INTERSTELLAR MATTER AT LARGE DISTANCES FROM THE GALACTIC PLANE

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ABSTRACT

The interstellar gas at large distances z from the galactic plane is studied by the absorption lines it produces on the spectrum of distant stars off the Milky Way. From the statistics of multiple lines in various ranges of z, it is shown that some gas clouds probably exist at $z = 1$ kpc. The number of clouds observed in $0\ 5 < z < 1$ kpc has been found to be larger than would be expected from the known distribution of their velocity components in the galactic plane. The apparent asymmetry in the distribution of high-velocity clouds is explained as the result of decreased chances of collisions in the z-direction and also in terms of an intrinsic anisotropy in the mechanism accelerating the clouds. The typical time required for the clouds to reach their actual probable height from $z = 0$ is evaluated to be 40×10^6 years From the line intensities and by assuming cosmic abundance of the elements, a relation between the linear dimensions and the densities of the clouds is established. Irrespective of whether the clouds are H I or H II regions, it is found that their continued existence for 40×10^6 years requires the operation of a process preventing them from expanding. The physical conditions prevailing in a galactic halo or corona exerting pressure on the clouds are next analyzed. It is shown how the observations rule out a halo with an electron temperature T_e around $10^{4°}$ K. A corona with $T_e = 10^{6°}$ K, as postulated by Spitzer, on the other hand, is found admissible, provided that the high-velocity clouds at high z are H II regions. The large energy input by conduction from the corona may be balanced by radiative losses only at about $T_e = 10^{4°}$ K. Next the ionization equilibrium in the clouds is briefly discussed, and it is suggested that the anomalous abundance ratio Na/Ca observed in interstellar space is the result of using an unrealistic mean stellar radiation field in the photoionization computations. In this context, the results of a calculation of the ionization equilibrium of aluminum is presented It is shown that the Al I line at λ 3964 should have a strength about one-twentieth that of Ca I λ 4226. In a final section the possible mechanisms by means of which interstellar clouds may be accelerated are discussed. It is shown how the operation of the Oort-Spitzer process requires a ratio between the total amounts of ionized and neutral interstellar matter much larger than is observed. The relevance of magnetic fields in accelerating small masses of ionized field-free material is thereby emphasized.

I. INTRODUCTION

Observations of interstellar absorption lines have been carried out extensively only in stars relatively near the galactic plane, the limitation naturally arising from the scarcity of background stars at higher galactic latitudes. The information available in regard to the distribution of interstellar gas at large distances z from the galactic plane is thus quite meager. And this situation has not been materially improved by the 21-cm line surveys, so far made, because the signals received with existing antennae in high galactic latitude directions are rather weak. The spatial arrangement of the interstellar gas clouds in the z-direction is, in principle, related to their velocity distribution in the same direction. The distribution of velocity components in the galactic plane has been determined by Blaauw (1952) from Adams' (1949) observations of Milky Way stars. On the other hand, the galactic magnetic field revealed by the polarization of starlight in interstellar space is known to have a large-scale symmetry with respect to the galactic plane. Because of the effect that the magnetic field may have on the motion of the clouds, it is of importance to investigate an possibile anisotropy in their velocity distribution. With the

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view to deriving information regarding this important attribute of the interstellar medium, we undertook[1] a survey of the interstellar absorption lines in all suitable high galactic latitude stars, accessible to the 100-inch and 200-inch telescopes, with dispersions not smaller than 10 A/mm. In this paper the results of the observations are presented first, and then their compatibility with known observational information is studied. In a final section the implication of our analysis in regard to various theories related to the structure, nature, and motions of the interstellar medium are discussed.

II. THE OBSERVATIONS

The mean thickness, $2z_{1/2}$, of the layer of interstellar gas, measured between the points where the density is half its value at the galactic plane, has been fixed as 240 pc by van Rhijn (1946), from the interstellar absorption lines, and as 220 pc by Schmidt (1957),

TABLE 1

RADIAL VELOCITIES OF INTERSTELLAR LINES IN HIGH GALACTIC LATITUDE STARS

HD*	b	Sp	m_v	z (pc)	V_s (km/sec)	ΔV (km/sec)	Plate	V†	Intensity
29248	−29°9	B2 III	4 12	240	+ 15	−17 4	WSA	+ 2 5, +21 0	1, 4
38666	−25 9	O9 5 V	5 20	300	+110	−19 9	Pb	+20.9, +40 1	4, 3
60848	+19 0	B0	7 2	390	+ 15	−11 3	Cc	+13 4	6
89688	+47 4	B3 V	6 5	370	+ 5	− 6 5	Cc	+ 7 6	4
97991	+52 4	B2	7 28	640	+ 24	− 6 3	Cbc	+ 0 5	5
91316	+54 0	B1 Ib	3 85	580	+ 42	− 4 4	WSA	−11 5, −2 0, +17 9	5, 2, 3
93521	+63 6	O9 Vp	6 89	1500?	− 16	+ 1 6	CaPb	−56 3, −35 6, −12 0, +5 1	3, 1, 5, 2
100600	+70 6	B3	6 0	340	+ 19	+ 1 3	PbCb	−6 0	2
104337	+41 7	B5	5 3	280	+ 2	− 2 4	WSA	−0.5	5b
119608	+42 4	B1 Ib	7 32	2700?	+ 23	+ 5 4	Pbb	−2 6, +18 5	5,3
135485	+34	B5p	8 3	250	− 12	+11 2	Pcc	− 5 5	2
149363	+25 2	B0 5 III	7 9	980	+115	+15 8	Pcc	−12 6	7b
149881	+34 8	B0 5 III	6 59	890	+ 13	+18 6	Cbc	−15 6	9b
156110	+34 8	B3 Vn	7 44	420	− 43	+18 8	Pbb	−38 7, −18 6	1, 6
203664	−28 5	B2 Vn	8 3	660	+ 40	+12 0	Ccc	− 8 2, +66 0	5, 3
206144	−46 5	B3 Vn	9 1	1200	+ 76	+ 6 5	Ccc	(−24 8), −9.8	1, 8
209008	−37 5	B3 III	5 99	440	− 7	+ 9 4	Cbb	−16 8, −2.8	2, 2
210191	−53 1	B2 V	5 74	360	− 5	− 5 2	Ccc	(−19 1), −2 4	2b, 3
212571	−45 8	B1p	4 64	230	+ 4	+ 6 7	WSA	−14 1, − 3 9	7, 2
214080	−58 2	B1 Ib	6 69	2000	0	+ 3 0	Ccb	− 4 0, +16 6	6, 2b
214930	−30 7	B2 IV	7 30	490	− 53	+ 8 8	Ccb	−10 9	5
215733	−37 0	B1 II	7 2	1200	− 23	+ 7 3	Ccb	−57 0, −44 5, −25 8, −11 4	2, 3, 4, 5
219188	−50 8	B0 5 III	6 93	900	+ 48	+ 3 7	Cbb	−28.9, −6.8, (+17 8)	2, 4, 1
220172	−63 5	B3 Vn	7 54	710	+ 13	+ 1 0	Cbb	−22 9, −2 2, +12 1	1, 4, 1

* HD 91316—ρ Leonis Int (A)K, 0 066, 0.022, 0.033 A; H: 0 037, 0 01, 0 017 D lines: (Spitzer and Routly 1952) Vel (km/sec) −5.8, +23.1; int. (A) D2, 0 124, 0 043, D1, 0 058, 0 012
HD 93521—Int (A) K, 0 051, 0 016, 0 095, 0 031; H, 0 030, 0 010, 0 057, 0 016 D lines: velocities: −36 7, −9 6; Int (A) D2, 0 02, 0.18; D1, 0 01, 0 14
HD 119608—Int (A) K, 0 078, 0 066; H, 0 052, 0.048; D2, 0.174, 0 104; D1, 0.134, 0.068
HD 135485—A spectroscopic analysis of this subluminous star by Stewart (1955) places it about 1 mag below the main sequence.
HD 203664—Int (A) K, 0 250, 0 088; H, 0.185, 0.063
HD 215733—Int (A) K, 0 051, 0 086, 0 090, 0 106; H, 0 026, 0 046, 0 055, 0 072

† Velocities of components considered uncertain because of weakness or blending are inclosed in parentheses

from the 21-cm line. Stars with $z_{1/2} < z < 200$ pc, suitable for observation of interstellar lines, are, however, bright enough to have been included by W. S. Adams (1949) in his extensive survey. For this reason we have selected for observation the stars with $z > 200$ pc contained in the list published by Morgan, Code, and Whitford (1955). A few additional objects have been taken directly from the *Henry Draper Catalogue*. No attempt was made to include stars fainter than about 9.0 mag., in order to avoid the uncertainties involved in the determination of spectroscopic distance moduli of possible peculiar blue stars. The results of the observations are summarized in Table 1, most of

[1] The observations reported in this paper were made by one of us (G. M.). Their discussion was carried out jointly by the authors at the Max Planck Institut für Physik und Astrophysik, Munich, Germany, during the tenure of their fellowships.

them referring to the Ca II lines. The stars are identified by their HD number and galactic latitude given in the first two columns. The apparent visual magnitudes and spectral types are given next, taken from the list by Morgan, Code, and Whitford (1955) when therein contained or otherwise from the *H. D. Catalogue*. The corresponding values of $|z|$ given in the fourth column have been derived from the spectroscopic distance moduli, and an interrogation point following the value of $|z|$ indicates uncertainty in the spectroscopic absolute magnitude or unavailability of color excess. The heliocentric radial velocity of the stars, V_s, and the correction ΔV to reduce them to the local standard of rest are given in the fifth column We have taken V_s from the Mount Wilson *Catalogue* (Wilson 1953) and computed ΔV from the apex constants determined by Blaauw (1952). Next we indicate the nature of the plates in which the interstellar lines were observed, the symbols "P" and "C" referring to the Palomar and Mount Wilson spectrographs, while the letters "a," "b," and "c" indicate the dispersions of the plates obtained: 2.7 A/mm for Ca plates, 4.5 A/mm for b plates, and 10 A/mm for c plates. The initials "WSA" denote that the observation is due to Adams (1949). The heliocentric radial velocities of the Ca II lines, or their various components, are given in the seventh column, and the corresponding estimated intensities, approximately in the scale used by Adams (1949), are given in the last column. Many of the stars contained in Table 1 are of spectral type sufficiently late to show the Ca II lines in their atmospheric spectra. The appearance of broad stellar lines does not prevent the detection of interstellar lines in their background, but it makes the measurement of their intensities very uncertain. For this reason we have not attempted to measure equivalent widths of the interstellar lines in every case. The intensities of the various components of K and H in those stars where measurements have been made are given in the notes to the table. For the procedures followed and the constants of the instrumental profiles we refer to the earlier paper of this series (Münch 1957). Also in the notes to the table are given the results of a few observations of the interstellar Na I lines and other relevant information.

III. ANALYSIS OF THE OBSERVATIONS

We begin by calling attention to the rather different appearance of the complex interstellar lines in high glactic latitude stars, illustrated in Figures 1 and 2, from that observed in stars near the galactic plane (Adams 1949; Münch 1957). In Milky Way stars at distances not greater than, say, 1 kpc from the sun, invariably one strong component, with a small Doppler shift, is observed, around which lines with larger shifts may appear with considerable smaller strength. In high galactic latitude stars with complex lines, in contrast, we observe the component with smallest velocity in the local standard of rest, with strength comparable to the others. The difference is, of course, due to the fact that the strong lines in the Milky Way either arise from the partial superposition of a number of weaker lines or are formed in extensive gas masses with considerable internal mass motions. In our case, the weakness of the various well-separated components suggests that they arise in single clouds. We may then gaining insight into the physical conditions prevailing in such clouds by studying these components.

Let us first ask the question of how high above the galactic plane clouds may be found. We cannot give a definite answer for the case of one given particular component, but we may consider the stars in various distance groups and find out how the mean number of components varies with distance. This has been done in Table 2, where we give the numbers of components n_-, n_+, and n_0, respectively, displaced to the violet, to the red, and nearly undisplaced, for three distance groups. Notwithstanding the low weight that can be given to small-number statistics, the increase with distance of the mean number of components per star would appear real. Among the five stars with $z > 1$ kpc, two show quadruple lines. The star with largest z shows only a double line, but both components are so strong that there can be little doubt about their complex structure. The inference that some of the observed components arise in gas masses located at distances from the galactic plane of the order of 1 kpc would thus seem justified. For the purpose of comparing with theoretical predictions, in Table 2 are given the approximate total numbers $\langle N \sin b \rangle$ of components at mean galactic latitudes of 45° for the stars with $500 < z < 1000$ pc and of 50° for $z > 1000$ pc. The corresponding number for the nearest stars is not given, as it does not have much significance.

A question requiring some consideration is the possibility that some of the gas clouds observed at large z might not be truly interstellar, but, instead, be somehow related to the stars on which they have been observed. The strongest argument against such a circumstellar nature of the clouds is provided by the large radial component of the relative motion between cloud and star. During a significant time—say the period of an elementary oscillation in the z-direction—the radial projection of the distance between cloud and star would become of the order of hundreds of parsecs, so that the physical relationship between star and cloud, even if it once existed, could not subsist for long.

TABLE 2

NUMBER OF INTERSTELLAR LINE COMPONENTS IN STARS AT VARIOUS HEIGHTS FROM GALACTIC PLANE

z (pc)	Numbers n_-	n_+	n_0	$(n_- + n_+)/n_0$	$\langle N \sin b \rangle$
200–500. . .	3	3	12	0 42	. . .
500–1000.	5	2	7	1 28	1 4
>1000. .	6	3	5	1 80	2 0

This consideration, however, does not exclude the possibility that the excitation of one particular cloud, to the extent necessary to become detectable by the interstellar absorption line it produces, may derive from the star being observed. We consider such a possibility in more detail below. For the time being, let us suppose that the gas masses producing the observed lines are truly interstellar and have the same nature as those observed near the galactic plane. We shall establish a rough upper limit to the number of clouds, $N(z, b)$, expected in a star at height z and galactic latitude b, on the discrete cloud model often employed to describe the structure of the interstellar medium (van de Hulst 1958). Let $n(z)$ be the number-density of clouds at height z; k the mean number of clouds intercepted in unit distance by a line of sight in the galactic plane; and πa^2 the cross-section of a cloud assumed constant. We then have

$$k = \pi a^2 n(0) . \tag{1}$$

If the clouds move in the z-direction like mass points in no other field of force but the gravitational attraction of the galaxy, their spatial distribution in the z-direction is uniquely determined by their velocity distribution. Representing the velocity distribution by

$$\psi(v) = \sum_i \frac{c_i}{\sigma_i \sqrt{(2\pi)}} e^{-v^2/2\sigma_i^2} \qquad \left(\sum_i c_i = 1\right), \tag{2}$$

we, have, quite generally,

$$n(z) = n(0) \sum_i c_i \exp\left\{-\frac{1}{\sigma_i^2}\int_0^z K(z)\, dz\right\}, \tag{3}$$

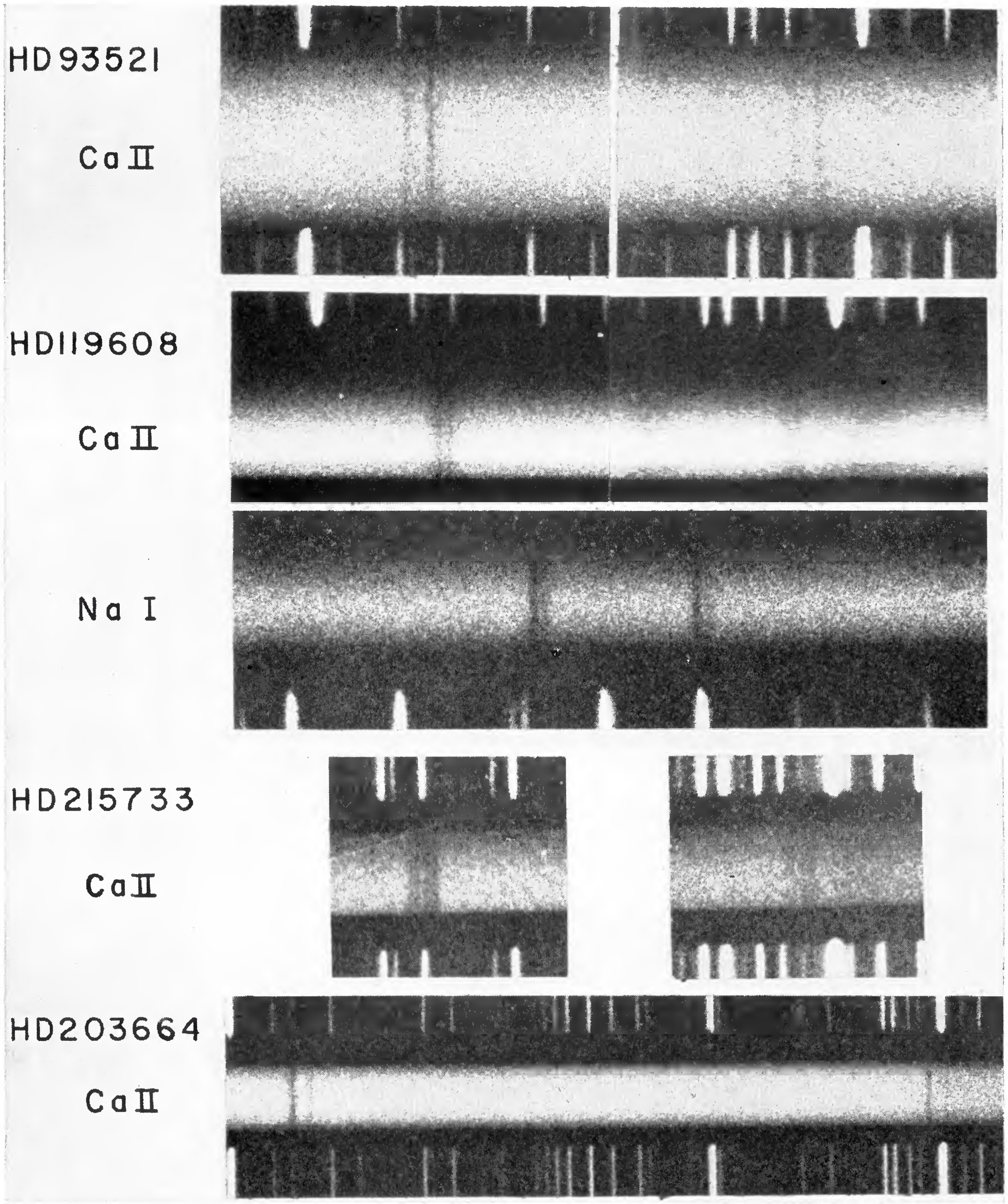

FIG. 1.—Interstellar absorption lines in stars at large distances from the galactic plane. The dispersion of the originals is 4.5 A/mm for the K (*left*) and H (*right*) lines of Ca II and 6.8 A/mm for the D lines. The spectrum of HD 203664 is reproduced from a 10.2 A/mm plate.

where $K(z)$ is the magnitude of the galactic gravitational force. The number sought is

$$N(z, b) = \pi a^2 \csc b \int_0^z n(z)\, dz, \tag{4}$$

an explicit representation of which may be obtained when

$$\int_0^z K(z)\, dz = \alpha^2 z^2. \tag{5}$$

If the values of $K(z)$ recently determined by Oort (1959) are required to satisfy a relation of the form (5) at $z = 1$ kpc, we obtain $\alpha = 43$ km/sec kpc. But then the potential of the form (5) is an underestimate for smaller values of z. For very small values of z—say $z < 0.1$ kpc—the actual potential function must be of the form (5), but from the values of $K(z)$ determined by Oort (1959) it follows that $\alpha = 64$ km/sec kpc, a value corresponding to an Oort limit $\bar{\rho} = 0.15\ \odot\ \mathrm{pc}^{-3}$. The use of an Oort limit nearly half as great, implied by $\alpha = 43$ km/sec kpc, then, will lead to less concentration to the

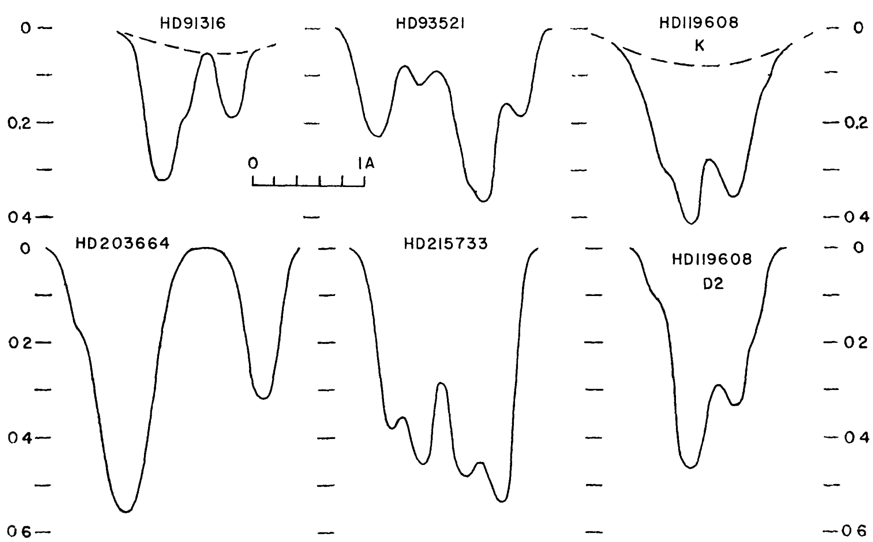

Fig. 2.—Profiles of interstellar absorption lines in the spectra of stars at high galactic latitude. For HD 119608 both the K and the D2 lines are given, for other stars only the K line. In HD 91316 and HD 119608 the broad feature attributed to the stellar atmosphere has been drawn in broken line. The profiles have not been corrected for instrumental broadening.

galactic plane than the exact values of $K(z)$ would do. And the values of $N(z, b)$ resulting from equations (3), (4), and (5),

$$N(z, b) = \frac{\sqrt{\pi}}{2} k \operatorname{cosec} b \sum_i \frac{\sigma_i c_i}{\alpha} \operatorname{Erf}\left(\frac{\alpha z}{\sigma_z}\right), \tag{6}$$

will then be upper bounds for the actual numbers in $z < 1$ kpc.

The velocity distribution of one velocity component in the galactic plane for an interstellar cloud has been found by Blaauw (1952) to be better represented by

$$\psi(v) = \frac{1}{2\eta} e^{-|v|/\eta}, \qquad \text{with} \qquad \eta = 5\text{km/sec}, \tag{7}$$

than by a function Gaussian in shape. This is because of the relatively high frequency with which high-velocity components ($|v| > 24$ km/sec) are observed in stars nearer than 0.5 kpc. Actually, the true frequency of high-velocity components is probably underestimated by equation (7), because Blaauw excluded from his statistics the stars in the Orion association, which show more high-velocity components than other stars at similar distances. We shall then approximate (7) by a function of the form (2) with parameters

$$\begin{aligned} c_1 &= 0.9\ , \qquad \sigma_1 = \ \ 5\ \mathrm{km/sec}\ , \\ c_2 &= 0.1\ , \qquad \sigma_2 = 25\ \mathrm{km/sec}\ , \end{aligned} \tag{I}$$

which give a frequency $f_{\mathrm{HV}}(\mathrm{I}) = 0.03$ for $|v| > 24$ km/sec. The function (7), in comparison, predicts a frequency of high velocities of only $f_{\mathrm{HV}}(\eta) = 0.008$. The numbers $N_{\mathrm{I}}(z, b) \sin b$ resulting from the parameters I in equation (6), using the value $k = 7$ kpc^{-1}, are given in Table 3 for $z = 0.5$, 1.0, and 2.0 kpc. In comparison with the observed

TABLE 3

EXPECTED NUMBER OF CLOUDS AT HIGH GALACTIC LATITUDE, $N(z, b) \sin b$

v (kpc)	PARAMETERS		z (kpc)	PARAMETERS		z (kpc)	PARAMETERS	
	I	II		I	II		I	II
0 5	0 91	1 21	1 0	0 99	1 67	2 0	1 00	1 97

values, we notice that, in a star at $z = 1$ kpc, the predicted numbers N_{I} are half as great. In order to obtain, with a function of the type (2) involving two terms, numbers $N(z, b) \sin b$ approaching the observed ones, we would have to choose

$$\begin{aligned} c_1 &= 0.8\ , \qquad \sigma_1 = \ \ 5\ \mathrm{km/sec}\ , \\ c_2 &= 0.2\ , \qquad \sigma_2 = 50\ \mathrm{km/sec}\ , \end{aligned} \tag{II}$$

as the corresponding numbers $N_{\mathrm{II}} \sin b$ shown in Table 3. With the parameters II one would predict a frequency for the high velocities of $f_{\mathrm{HV}}(\mathrm{II}) = 0.12$. There is no question that such frequency of high velocities is quite inconsistent with what is observed in the galactic plane. Also a velocity distribution of the form implied by II would be ruled out by the observed shape of the 21-cm line of hydrogen. The results of our observations thus suggest that the distribution of the clouds in the z-direction is not entirely consistent with what we know about their motion in the galactic plane. Because of the small numbers involved in our statistics and the simple model basis of our calculation, we cannot draw a strong conclusion. But it would appear logical to inquire into possible reasons for the existence of a lack of homogeneity and/or isotropy in the velocity distribution of the interstellar clouds. Two geometrical factors acting in the direction of explaining the observed effect are evident. The first is that high-velocity clouds moving in the z-direction will preserve their identity longer than those moving in the galactic plane as a consequence of the fewer collisions they may suffer. The mean thickness of the cloud layer, $z_{1/2}$, defined above as the root of the equation

$$n(z_{1/2}) = \tfrac{1}{2} n(0)\ , \tag{8}$$

has in our two models I and II the values 105 and 115 pc, respectively. These values are significantly smaller than the mean distance between cloud collisions in the plane, $k^{-1} = 140$ pc. It would be expected, then, that a cloud would reach the height $z_{1/2}$ more probably than that one in the plane would travel the distance k^{-1}. Once above the height

$z_{1/2}$, the clouds would probably not undergo mutual collisions and would move freely in the galactic gravitational field. In second place, it should be kept in mind that the clouds may expand as they move away from the galactic plane, and consequently they would present a larger cross-section at larger z. The reasons and nature of this expansion are discussed in detail below. Finally, besides these purely geometrical effects, there also exists the possibility that the mechanism accelerating the clouds may be intrinsically anisotropic. This aspect of the problem is considered in the final section of the paper.

In the preceding considerations, we have assumed that the separate kinematic units we are calling "clouds" maintain their identity indefinitely in the absence of mutual collisions. We shall now find out to what extent our observations require the clouds to be stable structures. We have already said that clouds unquestionably exist at heights of the order of 1 kpc. On the premise that such high-velocity clouds were formed in the galactic plane, knowing their present velocity components V_z in the z-direction and their heights z, we may compute the times τ elapsed since their formation ($z = 0$) and their initial velocity $V_z(0)$. Actually we do not know the cross-motion to compute $V_z(z)$, and, by adding vectorially to the radial velocity V a sufficiently large cross-motion in the proper direction, the times τ may be made as small as desired. Such a procedure, however, would lead to implausibly large values of $V_z(0)$. We thus suppose that the cross-motion vanished. As a particular example, consider the component observed at $V = -50$ km/sec in HD 215733, supposed to be at $z = 1$ kpc. With $V_z(z) = -30$ km/sec, we obtain $V_z(0) = 62$ km/sec and $\tau = 40 \times 10^6$ years. These numbers should be considered jointly with the dimensions of the clouds, which we evaluate next.

From the observed strengths of the interstellar lines of Ca II we may derive the numbers $\mathfrak{N}_{\mathrm{Ca\,II}}h$ of Ca II ions in a column with 1-cm^2 cross-section along the line of sight and the velocity dispersion of the ions b_λ. The high-velocity components we are dealing with have doublet ratios corresponding nearly to unsaturated lines, and we may obtain for them $\mathfrak{N}_{\mathrm{Ca\,II}}h$ independently of b_λ. As typical line strength we consider $W = 0.050$ A, the value observed for the component at -50 km/sec in HD 215733. We have, correspondingly,

$$\mathfrak{N}_{\mathrm{Ca\,II}}h = 3 \times 10^{11}\ \mathrm{cm}^{-2} = 10^{-7}\ \mathrm{pc\ cm}^{-3}\ . \tag{9}$$

To derive the total density, we have to consider the ionization equilibrium of Ca and to assume the abundance ratio of Ca atoms to those determining the density of free electons, $\mathfrak{N}_e$. Suppose, first, that the cloud is an H I region. For this case the electron temperature is taken as $T_e = 100°$ K, and the radiation field is cut off at $\lambda = 912$ A, and we have (Seaton 1951)

$$\frac{\mathfrak{N}_{\mathrm{Ca\,III}}\mathfrak{N}_e}{\mathfrak{N}_{\mathrm{Ca\,II}}} = 0.025\ . \tag{10}$$

We set $\mathfrak{N}_e$ equal to the number-density of elements with ionization potential less than that of hydrogen (effectively carbon) and assume a cosmic abundance ratio, so that we have

$$\mathfrak{N}_e = 3 \times 10^{-4}\mathfrak{N}_{\mathrm{H}}\ , \tag{11}$$

and then

$$\frac{\mathfrak{N}_{\mathrm{Ca\,III}}\mathfrak{N}_{\mathrm{H}}}{\mathfrak{N}_{\mathrm{Ca\,II}}} = 80\ (\mathrm{cm}^{-3})\ . \tag{12}$$

Introducing the observed value (9) of $\mathfrak{N}_{\mathrm{Ca\,II}}h$, we obtain

$$\mathfrak{N}_{\mathrm{Ca\,III}}\mathfrak{N}_{\mathrm{H}}h = 8 \times 10^{-6}\ (\mathrm{pc\ cm}^{-6})\ . \tag{13}$$

In equation (12) we see that, for any reasonable $\mathfrak{N}_{\mathrm{H}}$—say $\mathfrak{N}_{\mathrm{H}} \leq 10$ cm^{-3}—Ca is mostly in the form of Ca III. Assuming the cosmic abundance of calcium,

$$\mathfrak{N}_{\mathrm{Ca}} = 2.5 \times 10^{-6}\mathfrak{N}_{\mathrm{H}}\ , \tag{14}$$

we then have

$$h = 3.3 \mathfrak{N}_{\mathrm{H}}^{-2} \left(1 + \tfrac{1}{80} \mathfrak{N}_{\mathrm{H}}\right), \tag{15}$$

h measured in parsecs and $\mathfrak{N}_{\mathrm{H}}$ in cm^{-3}. The resulting dimensions of the clouds are given in Table 4.

Alternatively, suppose that we deal with an H II region. From Seaton's (1951) calculations, for $T_e = 10000°$ K and a radiation field extending beyond $\lambda = 912$ A, we have

$$\frac{\mathfrak{N}_{\mathrm{Ca\,III}} \mathfrak{N}_{\mathrm{H}}}{\mathfrak{N}_{\mathrm{Ca\,II}}} = 1.5\ (\mathrm{cm}^{-3}), \tag{16}$$

TABLE 4

LINEAR DIMENSIONS AND MASSES OF THE CLOUDS FOR VARIOUS DENSITIES

$\mathfrak{N}_{\mathrm{H}}$ (cm^{-3})	H I		H II	
	h (pc)	$\mathfrak{M}(\odot)$	h (pc)	$\mathfrak{M}(\odot)$
0 010 .	3 3×10^4	4 24 $\times10^9$	600	2.55 $\times10^4$
0 032	3.3×10^3	1 34 $\times10^7$	61	101
0 10	330	8 48 $\times10^4$	6 4	0 309
0 316 .	33	1 34 $\times10^2$	0 73	1 45 $\times10^{-3}$
1 00	3 33	0 436	0 10	1 18 $\times10^{-5}$
3 16	0 343	1 50 $\times10^{-3}$	0 019	2 37 $\times10^{-7}$
10 . .	0 037	5 98 $\times10^{-6}$	0 0046	1 15 $\times10^{-8}$
31 6. . .	0 0046	3 51 $\times10^{-8}$	0 0013	8 54 $\times10^{-10}$

where the electron density has been set equal to that of the protons. Again, introducing the observed value (9) for $\mathfrak{N}_{\mathrm{Ca\,II}} h$, we have

$$\mathfrak{N}_{\mathrm{Ca\,III}} \mathfrak{N}_{\mathrm{H}} h = (1.5 + \mathfrak{N}_{\mathrm{H}}) \times 10^{-7}, \tag{17}$$

and, adopting the cosmic abundance of calcium (eq. [14]), we obtain

$$h = 0.06 \mathfrak{N}_{\mathrm{H}}^{-2} \left(1 + \tfrac{2}{3} \mathfrak{N}_{\mathrm{H}}\right), \tag{18}$$

in the same units as in equation (15). The earlier calculations of Strömgren (1948) would have led to rather different relations than equations (15) and (18). For an H I region we would have obtained

$$h = 20 \mathfrak{N}_{\mathrm{H}}^{-2}, \tag{19}$$

and, for an H II region,

$$h = 0.2 \mathfrak{N}_{\mathrm{H}}^{-2} \left(1 + \tfrac{1}{5} \mathfrak{N}_{\mathrm{H}}\right). \tag{20}$$

It should be remarked here that the calculations of the ionization equilibrium are subject to considerable uncertainty because of the very unrealistic radiation field that has been adopted. We shall discuss this point later in more detail, but at this stage we adopt Seaton's results as being at least formally correct. From equations (15) and (18) we then obtain the dimensions given in Table 4, where the masses of the clouds, $\mathfrak{M}$, have been computed on the assumption of spherical symmetry.

We now return to the problem of the stability of the clouds during a time of the order of $\tau = 4 \times 10^7$ years. If they were moving in vacuum, they would expand with a velocity about three times that of sound. And in time τ, they would have dimensions 120 or 1200 pc, depending on whether they are H I or H II regions. The H II dimension is inadmissibly large. The H I dimension is not entirely out of consideration on geometrical grounds alone. However, according to equation (15), an H I cloud would have $\mathfrak{N}_H = 0.16 \text{ cm}^{-3}$ and a mass $\mathfrak{M} = 3 \times 10^4 \odot$. And the problem would then be to explain how such a large mass may acquire an initial velocity of 60 km/sec. As we shall discuss later, existing ideas regarding the process through which interstellar clouds are accelerated cannot possibly account for the large energies involved. On this basis we conclude that the interstellar gas clouds are subject to forces preventing them from expanding into vacuum.

It is of interest to note in Table 4 that the path length required to form the observed line is considerably smaller, at least by an order of magnitude when $\mathfrak{N}_H < 10 \text{ cm}^{-3}$, if the medium is an H II region than if it is an H I. To decide whether a line is formed in an H I or an H II region is not an easy matter, especially in the case of lines observed at high galactic latitudes. Just the ultraviolet radiation of the high-temperature stars on the spectra of which we have observed the interstellar lines may suffice to ionize the hydrogen in a cloud, or in part of a cloud, to the extent required. To show this, we recall that if to a given star there corresponds a Strömgren sphere of radius $s_0 \mathfrak{N}_H^{-2/3}$, in a cloud placed at a distance r from it, an H II region of thickness L given by (Strömgren 1948)

$$L = \frac{1}{3} s_0^3 (r \mathfrak{N}_H)^{-2} \tag{21}$$

will be produced, provided that $r \gg L$ and the space between star and cloud is transparent to radiation beyond the Lyman limit. The maximum distance r from the star at which the cloud may be located and still be an H II region is then obtained by identifying L with the path length h given by equation (18):

$$r = 4.24 \, s_0^{3/2} (1 + \tfrac{2}{3} \mathfrak{N}_H)^{-1/2} , \tag{22}$$

where both r and s_0 are measured in parsecs. For a B1 II star such as HD 215733, $M_v = -4.0$ mag., and $s_0 = 34$ pc, about twice as large as for a main-sequence star of the same spectral class. We thus have

$$r = 840 \, (1 + \tfrac{2}{3} \mathfrak{N}_H)^{-1/2} \text{(pc)} . \tag{23}$$

For likely values of $\mathfrak{N}_H$ say—$\mathfrak{N}_H < 10 \text{ cm}^{-3}$ —then the cloud may be as far as 300 pc from the star and still be an H II region. Such a distance is large enough to make plausible the hypothesis that at least some of the high-velocity clouds observed at large heights above the galactic plane are H II regions. It should be emphasized that a clear-cut decision between the alternative formation of the high-velocity components in H I or H II regions cannot be reached directly with existing observational means. Were they H II regions, their emission measures, $\mathfrak{N}_H^2 h$, would be far too small to be measurable. The emission of one single H I cloud of the dimensions given in Table 4 would also be undetectable in 21-cm radiation. The probable angular dimensions implied by the values of h would be below the resolving power of existing antennae. Also the excess peak brightness temperature, which varies as $\mathfrak{N}_H h$, is easily shown to be of the order of a few hundredths of a degree Kelvin in a band width of 5 km/sec. The negative result obtained by Lawrence (1956) in his attempt to detect in 21-cm the components we have observed in some of the high galactic latitude stars of Table 1 is thus easily understood. However, further work on this subject with the larger telescopes now available may indirectly provide the answer. Especially promising in this direction would seem the results obtained recently by van de Hulst (1958) from an analysis of 21-cm line profiles at closely spaced positions, which suggest for the interstellar hydrogen a smoother distribution in space than the interstellar absorption lines have indicated.

IV. THE GALACTIC CORONA

The existence of an interstellar galactic corona has been postulated as a basis of recent theories related to the stability of the interstellar clouds (Pickelner 1953*a*, *b;* Schlüter 1955; Spitzer 1956). We shall discuss in this section such theories as far as our results have a bearing on them. The first suggestion for a tenouus gaseous envelope of the galaxy was made by Schklovsky (1952), in order to explain the geometry of the continuous radio emission observed in the meter range. This radiation seems to arise (Baldwin 1955; Mills 1959) from a spheroidal distribution of sources with small flattening (axial ratio no less than 0.5) and extending to about 15 kpc from the galactic center. Soon after Schklovsky, Pickelner (1953*a*, *b*) postulated a similar halo or corona as carrier gas of a magnetic field which contains the cosmic rays within the galaxy. Specifically, Pickelner and Schklovsky (1958) visualize a nearly homogeneous medium, of density near 0.1 atom/cm^3, random mass motions of the order of 70 km/sec, and a temperature such that hydrogen is barely ionized. The support of such a halo is not hydrostatic, and its radio emission is presumably of non-thermal origin. As observational evidence for the existence of this type of corona, Pickelner has cited the presence of wide Ca II absorption lines in the spectra of B supergiant stars. These lines had been attributed by Spitzer, Epstein, and Li Hen (1950) to the corresponding stellar atmospheres. The stellar origin of the H and K lines observed in the spectra of B supergiants is unquestionable, in view of the correlation between the intensity of these lines and the spectral types of the stars, which Spitzer (1956) has emphasized. We may give a specific example among the stars of Table 1, by mentioning that HD 93516 of type B1 I*b* shows the wide and shallow H and K lines, on the background of which three sharp interstellar components appear. In contrast, the star HD 93521 of type O9 V, although in the same part of the sky and probably more distant than HD 93516, does not show a trace of the wide lines, and the four narrow interstellar lines have as background a flat continuum. The observational fact mentioned by Pickelner as evidence for a corona with the properties he considered thus seem to be irrelevant to the point. But it should be remarked that if the galactic halo postulated by Pickelner existed, it should produce very strong interstellar lines, for conditions there would approach those in H II regions. The path length required to produce an unsaturated line with a central depth greater than 0.5 in a medium of density $\mathfrak{N}_H = 0.1$ cm^{-3}, for an assumed Doppler width of 4.5 km/sec, is, according to equation (18), only 6 pc. In a path length of 1 kpc and for a Doppler width 18 times larger, then, the line formed would be much stronger than those observed in B supergiants (central depths of the order of 0.1). We thus conclude that the physical conditions considered by Pickelner and Schklovsky (1958) to prevail in the galactic halo are not realistic. For similar reasons, the hypothesis advanced by Schlüter and Biermann (Schlüter 1955), that the interstellar gas clouds, assumed H I regions, are in pressure equilibrium with an H II intercloud medium, is untenable when applied to the interpretation of the lines in distant stars at high galactic latitude. It is not implied that an intercloud medium with $T_e = 10000°$ K and $\mathfrak{N}_H = 0.1$ cm^{-3} would also be detectable in distant stars near the galactic plane. If the clouds occupy a fractional volume of 0.05, the ratio of path lengths between and in the clouds would be around 3, instead of the value 50 required by equations (15) and (18) to obtain the same unsaturated line strength in the H I and H II regions, assumed in pressure equilibrium. Also we emphasize that our calculations do not apply to ordinary high-density H II regions, for in the close neighborhood of hot stars the ionization of Ca II (or Na I) will be enhanced with respect to that produced by the "average" radiation field employed by Seaton (1951) and Strömgren (1948) in their calculations.

Under the conditions contemplated by Spitzer (1956) as prevailing in the galactic corona, one does not encounter the serious discrepancy with observations that we have just pointed out. At the kinetic temperature required by a large extension above the galactic plane, $T_e \approx 10^6$ ° K, the ionization is so high that no interstellar absorption line can be expected in the accessible region of the spectrum. The density required to attain pressure equilibrium with H I clouds is, on the other hand, so low, $N_H = 5 \times 10^{-4}$ cm^{-3}, that it would also be unobservable in emission by available means. Spitzer has verified that the cooling rate in such a gas, by radiative processes and by conduction to the imbedded cold matter, is sufficiently low that its origin could be primordial. His calculation of the cooling by conduction may be objected to on the grounds that he assumed the heat sink to be a homogeneous substratum. Obviously, the cooling rate with the sinks in disconnected pockets occupying only 5 per cent of the volume will be considerably faster. The evaluation of the cooling rate in a more realistic model would be a problem of great difficulty. But it is not of crucial importance, because the possibility that the corona may be continuously heating up by corpuscular radiation from stars or by the dissipation of pressure waves generated by turbulence in the cool gas cannot be discounted. Within the framework of Spitzer's model for the corona, we may ask, however, whether and H I cloud, of the dimensions required by the interstellar line intensities, can remain in pressure equilibrium with the hypohetical corona for a time of the order of 40×10^6 years without dissipating. To analyze in an approximate fashion this question, we consider a spherical H I cloud of linear dimensions h and density $\mathfrak{N}_H$ imbedded in a gas with mean particle energy $3kT/2 = 3.1 \times 10^{-10}$ erg. The r.m.s. velocity of the free electron then is $V_e = 7 \times 10^8$ cm/sec. The cross-section for ionization σ_{eH} of an H atom by an electron at 130 ev is about $0.5\ \pi a_0^2 = 4.4 \times 10^{-17}$ cm^2 and that for line excitation has about the same value (Massey and Burhop 1952). The mean-free-path of a coronal electron in the H I cloud then is

$$l_I = (\sigma_{eH}\mathfrak{N}_H)^{-1} = 7.4 \times 10^{-3}\mathfrak{N}_H^{-1}\,(\mathrm{pc})\,. \tag{24}$$

From the linear dimensions of the cloud given by equation (15) it follows that always $l_I < h$, which means that all electrons hitting the cloud will be absorbed, thus producing ionization. Since the mean velocity across a fixed plane is one-fourth of the r.m.s. velocity, the energy input per square centimeter and second will then be

$$G_{eH} = \frac{1}{8l_I} V_e N_e E_e = 4 \times 10^{-22}\mathfrak{N}_H^2 \text{ erg cm}^{-2} \text{ sec}^{-1}\,, \tag{25}$$

where we have supposed that only half the energy goes into thermal energy, the other half being lost in line emission. The coronal protons also produce heating, but at a lower rate because of their lower velocity. In a steady state, the electrical neutrality of the cloud is preserved by secondary electrons of the cloud returning to the corona or by the creation of a space charge which limits the electron input to the cloud. In either case the energy input is less than equation (25), by a factor of around 40. An exact description of the thermal history of such a cloud would be a complex problem, depending on a variety of radiative processes and also hydrodynamic effects. An energy input of 10^{-23} erg/cm^2/sec is, however, so large compared with the rate at which an H I cloud may lose energy by radiation (Savedoff 1955) that it is difficult to avoid the conclusion that the cloud will heat up, until it becomes able to radiate energy at a rate comparable with the energy input. As the cloud heats up, it will expand, and its degree of ionization will increase. When the hydrogen is essentially ionized and the kinetic temperature is around 10^4 ° K (H II conditions), the time needed for the coronal electrons to relax into equilibrium is comparable to the flight time of the electron through the cloud if undeflected. The energy input from the coronal electrons would then be

$$G_{ep} = \frac{3}{4h} V_e N_e E_e \tag{26}$$

if the cloud gained energy at the rate set by the electron velocity. Again, because of the required over-all neutrality of the cloud, it is expected that the actual rate will be fixed by the velocity of the coronal protons rather than by that of the electrons. Assuming that the H II cloud is in pressure equilibrium with the corona, $N_e = 10^{-2}\,\mathfrak{N}_{\mathrm{H}}$, we introduce in equation (26) the dimensions of the cloud given by equation (18) to obtain

$$G_e = 10^{-22}\,\frac{\mathfrak{N}_{\mathrm{H}}^3}{1+2\mathfrak{N}_{\mathrm{H}}/3}\ \mathrm{erg/cm^3/sec}\,. \tag{27}$$

From the work of Savedoff and Spitzer (Savedoff 1955) it is known that an H II region of standard composition loses energy by radiation in nebular forbidden lines at a rate given approximately by

$$L_{ei} = 8\times 10^{-24}\mathfrak{N}_{\mathrm{H}}^2\ \mathrm{erg/cm^3/sec}\,. \tag{28}$$

An equilbrium between the losses and gain of energy, then, could be established for a density around $\mathfrak{N}_{\mathrm{H}} = 0.1\ \mathrm{cm}^{-3}$ and a linear dimension of 10 pc. The time required for this state of equilibrium to be established is less than 10^6 years. Beyond this stage, the particles of the cloud diffuse into the corona at a slow rate. From the values of the diffusion coefficients given by Spitzer (1956) it may be verified that the spread of the cloud in a time $\tau = 4\times 10^7$ years is not significant compared with the dimensions of the cloud. The existence of a sizable magnetic field would somewhat reduce the conduction of heat to the cloud from the corona, although it would require a rather complex field structure to reduce the conductivity by a factor much larger than 3. Further, if a magnetic field is postulated to isolate thermically the cloud from the corona, the magnetic pressure, by definition, would play a role in the equilibrium equations. The coronal densities thereby deduced could then be considerably different from those postulated by Spitzer. Our analysis shows that a field-free cloud may exist in the corona as an H II region for significant intervals of time, and our estimates for the dimensions of the clouds are consistent with the densities and temperatures prevailing in the corona, as postulated by Spitzer.

The study of the possible heating effects of the cool large clouds in the galactic plane by the coronal gas remains to be carried through. The much larger dimensions of such clouds would probably make their heating time long compared with their lifetime set by mutual collisions. However, eventually we shall have to face the unsolved problem of how the clouds are formed to start with. Their stability may indeed be understood by the pressure exerted by the corona, but not so their formation. Several effective mechanisms to disrupt the clouds are known, but not a single process operating in the opposite sense has been studied. In this context we may recall that the expanding motions of the interstellar gas observed in the nuclear regions of the galactic system (Rougoor and Oort 1960) and M31 (Münch 1960) suggest that coronal material may condense into cool clouds. The conditions under which such a condensation process is taking place are not understood at all yet. But undoubtedly they are related to the whole problem of the origin of the cloud structure of the interstellar medium.

V. THE NATURE OF THE HIGH-VELOCITY CLOUDS

The existence of a fundamental difference between the physical conditions prevailing in high- and low-velocity clouds has long been known. It is revealed most strikingly by the different behavior of the Ca II and Na I lines with large and small Doppler shifts. The high-velocity components show a line of Ca II much stronger than that of Na I, while the reverse is true in strong low-velocity lines. The double line observed in HD 119608, reproduced in Figure 1, clearly illustrates the phenomenon. Spitzer and Routly (1952) have shown that the behavior of the Na I lines in high-velocity clouds could be understood if the kinetic temperature of the clouds were higher than about 5000° K. The hypothesis held here, that high-velocity clouds are maintained as H II regions by heat conduction from the corona, would thus be complemented by Spitzer and Routly's explanation. The well-known difficulty related to the abundance ratios of Na and Ca remains unsolved, however. By the doublet ratio method and the ionization corrections, it has been found that in low-velocity clouds the abundance ratio between sodium and calcium $\mathfrak{N}(\mathrm{Na})/\mathfrak{N}(\mathrm{Ca})$ is of the order of 60, as compared with a number of the order of unity for the cosmic abundance ratio. In high-velocity clouds, on the other hand, using the same ionization equations, a ratio of the order of unity is found. If our explanation for the high kinetic temperature of high-velocity clouds is correct, the agreement between the abundance ratio in high-velocity clouds and the cosmic value is fortuitous. And the most likely explanation of the abundance discrepancy must be sought in the incorrect stellar radiation field used in the calculations of the state of ionization. Further, we have to suppose that the radiation field is different in high- and low-velocity clouds. Such a hypothesis would not seem unreasonable, when it is considered that the extinction produced by the interstellar dust, largely confined to the spiral arms, would affect the ionization equilibrium significantly.

TABLE 5

PHOTOIONIZATION (Γ) AND RECOMBINATION (α) COEFFICIENTS FOR ALUMINUM IN INTERSTELLAR SPACE

ION	Γ (sec⁻¹)	α (cm³ sec⁻¹)	
		$T_e=100°$ K	$T_e=10000°$ K
Al I	$6\ 6\times10^{-10}$	$6\ 0\times10^{-12}$	$1\ 9\times10^{-13}$
Al II .	$1\ 43\times10^{-14}$	$6\ 6\times10^{-11}$	$4\ 6\times10^{-12}$

The different behavior of the Na I and Ca II lines in high- and low-velocity clouds could be understood alternatively, if different metallic atoms were locked up in the solid phase to an extent depending on their chemical bonds. Although it is difficult to foresee why calcium would preferentially adhere to solids in clouds containing dust, it is of interest in this context to comment on the absence of the resonance line of aluminum in the interstellar spectrum. The cosmic abundance of Al is about equal to that of Ca and Na. The ionization potential of Al II is 18.8 ev, so that most Al in interstellar space should be singly ionized. In order to estimate the concentration of Al I, we have evaluated the photoionization and recombination rates of Al I and Al II, using the f-values given in the appendix and a Planck radiation field with $T_r = 10000°$ K diluted by a factor $W = 10^{-14}$. The calculation for electron temperatures of 100° and 10000° K is summarized in Table 5.[2]

The abundance ratios between the first three states of ionization, then, are

$$T_e = 100°\mathrm{K}: \quad \frac{\mathfrak{N}(\mathrm{Al\ I})}{\mathfrak{N}(\mathrm{Al\ II})} = 9\times10^{3}N_e\,, \qquad \frac{\mathfrak{N}(\mathrm{Al\ II})}{\mathfrak{N}(\mathrm{Al\ III})} = 4600N_e\,,$$

$$T_e = 10000\mathrm{K}: \quad \frac{\mathfrak{N}(\mathrm{Al\ I})}{\mathfrak{N}(\mathrm{Al\ II})} = 2.9\times10^{-4}N_e\,, \qquad \frac{\mathfrak{N}(\mathrm{Al\ II})}{\mathfrak{N}(\mathrm{Al\ III})} = 324N_e\,.$$

[2] After we had finished computing the ionization equilibrium of Al I, it came to our knowledge that Burgess, Field, and Michie (1960) had also carried out a similar calculation. Although the work of these authors has appeared in print, there is still some interest in presenting our results, as they have been arrived at by a different method from that of the previous authors.

Since the cosmic abundance of Al and Ca are about equal, from these numbers and the calculation of Seaton (1951) for Ca I, we find that, in H I conditions (radiation field cutoff at 912 A and $T_e = 100^\circ$ K),

$$N_e \mathfrak{N}\,(\text{Al I}) = 0.05\,\mathfrak{N}\text{I}\,(\text{Ca I})\,, \tag{29}$$

and on this basis we may compare the strength of a possible Al I line at λ 3944 A with the λ 4227 line of Ca I. This weak interstellar line has been observed only in a few stars, appearing strongest in χ^2 Orionis, where its strength is 0.014 A (Dunham 1939). The strength of the interstellar Ca II lines observed in the same star, together with the ionization conditions, requires an electron density $N_e = 0.066$ cm^{-3} (Seaton 1951). Since the f-value of the λ 3944 line is 0.066 (Biermann and Lübeck 1948), while that of λ 4227 is unity, relation (29) implies that the strength of the λ 3944 line of Al I in χ^2 Orionis should be of the order of 1 mA, essentially unobservable by existing observational techniques. The comparison made by Burguess, Field, and Michie (1960) of the strength of Al I λ 3944 with that of a Na I interstellar line provided a similar conclusion. And on the basis of the calculations of these authors, as well as on ours, the negative results obtained by Rogerson, Spitzer, and Bahng (1959) are readily understood.

VI. ON THE ORIGIN OF THE HIGH-VELOCITY CLOUDS

We have shown before how high values for the velocity components of the interstellar clouds seem to occur more frequently in the z-direction than in the galactic plane. The question then arises as to whether the higher velocities in the z-direction can be understood on the basis of theories currently held to explain the origin of the motions present in the interstellar medium. A mechanism by means of which interstellar clouds in general may be accelerated has been proposed by Oort and Spitzer (1955) and operates essentially by the pressure gradients existing across the boundaries between H I and H II regions. From a pure observational point of view there is good evidence favoring the basic idea of the Oort-Spitzer theory. In agreement with its predictions, it is found that a large fraction of the high-velocity components in nearby stars can be related to known O-associations. In their simplified treatment, Oort and Spitzer supposed that when a neutral cloud became exposed to the ultraviolet radiation of a newly created O-type star, the ionized matter would leave the cloud with a constant velocity V in directions predominantly pointing toward the star. In order to conserve momentum, then, the neutral matter would move in the opposite direction, in the manner of a reaction rocket. The mass $\mathfrak{M}(v)$ of neutral matter that moves away with velocity v is related to the initial mass $\mathfrak{M}_0$ by

$$\mathfrak{M}(v) = \mathfrak{M}_0 e^{-(v-v_0)/V}\,, \tag{30}$$

where v_0 is the initial velocity of the mass. A cloud initially at rest may reach a large velocity, say 100 km/sec, with a mass ratio $\mathfrak{M}/\mathfrak{M}_0 = 0.007$, when V is taken as 20 km/sec, the value adopted by Oort and Spitzer. In a more detailed examination of the problems involved in this theory, however, Kahn (1954) has shown that the use of a constant-streaming velocity V is not justified. Actually, when a neutral gas cloud becomes exposed to ultraviolet radiation, the ionized material produced gives rise to a pressure wave traveling into the neutral part of the cloud. The newly formed ionized material, moreover, has a non-vanishing absorption coefficient, thereby diminishing the radiation flux available for further ionization. From Kahn's analysis it appears that only under rather extreme conditions can the rocket effect operate to produce velocities much in excess of the velocity of sound in the H II region.

Another objection, of a more general nature, may be raised against the effectiveness of the Oort-Spitzer process to produce *all* the high velocities observed. And it is that, in order to have the mass $\mathfrak{M}(v)$ moving with velocity v, the mass $\mathfrak{M}_0 - \mathfrak{M}(v)$ must become ionized. If the velocity distribution of the interstellar clouds, $\psi(v)$, is known, then, in a quasistationary state, the relative amount F by mass of ionized matter is fixed. By "quasistationary" conditions we mean that the time during which a cool cloud would keep its kinetic energy is comparable to the lifetime of the ionized gas. In the model of Oort and Spitzer such a condition is implicitly assumed, for the time between cloud collisions, say 10^7 years, is of the same order as the lifetime of the H II regions. Assuming that the velocities ultimately reached by a gas cloud do not depend on the initial mass, in the model underlying equation (30) we would have

$$F = 1 - 2 \int_0^{\infty} \psi(v)\, e^{-v/V} d v , \tag{31}$$

where we have supposed that, on the average, the neutral gas is at rest with respect to the H II regions. For a velocity distribution of the form (7) we have

$$F = 1 - \frac{V}{\eta + V} , \tag{32}$$

and thus, for $V = 20$ km/sec and $\eta = 5$ km/sec, we find $F = 0.2$. For a velocity distribution of the form (6) we would have

$$F = 1 - \sum_i c_i \exp\left(\frac{\sigma_i^2}{2 v^2}\right)\left[1 - \operatorname{Erf}\left(\frac{\sigma_i}{V\sqrt{2}}\right)\right] , \tag{33}$$

and for the values II of the parameters involved we have $F = 0.28$. Now, observationally, the total mass ratio between ionized and neutral hydrogen is a quantity difficult to evaluate. But we may follow here the recent discussion by Westerhout (1958), who suggests a value not greater than $F = 0.05$. On this basis it would appear that the total amount of ionized gas existing in the galaxy is not sufficient to explain the observed motions of the interstellar neutral gas in terms of the Oort-Spitzer process. This objection could well be disposed of, if the conditions in the interstellar medium were such that the cool matter did not dissipate its kinetic energy of mass motion in 10^7 years. As a consequence of the magnetic fields carried by the large clouds near the galactic plane, collisions between them may be considerably elastic (Parker 1958). In such a case, however, the effects of magnetic forces in the accelerating mechanism themselves become of relevance. It is then of interest to discuss additional processes which may impart large motions to matter in the interstellar medium.

In relation to solar physics, Schlüter (1954) has suggested a process through the operation of which a gas cloud may be accelerated in the presence of magnetic fields. A simplified model of this "melon-seed" mechanism has been analyzed by Parker (1957), who has also suggested that it may operate under suitable conditions in the interstellar space. Qualitatively, the manner in which the mechanism operates may be described as follows. When a gas cloud, with or without an internal magnetic field, finds itself, as a consequence of convective or turbulent motions, between the lines of force of an external magnetic field, it will experience a force toward the directions of decreasing field strength. The magnitude of the velocity that it may finally reach depends on the geometry of the external field and on its internal magnetic properties. When it is field-free and the external field is homogeneous in a certain sense, Parker (1957) has shown that the velocity V which the cloud may reach has an upper bound given by

$$V \leq U_0 \left[\frac{2\gamma}{3(\gamma - 1)}\right]^{1/2} , \tag{34}$$

where U_0 is the velocity of sound in the cloud and γ is its polytropic exponent. When the cloud, on the contrary, has an internal magnetic pressure much greater than its gas pressure, then the limiting velocity is essentially the velocity of the Alfvên wave. For the case of the high-velocity interstellar clouds, we visualize a situation in which a bit of field-free matter, blown off an H II region through the action of the Oort-Spitzer process, will tend to slip off between the lines of force of the general galactic magnetic field. No direct observational evidence pointing to a decrease in the galactic magnetic field strength in directions perpendicular to the plane is available, but it would seem plausible on general gounds that such is the case. We suppose that the gas cloud does not have an internal field, because otherwise it would tend to expand as it moved to regions of decreasing external field and the problem of the stability of the high galactic latitude clouds for times of 5×10^7 years would become acute. The expanding tendency produced by the gas pressure of a field-free cloud could well be balanced by a high-temperature corona, in the manner considered in the preceding paragraph. From equation (34) we see that if the gas mass under consideration became ionized in the initial phase of its motion, it would have a large U_0, and also during subsequent expansions or contractions it would behave more nearly isothermically ($\gamma \simeq 1$). Very large values of the final velocity V could then be attained preferentially in directions perpendicular to the galactic plane.

We are indebted to members of the Numerical Analysis Center of the University of Colorado for their aid in programing and running the calculations. We thank Mrs. Stephanie McAlister for carrying out most of the radial integrals.

APPENDIX

Photoelectric Absorption Coefficients of Aluminum

Wave functions for various discrete states of Al I and Al II have been evaluated by Biermann (1943) and Biermann and Harting (1943), using a Hartree-type approximation. In order to derive photoionization cross-sections, we had only to calculate wave functions for the positive energy states. The self-consistent field for Al II is given by Biermann and Harting (1943), but the Al I field was not available. We had, thus, to synthesize this field by taking the Al II field, adding the potential of the last electron, and then multiplying by the "polarization potential" used by Biermann (1943) in his work on Al I. The potential thus derived was tested by verifying whether the Al I wave function given by Biermann (1943) was indeed the solution of the Schrödinger equation with the potential arrived at. This was found to be the case.

The positive energy solutions of the Schrödinger wave equation with the Hartree potential were calculated on the Bendix G-15 calculator of the University of Colorado Numerical Analysis Center, using the Runge-Kutta method. The normalization of the wave functions was carried out by the method described by Green (1949). The values of $df/d\epsilon$ were then calculated, using the standard formulae (Green and Weber 1950). Both dipole and momentum integrals were calculated. As Green and Weber correctly point out, agreement of the dipole and momentum integrals implies only that a correct solution of the Schrödinger equation has been found, but it says nothing about the correctness of the Schrödinger equation used. Nevertheless, the agreement between the two values provides some reliability on the calculations.

In Table AI, the following data for Al I are given: The energy of the photoelectron in Rydbergs; the values of $df/d\epsilon$, using both dipole and momentum wave function integrals; the value of $l - D$ for each case, $l - D$ being defined as the ratio of the radial integral to whichever of its parts, positive or negative, is the larger; finally, the sum of $df/d\epsilon$ for 3p–s and 3p–d, using the value from the momentum integral, because $l - D$ is always larger there, implying less cancellation. Similar values for Al II are also given. For the latter, the agreement of dipole and momentum integrals is not so good, because the theoretical ionization energy of 1.212 Rydbergs found by Biermann and Harting is significantly different from the observed value of 1.385 Ryd, and observed wave lengths were used here.

The values of $df/d\epsilon$ for Al I are somewhat unusual, because there is virtually complete cancellation of positive and negative parts of the radial integral at $E = 0.5$. It is not common to have this cancellation at such a low energy, but apparently it is not unknown either. The values of Al II are nearly constant for the three frequencies calculated and are similar to the values for Ca II. An interesting problem arises in Al I, since in an electron configuration $3s^23p$ it is possible to ionize a 3s electron instead of the 3p electron. This gives rise to a whole series of autoionization states lying above the ionization limit of Al I, beginning with $3s3p^2$, which is 0.43 ev above the limit. The existence of this level is confirmed by the work of McAllister (1959), which shows that the $3s^23p$–$3s3p^2$ doublet at λλ 1932–1936 A is the strongest absorption line in the solar spectrum in the λλ 1800–2300 A range. McAllister (1959) has also produced the lines in an arc. Since no wave function for the 3s electron is available, it is impossible to calculate the values for both autoionization and direct ionization from 3s. Since the ionization limit is more than 10 volts for the latter process, it should not be too important. Further calculations are required on the effect of the autoionization levels.

McAllister's work gives qualitative confirmation to the relatively high values of $df/d\epsilon$ for Al I found here. The emission continuum is quite strong in the Al arc, and the continuous absorption of Al I also seems to be appreciable in the solar spectrum.

TABLE AI

PHOTOIONIZATION COEFFICIENTS FOR AL I AND AL II

Al I (5 98 ev — 0 4395 Ryd)

ν (Ryd)	p–s				p–d				SUM
	Dip	1−D	Mom	1−D	Dip	1−D	Mom	Dip	
0 4395	0 151	0 576	0 166	0 629	1 105	0 711	1 097	0 757	1 263
0 4795	141	529	142	608	0 682	615	0 707	692	0 849
0 6895	0653	365	0681	490	0 0813	267	0 0860	376	0 154
0 9395	0388	277	0344	407	0 0026	051	0 0020	081	0 0364
1 2395	....	...	....	....	0 0064	076	0 0040	124	. ....
1 4395	0112	143	0128	304	0 0112	098	0 0095	192	0 0223
2 4395	0 0034	0 072	0 0041	0 213	0 0211	0 123	0 0181	0 298	0 0222

Al II (18 82 ev — 1 385 Ryd)

ν (Ryd)	s–p			
	Dip	1−D	Mom	1−D
1 425	0 0244	0 219	0 0160	0 258
1 635	0226	167	0172	263
2 385	0 0248	0 167	0 0217	0 339

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