated with the major filament. The velocity dispersions within Heiles's sheets are smaller, only about 3 km s^{-1}.

(b) SHEETS AND FILAMENTS

(i) *Structure*

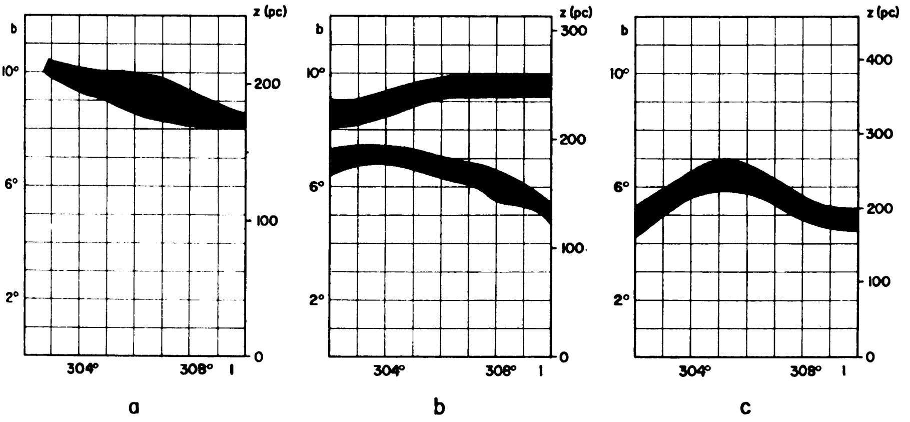
We have recently learned that sheets and filaments – especially the latter – are very common in the interstellar medium. Sheets appear to have been seen first by Heiles (1967) in his detailed study of the region $l=100°$ to 140°, $b=13°$ to 17°. These sheets are coherent over a large fraction of the whole area surveyed, or perhaps even a larger area. Motions within a sheet are small, with dispersions of 2.1 and 3.4 km s^{-1} for two sheets. The velocity of a sheet varies slowly, if at all, with position. Another sheet has been found in the Taurus region by Baker (1973b), who suspects the sheets may form a ring-like structure around the solar neighborhood. Herbig (1968), using optical techniques, finds a large sheet in front of ζ Oph from interstellar absorption lines.

Sancisi and van Woerden (1970) saw a filamentary-shaped feature near $l=350°$, $b=20°$. This object is barely visible on Figure 2. It is 4° wide and 14° long, perhaps longer because it may extend beyond their southern declination limit of $-30°$. Its linear dimensions are probably about 15×45 pc, with a density about 2 cm^{-3}. This object is elongated perpendicular to the magnetic field. However, it is bounded on one side by dust (which would tend to convert the H I into H_2, see Heiles, 1971) and on the other by bright nebulae (converting H I to H II). Thus its apparent elongation as seen in the 21-cm line of H I is probably simply a result of conversion of H I to other forms. In this case its orientation with respect to optical polarization is irrelevant, and it is a filament of a completely different class than those discussed immediately below.

A large number of filaments have recently been seen in the interstellar gas. Many of these are apparently aligned with optical polarization, hence presumably the magnetic field. Of course, this result is not without its precedents; dust filaments on widely different length scales have long been known to be aligned with the magnetic field. Shajn (1955) finds large dust filaments, degrees in angular size, oriented parallel to the field in large regions in Perseus, Taurus, Cygnus, Ophiuchus, and near IC 1396. He and others also find the very small filaments in the Pleiades oriented parallel to the magnetic field (see review by Hall and Serkowski, 1963). Furthermore, dust clouds and intermediate-velocity clouds (Verschuur, 1970a) and some low-velocity clouds (Verschuur, 1970b and private communication; Heiles and Jenkins, 1974) are aligned with the field.

Figure 2 (a) shows the large filaments seen in H I especially well. Near $l=0°$ at high positive latitudes a number of filaments appear to arch out of the large Ophiuchus cloud where Gould's belt achieves its maximum displacement to positive latitudes (see Table I); these are also parallel to optical polarization. An apparently similar filament arches out of the Orion-Perseus gas complex near $l=180°$ at negative latitudes; the scant optical data which exist in this region also suggests alignment with the interstellar magnetic field. This filament, in contrast to the one just mentioned, contains appreciable velocity structure along its length. A portion of this filament has been studied in detail, at high resolution, by Verschuur (1973b). Yet another large filament rises perpendicular to the galactic plane near the north celestial pole ($l \cong 120°$, $b \cong 30°$); again, optical polarization data is scanty here, but suggests alignment. This filament has appreciable velocity structure both along and perpendicular to its axis. Some of the filamentary structures are extremely long, extending up to 80° or so in projection on the sky. A typical large filament has density $\cong 30$ cm^{-3}, diameter $\cong 2$ pc, and mass $\cong 6$ $M_\odot$ per parsec of length.

Long filamentary structures similar to those seen in Figure 2 have been observed in regions other than the solar neighborhood. (All those seen in Figure 2a are located at intermediate to high galactic latitudes, and are therefore nearby, probably all within a few hundred parsecs and some within 100 pc). Vieira (1971) has examined a portion of the southern sky near $l = 306°$, $b = 6°$, and finds two prominent filamentary structures and an elongated cloud (which might in fact be another filament). The two filaments were seen at two velocities, one at -20 and one at -30 km s^{-1}. The -20 km s^{-1} feature is really a double filament with $z \cong 160$ and 240 pc, both of which run more or less in a straight line across the whole extent of the observed region. The -30 km s^{-1} feature has $z \cong 190$ to 250 pc, variable because this filament meanders crookedly. Both the elongated cloud and the double filament at -20 km s^{-1} are aligned parallel to the optical polarization; we cannot specify the polarization direction for the other filament because it is too distant (2.2 kpc). Physical properties must be derived using kinematical distances, which are rather uncertain since the radial velocities are not large. All have projected densities $\cong 10^{21}$ cm^{-2}, diameters of almost 1° (about 30 pc), and volume densities $\cong 10$ cm^{-3}. The latter two parameters may be affected to a significant extent by the angular resolution of the telescope, about 0.5°.



a b c

Fig. 4. Filamentary structure at a distance of 1 to 2 kpc. From Vieira (1971).

All the filaments contain about 30 $M_\odot$ per parsec of length, not inconsistent with that for the nearby filaments discussed above, especially considering the uncertainties in distance.

Weaver's (1974) map of the z extensions of the outer arm of the Galaxy also shows the presence of filamentary structure. Apparently, then, the existence of the large filaments, at least some of which seem to arch up out of the galactic plane, is common.

There are other intermediate and high galactic latitude regions which contain filamentary structure with a smaller characteristic angular size, and therefore presumably linear size as well. Dieter (1964, 1965) surveyed the galactic poles, in particular the North Galactic Pole. She found definite cloudlike structures, some at normal low velocities and some at the characteristic intermediate negative velocities. Here, of course, we concentrate on the low velocity gas. She found several condensations with properties very close to those of the 'standard cloud' (Spitzer, 1968b): diameter 7 pc, $n_H = 10\ \text{cm}^{-3}$, and mass $= 30\ M_\odot$. However, these clouds are elongated, in a direction parallel to the magnetic field as inferred from both optical (Mathewson and Ford, 1970) and radio (Bingham, 1966; Spoelstra, 1972) polarization. These filaments lie just outside of the North Polar Spur in the region where it reaches its maximum extent in galactic latitude.

Near $l = 40°$ for positive latitudes nearer to the galactic plane there is also filamentary structure, here in profusion (see Figure 2a). These also lie just outside the NPS. They are aligned perpendicular to the galactic plane, and parallel to the magnetic field as inferred from both optical (Mathewson and Ford, 1970) and radio (Spoelstra, 1971, 1972) polarization. They are partially contained in Verschuur's (1973d) regions *C* and *D*, studied with the high angular resolution afforded by the NRAO 300-ft telescope. Verschuur (1973c) also found filamentary structure aligned with the magnetic field in regions *A* and *B*. He confirms the general impression gained from Figure 2a.

Other regions contain filamentary structure whose orientation with respect to the magnetic field is presently uncertain, mainly because of insufficient optical polarization data. These occur at positive latitudes for $l = 180°$ to $270°$ and at negative latitudes for $l = 30°$ to $140°$. Many of these are extremely delicate and beautifully shaped and can be fully appreciated only by staring at the relevant areas of Figure 2a for a minute or so.

(ii) *Internal Motions*

What are the velocity fields within these filaments? First we consider the very long filaments visible in Figure 2a. Little in the way of detailed analysis has been done, but a qualitative feeling can be obtained from the color photographs in which color indicates velocity (Heiles and Jenkins, 1974). These show that some filaments have essentially no relative Doppler motions along their length while some show considerable velocity differences but with small velocity gradients, as indicated above. The one near $l = 120°$, $b = 30°$, has rather chaotic velocity structure along both its length and width. The kinematics therefore depends on which filament we examine. However, we must remember that we can only measure the line-of-sight component of velocity, and unfortunately the line-of-sight geometry (i.e., distance as a function of position along a filament) is unknown. Even for those filaments showing relative motion with position along the length, we cannot say whether the gas is expanding, contracting, or moving perpendicular to the axis of the filament.

The smaller scale filaments discussed by Verschuur (1973b, c, d) in regions *A*, *B*, *C*, *D*, and *E* show kinematical structure whose magnitude depends on the regions. The sense of the structure is always the same, with velocity differences occurring along the length of the filament. Region *A* shows only small velocity gradients, regions *B* and *E* intermediate gradients, and regions *C* and *D* very large gradients. Only in one case do we have definitive information on the line-of-sight field geometry, in regions *C* and *D*. This comes from optical and radio polarization studies. These show that the component of the field projected on the plane of the sky runs nearly perpendicular to the galactic plane, and of course parallel to the filaments; the lack of Faraday rotation in the radio shows that there can be very little component of the field parallel to the line of sight.

Therefore, since the Doppler gradients run along the length of the filaments which are themselves aligned with the magnetic field and have no line-of-sight component, we have the following possibilities:

(i) The gas is actually moving perpendicular to the magnetic field. This possibility violates the fundamental theoretical precepts of magnetogasdynamics.

(ii) The filaments are not really aligned parallel to the magnetic field, but only appear so in projection on the sky. This possibility requires a favored location of the Earth, since the apparent alignment of field and filaments appear in several regions located in completely different parts of the sky.

(iii) There are no electrons in these regions, so that a line-of-sight field component would remain undetected by Faraday rotation studies. This violates the generally accepted theories and observations of the ionization balance in the interstellar gas.

(iv) The gas is moving parallel to the field and the field has a very small inclination to the line of sight. This would mean that the observed velocities represent only a tiny fraction of the true gas velocities because of projection effects.

(v) Both the gas and field are moving perpendicular to the magnetic field together as in an Alfvén wave. The waves would be propagating either towards or away from the galactic plane, in a direction along the magnetic field but perpendicular to the line of sight. Alfvén waves, being transverse waves, would allow us to see the mass motion involved in the transverse vibration.

The last possibility seems the only acceptable one. Verschuur's maps show significant velocity changes in angles of a few degrees; given the distance to these filaments (about 60 pc, from optical polarization work) this implies a wavelength scale of a few pc. If the Alfvén velocity is 10 km s^{-1}, the relevant time scale is about 10^5 yr. This is comparable to the cooling time scale. The Alfvén wave is strong enough so that compressibility of the gas cannot be neglected. A theoretical treatment of these waves would not be simple.

Although the above argument is based on only a cursory look at Verschuur's data, the fundamental conclusion that we see motion of gas and field together in a direction perpendicular to that of the average field direction seems almost inescapable.

(c) ACTIVE REGIONS

As a preliminary, we emphasize that all masses quoted below are H I only as derived from the 21-cm line. The velocities of these objects are large enough so that one would naively expect most of the gas to be H II. Thus, total masses may be seriously underestimated.

A number of authors have found H I in a kinematical state which is apparently produced by an external event, such as a supernova explosion. The most clear-cut case of this specific type of association, i.e., with the supernova HB 21, has been made by Assousa and Erkes (1973). They find a shell of 3000 $M_{\odot}$, density 2.5 cm^{-3}, radius 25 pc, expansion velocity 25 km s^{-1}; the dependence of velocity on position mimics that of an ideal uniform expanding shell to a surprising degree, given the expected degree of density fluctuation in the interstellar medium on that length scale.

An apparently expanding, very large (diameter 30°) shell of H I with an apparent center of $l = 310°$, $b = 45°$, was found by Fejes (1971). It is characterized by triple-peaked profiles and has an expansion velocity of 30 to 40 km s^{-1}. Its total mass is perhaps 2000 $M_{\odot}$. One edge of this object is close to the southern declination limit of the Dwingeloo telescope, and it would be desirable for the southern observers to survey the nearby portion of sky to ensure that the object is really self-contained within a diameter of 30°.

Another expanding shell around the Rosette nebula was found by Raimond (1966). Its expansion velocity is 25 km s^{-1}, diameter 8 pc, mass 4000 $M_{\odot}$. This is an example of an expanding shell presumably produced by an object less energetic than a supernova, although the amount of kinetic energy in the shell is nevertheless very large.

A number of observers have found correlations of H I and the radio continuum loops. The correlation of H I and the North Polar Spur (NPS), or Loop I, is quite apparent (Berkhuijsen *et al.*, 1971). This correlation takes two forms. One is the correlation of column density H I with the outer (?) *gradients* of the continuum loops. This is evident in Figure 2a for the NPS; a comparison with the radio continuum map of Berkhuijsen (1971), particularly when presented in photographic form (Heiles and Jenkins, 1974), shows very clearly that the hydrogen is lined up just like the continuum, but about 5° higher in galactic longitude. The clouds of Dieter (1965) near the North Galactic Pole continue this association and are also elongated in the direction of the optical polarization, which is in turn aligned with the NPS (Loop I).

The second form taken by the H I continuum correlation concerns the velocity structure. Within five degrees longitude of the points where Loops I and III cross $b = 30°$ there are relatively small-diameter features with very high velocity dispersions, greater than 40 km s^{-1}. Correlations with other loops discussed by Berkhijsen *et al.* (1971) are not convincing to this author. Fejes and Verschuur (1973), however, find what appears to be a significant correlation of H I density and velocity structure with Loop III. At $l = 90°$, where loop III crosses $b = +17.8°$, there is a deficiency of H I relative to that at surrounding longitudes; at $l = 155°$, where Loop III crosses the same latitude again, the H I profile splits into two components separated by about 15 km s^{-1}. Maps of H I column density within narrow velocity intervals centered at −32, +5, and +12 km s^{-1} show that the hydrogen structure is oriented parallel to the loops in this region. The positive velocity components are the same cloud seen in optical Na I by Hobbs (1969) in front of the Pleiades, discussed in Section IIc of the present paper. Whether the correlations found by Fejes and Verschuur (1973) are truly significant or simply accidental can best be determined by studying the H I-continuum relation around the whole perimeter of Loop III. Although examination of Figure 2a does not suggest that the correlation will necessarily continue around the whole perimeter, Figure 2a is made by integrating over a 40 km s^{-1} interval in velocity. Fejes and Verschuur show that one must consider smaller velocity intervals to make many of these elongated H I features stand out.

Finally, there may exist other somewhat less active regions in which H I is influenced by stars. Baker (1973a) has found a number of these, which are easily visible on the contour maps of Heiles and Habing (1973). Verschuur (1969) has found what appears to be a tunnel in H I produced by a B2 star moving through the gas. The tunnel is about 10 pc in diameter, 31 pc long, and contains 500 $M_{\odot}$ at density 9 cm^{-3} of what is now H II. It shows as a relative deficiency of H I emission. This seems vaguely reminiscent of the ideas of Hills (1972) concerning the effects of stars on the structure of H I and H II in the interstellar medium. Such interactions between hot stars and gas in relative motion might represent a mechanism to provide significant kinetic and perhaps thermal energy input to the gas.

(d) SUMMARY

In his latest studies Verschuur reaches the same conclusion regarding the spatial velocity structure of the gas as did Helfer and Tatel (1959) in the earliest study. Much more structure is visible in column density maps made from small velocity ranges than in the corresponding map from a large velocity range. Thus, to repeat the words of Helfer and Tatel (1959), "many of the fine details in the line profile result from local turbulence rather than from the existence of sizable discrete clouds." When the "turbulence" is integrated over velocity, regions look quite smooth in the distribution of column density. It is then hard to understand how the analyses of the angular distribution of interstellar reddening arrive at small length scales (see Section I), and we instinctively suspect (without having seriously investigated the question) these analyses to be incorrect in this regard. The clouds found with today's modern instrumentation are very small, typically with mass$\cong$20 $M_{\odot}$, density$\cong$50 cm^{-3}, and diameter$\cong$3 pc. This phenomenon of small-scale structure in velocity and position, having been noticed in all regions observed with the narrow beam of the NRAO 300-ft, may be ubiquitous, at least within large gas aggregates.

However, the turbulence referred to by Helfer and Tatel, and by many others more recently, *is not* turbulence in the rigorous sense. The word 'turbulence' connotes the existence of momentum transfer by turbulent viscosity (cloud collisions, in astronomical terminology). These do not necessarily occur. Both the shapes and velocities of Verschuur's 'turbulent' elements are highly organized with respect to the magnetic field. One gains the impression that the gas is moving along the magnetic field, and in one case we see something resembling an Alfvén wave. The field, in turn, has uniformity on an angular scale which is much larger than the 'turbulent' elements. Like cars travelling on a highway, they might well never collide – they are all moving in the same direction together. The qualitative difference between turbulence and the observed situation in these regions is immense, and we must be less capricious in our use of this word.

The randomness in position implied by the interstellar cloud model does not usually exist. The delicate filaments seen in regions containing no large gas aggregates in Figure 2a can hardly fit the spirit of the cloud model. Neither do the large filaments, nor the gas associated with the North Polar Spur in which we apparently see Alfvén type motions, nor do the active regions.

The internal structural details of the large gas aggregates themselves have not yet been adequately studied. One of the few studies of these is van Woerden's (1967); if his results are representative, and there is reason to believe they are not, the standard cloud model might indeed apply *within* the aggregates.

V. Dust Clouds

Dust clouds are usually invisible in the H I line (Heiles, 1969; Mahoney, 1972) because of conversion to H_2. This conversion was predicted several years ago (Hollenbach *et al.*, 1971), and recent UV data have completely corroborated the theoretical predictions (Carruthers, 1970; Spitzer *et al.*, 1973). The properties of dust clouds have been discussed in several recent review papers (Heiles, 1971; Rank *et al.*, 1971; Gordon and Snyder, 1973; Solomon, 1973) and accordingly we shall treat this subject very briefly and emphasize some points which we feel to be particularly important.

The amount of dust contained in a cloud is easily estimated if the distance and extinction are known. The distance can readily be obtained, at least approximately. Often the extinction is so high that essentially nothing can be seen through the cloud; in such cases only lower limits can be obtained. Grasdalen (1973) has analyzed the appearance of small reflection nebulae within some dark clouds and finds that these lower limits may be smaller than the true extinctions by a factor of 10 or so.

Once the amount of dust is known the total mass can be derived simply by assuming that hydrogen and helium are not contained in the dust grains. A lower limit to the total mass is then obtained simply by multiplying the mass of dust by the mass ratio of (hydrogen + helium)/heavy elements, a factor of about 100. The derived masses are lower limits, often in two senses, then: one, the derived mass of dust is itself a lower limit; two, not all the heavy elements exist in the form of solid dust particles (the observation of molecular lines assures us that this is the case).

There is an independent and much more direct way to obtain a lower limit to the mass of gas in the clouds. Many molecular lines require high collision rates to bring their excitation temperature above the 3 K blackbody temperature so that they can be seen in emission. Collisions with neutrals, particularly H_2, is the generally accepted mechanism for this excitation. In many cases the excitation temperatures are known quite well, and this provides lower limits on the required H_2 volume density. This, together with the angular extent of the molecular emission and a distance estimate for the cloud obtained optically, provide a lower limit for the H_2 mass directly. Radiation trapping for optically thick molecular lines can reduce the required density to a degree which is currently uncertain, but these effects are probably important only for the very large clouds near the galactic center and H II regions, rather than the usual interstellar dust clouds.

Lower limits for mass derived using the two methods agree quite well. Derived densities range up to 2400 cm^{-3}, masses to 2000 $M_\odot$, and radii to 6 pc (see Hollenbach *et al.*, 1971). Self-gravity may overcome internal pressure in many clouds; numerical estimates come close to the borderline. If the true values of mass are much larger than the lower limits – for example, if Grasdalen's extinction estimates are indeed both correct and representative – then gravity certainly dominates in at least some clouds. This is perhaps surprising in view of the tendency for elongated dust clouds to be aligned parallel to the interstellar magnetic field (Shajn, 1955; Hall and Serkowski, 1963; Verschuur, 1970a). Perhaps the magnetic field pressure is stronger than the internal gas pressure. There is some observational support for this view, since grains in the Ophiuchus cloud show a high degree of alignment (Carrasco *et al.*, 1973).

Clouds located near H II regions or the galactic center dwarf the usual interstellar dust clouds discussed above. The distinction between these may not be too sharp, however. An intermediate case has been found by Kutner *et al.* (1973), who have detected a 10^5 $M_\odot$ cloud in the vicinity of Orion B, far enough away so that it is not really associated directly with this H II region. The clarification of this situation requires a large scale CO survey.

Hollenbach *et al.* (1971) have performed a statistical analysis of the dust clouds in Lynds' (1962) catalog with the aim of deriving the total mass resident in these clouds. They find the astounding result that *fully 40% of all the interstellar matter is located in dust clouds, and is invisible* to radio astronomers because the H I has turned to H_2. The distribution of these clouds in the sky, shown in Figure 2d from a catalog on computer cards kindly supplied recently by Lynds, shows that the distribution of these clouds is not random. Most are imbedded within the large gas complexes visible in the H I map of Figure 2a. Although this may affect the statistical results of Hollenbach *et al.* to some degree, the basic conclusion remains. A large fraction of the gas in these complexes is located in very dense clouds where the hydrogen is mainly H_2.

Do these clouds move randomly, with the resultant possibilities of cloud-cloud collisions? Probably not. The gas they now contain must have flowed along the magnetic field when the cloud was forming; it seems unlikely, then, that two clouds could exist close together on the same tube of magnetic flux. Thus they can collide only by moving across the field. But the dust clouds are elongated in the direction of the field (Verschuur, 1970a), so the field is important in their dynamics and the cloud cannot move across the field. Therefore the clouds can collide only rarely, if ever. They should evolve completely independently.

VI. Summary

A comprehensive summary of this paper would simply repeat the points emphasized in the summaries of individual sections. Comments showing our disapproval of the standard cloud model have been liberally interspersed among the material of this paper. Accordingly, a summary seems superfluous.

For those readers who cannot afford the time to read the entire article, the sections having the broadest range of interest are probably Sections IVb, V, and the summaries of Sections II and IV.

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DISCUSSION

Heiles: This distribution of shapes seems completely different from what you found in Orion, which I think is very significant, because I think it says that the shape depends on where you look. This particular area, on the Hat Creek survey photograph produced by Jenkins and myself, shows a filamentary-type structure with a great big hole in the middle. The hole in the middle is right on top of a hole in the radio continuum. So I think this region is an unusual one where there has been some sort of event, probably an explosion, which has blown both the radio continuum and the neutral hydrogen out of this hole, and it is all concentrated around the edge, with a diameter of some 20° or 30°. So maybe some of these particular shapes are not representative of the interstellar medium in general but only this funny kind of region in particular. I hope you continue your studies in other regions.

Van Woerden: It is quite a big job. We had selected this region because it had no optical peculiarities about it. In Orion, though, I would say that there are quite irregular shapes, at least in some of the clouds. But maybe the resolution into clouds is not as good there as in this region.

Greenberg: What are the scales of the various filaments we have seen? Are the scales of the dust clouds the same as the scales of these filaments?

Heiles: In the Pleiades you see filaments that are much less than 1 pc – 0.01 pc or something like that. And then you see a continuous distribution of sizes all the way up to things on the hydrogen photograph which are 40° to 70° long and an equivalent number of parsecs long. On the galactic scale, in Weaver's picture those things occupy 10° in length but they are much further away. In the middle of Andromeda things sort of look filamentary, but on a size scale of kiloparsec. So it's all the way from 0.01 pc or less up to kiloparsec. I suppose one ought to try and derive the spectrum.

Oort: In connection with the problem of the stability or the collapse of dust clouds which Heiles has discussed, I want to draw attention to the fact that even the denser dust clouds often have shapes which show clearly that they are not equilibrium structures. Furthermore, it should be remembered that every cloud condensed from the interstellar medium must have considerable angular momentum. This will prevent rapid collapse. In fact, it is more of a problem how stars can be formed at all in the presence of this angular momentum than how their formation would rapidly use up the gas in these dense clouds.

Heiles: Theoreticians tell us that clouds will be unstable to either collapse or expansion. However, the existence of so much matter in dust clouds implies that they are stable. So it seems to me these structures are not understood.

Mathewson: This filamentary structure which is evident at high latitude seems to me to be more of a general characteristic of the interstellar medium. My unified magnetic field model has a helical field, which may also be a general characteristic of this region of a spiral arm. There is also another model of lots of supernova remnants, lots of loops, which has been put forward. It seems to me that with your data you could distinguish between these two. Looking at your velocities, I would consider it favors the characteristic of the general magnetic field of the spiral arm rather than lots of explosions. How do you feel about that?

Heiles: I am of two minds. I think it depends on where you look. The one filament around the north celestial pole, near $l \sim 30°$, which we were just talking about, I think, is lined up precisely on a hole in the continuum. Much of the intermediate velocity gas is lined up on the continuum loops. Both of these look like explosive events. On the other hand, some of the major filaments coming out of Ophiuchus follow the field very obviously. You can trace them all the way around to the southern declination limit of $-30°$. Then starting over in Orion, you can trace a filament to the southern declination limit of $-30°$. Those filaments may be actually one and the same. If so, it would be in favor of the helical field with the gas aligned right along it. So I think it may depend on just which filaments one talks about.

Mathewson: Would you expect the continuum to also coincide with your filaments? It's quite natural to think that if these things are explained by an explosion then the magnetic field is concentrated in the filaments, and also the dust. It would be a natural consequence even if it were just a general characteristic of the interstellar medium. I don't think you would need any explosion.

Heiles: The only reason I say that some of those are probably explosions is because of the velocity fields in the hydrogen which occur there – a very large velocity difference of some sort. In other ones, only 5 or 10 km s^{-1}, so no problem. That's why I distinguish between those two.

Burke: Although the interstellar magnetic field certainly exists, it is not so clear that it has an important effect on the H I motions, as Heiles implies. For example, the mere existence of filaments does not require a magnetic field. The known properties of the hot and cold components allow them to be in approximate pressure equilibrium. Filamentary structures in a gas in approximate pressure equilibrium are then entirely natural, with no intervention of a magnetic field. This can be seen easily in the case of cigar smoke curling through the air in a room even when the air is quite actively stirred. The production of thin sheets by expanding shock fronts is also quite natural. The magnetic field, therefore, may well be a passive participant, dragged along by more energetic processes, having minor effects on the gas dynamics.

Heiles: It's only an impression from looking at things that the field controls the gas rather than vice-versa. We are going to try to pin this down by Zeeman measurements.