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OBSERVATIONS OF THE SPATIAL STRUCTURE OF INTERSTELLAR HYDROGEN. II. OPTICAL DETERMINATION OF DISTANCES IN A SMALL REGION

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ABSTRACT

A configuration of interstellar neutral hydrogen, suggested earlier to be in the form of sheets, is examined in more detail, by using both the 21-cm radio data and optical spectra of stars in that region of the sky showing interstellar absorption lines. We conclude that the sheets are fairly thin, with a thickness of the order of less than 10 pc, and that they are approaching each other and are in fact colliding supersonically in one region.

I. INTRODUCTION

The 21-cm line emission of neutral hydrogen in the region $l^{II} = 100°–140°$, $b^{II} = 13°–17°$ has been mapped with the NRAO 300-foot telescope (Heiles 1966) and discussed by Heiles (1967; hereafter referred to as Paper I). He found that the large-scale distribution of hydrogen in this region is describable in terms of two large, thin sheets having a relative difference in line-of-sight velocity of about 10 km sec^{-1}. It was shown from geometrical considerations that the thickness of each sheet is less than about 10 pc. Near one end of the region the velocities of the two sheets become equal, in a way which suggests they are interacting and thus are located in the same region of space. Other features, such as cloudlets and a broad diffuse component, were also found.

The most basic observational question concerning the sheets is whether they are approaching or receding from each other. This paper represents our attempt to answer this question by comparing the interstellar optical absorption lines of stars located at different distances in the direction of the sheets. Sheet thicknesses are also derived from comparison of the optical and radio data. If each sheet produces an absorption line, then the spectrum of a star located between the two will exhibit a line arising only from the nearer sheet, but the spectrum of a star located behind both sheets will exhibit two lines, or a blended feature with an intermediate velocity; the spectrum of a star located in front of both should exhibit no lines. Habing (1969) has analyzed many radio and optical spectra and has found that a radio feature always produces a corresponding optical feature unless the star is in front of the hydrogen.

II. OBSERVATIONS

The 120-inch telescope at Lick Observatory was used to obtain high-dispersion spectra (8.2 Å mm^{-1} except as noted in Table 1) of many stars in this region in the vicinity of the sodium D-lines, and in some cases the calcium H- and K-lines. Radial velocities V_{opt} were measured for the interstellar absorption lines and reduced to the local standard of rest, as in Paper I. The equivalent widths were also measured. Separation of the lines into components, except in one case, was not possible. These data are presented in Table 1. The mean error in V_{opt} is ± 2 km sec^{-1}.

We have estimated the distances r to the stars in question, given in Table 1 in parsecs, by using the values for absolute magnitudes given by Blaauw (1963) to compare apparent and absolute magnitudes. $B - V$ measurements are given for HD 1141, HD 210873, and HD 205021 by Hoffleit (1964), from which the extinction can be obtained

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TABLE 1

STARS OBSERVED FOR OPTICAL INTERSTELLAR ABSORPTION LINES

HD	SPECTRAL TYPE	l^{II}	b^{II}	V_{opt}	V_H LVS	V_H HVS	r (pc)	$N_{Na\,I}$, $N_{Ca\,II}$ ($\times 10^{12}$ cm^{-2})	N_H ($\times 10^{20}$ cm^{-2})	h (pc)	n_H (cm^{-3})	LOCATION
1141......	B9	120.88	14.20	−1.0	−1.3	−14.2	132	0.36	1.1	3.1± 1.2	11.5	B
1359......	B9	120.93	13.53	+0.7	−0.5	− 7.5	208	0.15	0.9	5.1± 2.0	5.7	B
2083......	B2	120.92	9.01	−8.9*	−3.3	−12.0	925	2.27	0.9	...	...	A
				−1.0*				1.92	0.5	...	...	
				−2.1†				12.76	1.4	...	...	
2169......	B9	121.81	17.21	...	+0.6	−10.3	142	.....	1.3	...	...	C
9899......	B9	125.57	14.32	+2.2	+2.4	− 2.8	148	2.16	1.6	1.1± 0.4	47.1	B
15472......	B3	131.12	9.10	−4.0	+2.0	−14.0	693	193.60	3.6	...	....	A
16137......	B9	129.56	14.56	−1.9	+0.5	−13.0	267	1.58	1.9	2.1± 0.8	29.3	B
				†								
19275......	A2	132.17	14.12	†	−0.2	−11.0	57	...	...	...	...	C
21610......	A0	134.07	14.10	...	−1.2	−13.3	107	...	...	...	...	C
23401......	A0	136.33	13.25	...	+0.1	−15.8	52	...	...	...	...	C
202900......	B3	113.17	20.46	−5.6‡	−2.9	− 2.9	447	15.90	3.0	...	...	A
205021......	B1	107.41	13.82	−6.3	−3.5	− 8.0	230	...	5.7	...	...	A
				−3.8†								
				−5.4†								
207484......	B9	109.69	14.38	−2.2	−5.0	− 5.0	257	1.33	2.1	...	...	A
208361......	B9	109.67	13.40	−8.7	−0.1	−10.5	289	13.60	3.6	...	...	A
				−7.2								
208375......	B9	110.27	14.13	−2.0*	−1.0	− 9.5	191	15.60	1.7	0.2± 0.4	275.1	B
208510......	B9	109.97	13.79	...	−1.0	−10.5	176	...	...	...	...	C
210873......	B9	111.16	13.00	−6.2*	+0.5	−10.0	142	1.20	6.3	...	...	A
				−4.6†								
222461......	B9	119.65	17.41	−4.3	−3.0	−10.0	278	§	0.7	...	...	B
223959......	B8	112.98	17.17	−3.6	−0.7	−14.0	383	204.10	1.0	...	...	A
141569......	B9	4.30	36.75	−2.4	...	...	...	1.35	7.8	42.1±17.0	6.0	...

* Plate dispersion = 4.1 Å mm^{-1}.
† Ca II H and K.
‡ Plate dispersion = 16.2 Å mm^{-1}.
§ No intensity calibration obtained for this plate.

from the intrinsic colors given by Johnson (1963), under the assumption that R, the ratio of total to selective extinction, is equal to 3. For the remaining stars we assumed an extinction in the visual of 1 mag kpc^{-1}. All stars were assumed to be on the main sequence, luminosity class V; hence all of our distance estimates are lower limits. The distance for one star, HD 2083, is known with more confidence due to the extensive work of Andrews (1968).

The number of absorbing atoms in the line of sight was computed from the measured equivalent widths. Various methods have been used in the past for this purpose. Strömgren (1948) based his determination of the column density of sodium on the ratio of equivalent widths of the two sodium D-lines. But this method is not trustworthy, especially for strong lines. For example, Herbig (1968) has found that it yields a value too low by a factor of 10 from the value obtained by fitting measurements of all four sodium lines in the multiplet λλ3002.34, 3002.94, 5889.95, and 5895.92 to a theoretical curve of growth.

In the present case additional information exists in the form of the radio data. The half-width at half-intensity of the 21-cm line profiles corresponding to each component was measured. Hydrogen in space is typically at a temperature near 100° K (van de Hulst, Muller, and Oort 1954), although recent work indicates that the temperature associated with 21-cm emission is widely variable (Radhakrishnan and Murray 1969; Verschuur 1969). The measured half-width of the 21-cm line is typically about 3 km sec^{-1}, whereas hydrogen at 100° K would produce a half-width of only 1.1 km sec^{-1}; hence most of the broadening is due to macroscopic, probably turbulent, motion. Since the sodium atoms also participate in this motion, this is also the intrinsic half-width of the optical line of sodium. The expected half-width of the sodium line was computed for each component from the 21-cm half-width, with a kinetic temperature of 100° K assumed. This can be used in the usual theoretical curve of growth (e.g., Ambartsumyan 1958), and the column density for sodium can be determined. Since the thermal line broadening is very small compared with that due to macroscopic motions, the value of the column density so determined is insensitive to the value assumed for the kinetic temperature.

The precise degree of line saturation is uncertain. Most of the lines, however, fall on the linear part of the curve of growth. Since the column density in this case is proportional to the equivalent width, the fractional uncertainty in the column density is equal to the fractional uncertainty in the equivalent width, which we estimate as 40 percent. For those lines that fall in the transition region between the linear and logarithmic parts of the curve of growth, an additional error exists in the derived number of Na I. This error applies to the stronger lines and arises from the uncertainty in the degree of saturation. Errors of this type alone would most probably lead to an underestimate of the number of atoms and hence an overestimate of the thickness, but we quote them as symmetrical. The uncertainities in h given in Table 1 include both of these sources of error.

Column densities for hydrogen are given directly by the radio measurements, because the brightness temperatures are small compared with 100° K. The column density for hydrogen $N_{\rm H}$ was computed from the area under the component of the profile corresponding in velocity to the optical feature, and the contribution from the low-density background component was subtracted out as in Paper I. The velocities of the peaks of the hydrogen profiles, $V_{\rm H}$, reduced to the local standard of rest, are given in Table 1, where LVS and HVS refer to the low-velocity and high-velocity sheets, respectively. The uncertainty in $V_{\rm H}$ is about ± 1 km sec^{-1}.

III. DISTANCES AND RELATIVE MOTION OF THE SHEETS

Stars which are behind both sheets will show a blended optical line whose velocity lies between the velocities of the two sheets; stars located between the two sheets will show a line whose velocity is that of the nearer sheet; and stars in front of both will show no line. A study of Table 1 reveals that the optical-line velocity, $V_{\rm opt}$, is either roughly equal to the velocity of the low-velocity sheet $V_{\rm LVS}$, near 0 km sec^{-1}, or roughly midway between the velocities of the two sheets. Thus the low-velocity sheet is nearer. The nearer sheet is moving toward us less rapidly than the more distant sheet, so they are *approaching* each other.

Stars we interpret to be behind both sheets are denoted in the last column of Table 1 by the symbol A; between the sheets, by the symbol B; in front of both, by the symbol C. The most distant star in front of both sheets is HD 208510, 176 pc away. The mean distance from the three most distant stars between the sheets is 250 pc. The nearest star behind both sheets is HD 210873, 142 pc away, but this star is behind the region where the sheets have merged; the next nearest star behind both sheets is HD 205021, 230 pc away. Uncertainty in distance due to the unknown luminosity class requires us to regard these distances as lower limits.

It is thus impossible to establish the precise distances of the sheets. Nonetheless, the data in Table 1 indicate a general trend that the low-velocity sheet is closer than the other. The mean distance of stars in group B (those between the sheets) is 195 pc. We adopt 200 pc as the distance to the complex, recognizing that this is probably an underestimate. The number of stars is too small to establish any trends in distance as a function of position, but of course there is no reason to assume that the sheets are parallel to each other or perpendicular to the line of sight.

IV. THICKNESS OF THE SHEETS

Knowledge of the column density permits an estimation of the line-of-sight thickness h of the sheet by solution of the equations of statistical equilibrium for the relative ionization of sodium. By combining these, one obtains the relation

$$h = \frac{n_e}{n_{\rm H}} \frac{\alpha}{\Gamma} N_{\rm H} \left(\frac{N_{\rm Na}}{N_{\rm Na\,I}} - 1 \right), \tag{1}$$

where n_e and $n_{\rm H}$ are the number densities of electrons and hydrogen, respectively; N is the column density, and α and Γ are the recombination and ionization coefficients, respectively (see Herbig 1968). A similar equation applies to calcium. We have used the revised values of the ionization coefficients found by Habing (1969).

The values of all of the quantities which enter into equation (1) are uncertain to some degree. The most reliable ones are those for α and Γ (Habing 1969). $N_{\rm H}$, which is measured directly by the radio observations because the 21-cm optical depth is small in most of the region (Paper I), is correct only if we can distinguish what fraction of the hydrogen in the line of sight is in front of the star. The procedure for doing this was outlined in § II; it involves matching the velocity of the optical interstellar absorption lines with the appropriate component(s) of the hydrogen radio line as well as estimating the contribution by the background (see Paper I). $N_{\rm Na}$ is obtained by assuming a standard chemical composition ($N_{\rm Na}/N_{\rm H} = 2 \times 10^{-6}$, $N_{\rm Ca}/N_{\rm H} = 10^{-6}$; see Aller 1961), and, unless this standard is incorrect, error in $N_{\rm Na}$ can occur only if a significant amount of Na is accreted onto the dust grains (Field, Goldsmith, and Habing 1969). The importance of this process is illustrated by the well-known problem of Ca underabundance noticed by Routly and Spitzer (1952) and Herbig (1968) among others, and is illustrated in the present paper by the star HD 2083, for which calcium appears underabundant with respect to sodium by a factor of 6, as well as by HD 16137, for which sodium lines were measured but no calcium lines were detected. Following Field *et al.* (1969), we have assumed a depletion factor of 10.

The quantity $n_e/n_{\rm H}$ depends on the ionization rate per hydrogen atom due to cosmic rays and on the amounts of depletion of many heavy elements, principally carbon

(Field *et al.* 1969). If there is no depletion, then n_e/n_H has a minimum value of 3×10^{-4}, resulting from photoionization of heavy elements whose ionization potential is less than that of hydrogen. However, additional electrons may be contributed by ionization of hydrogen by cosmic rays. Theoretical calculations by Hjellming, Gordon, and Gordon (1969), who used heating by low-energy cosmic rays, give n_e/n_H in the range 1×10^{-3} to 1×10^{-2} inside a condensation. In deriving the thickness quoted in Table 1, we assumed $n_e/n_H = 3 \times 10^{-3}$. The errors in h given in Table 1 reflect the uncertainties in the observationally determined quantities $N_{\rm Na\,I}$ and N_H alone, as discussed in § II. The additional uncertainty in h due to the uncertainty in n_e/n_H is directly proportional to this latter uncertainty.

A further source of error in determining the thickness is the existence of blended features due to separate condensations in the line of sight. The derivation of equation (1) assumes a single, uniform condensation, and in fact the production of optical interstellar lines is due preferentially to high-density regions. Also, if the star lies behind both sheets, the value derived for the thickness will be larger than the thickness of each individual sheet, since both the radio and optical lines will increase in equivalent width.

For these reasons we consider only those cases for which the star lies behond only one sheet (stars of class B in Table 1) as revealed by the coincidence of the optical velocity and a component of radio velocity. We thereby obtain the thickness of the nearer sheet only. We find N_H by considering the approximate profile area under the low-velocity component alone. Since the galactic latitudes are relatively high, little area should be contributed by hydrogen from beyond the star, unless the star is imbedded in the low-velocity hydrogen itself. Five stars are of class B, for which the derived thicknesses, given in Table 1, vary from 0.2 to 5.1 pc. The other dimensions are much larger, so the material is distributed in sheetlike condensations. A small thickness, 0.15 pc, was also found for the material in front of ζ Oph by Herbig (1968). We conclude that the distribution is sheetlike both for the case of ζ Oph and for the present case. Furthermore, our calculation of h and the conclusions of this section are independent of the distance estimate obtained in § III.

V. DISCUSSION

The radio data discussed in Paper I indicate that the sheets coexist in space near one end of the region. The sheets are approaching each other; it seems reasonable to conclude that in this region they have collided. This is consistent with the tentative conclusion of Paper I, which was drawn on the basis of the existence of young, hot stars and dust clouds in the region of collision. In addition, normal OH emission has been detected (Heiles 1968) in one of these dust clouds, in the region into which the collision front is moving, at a radial velocity intermediate between that of the two sheets. The relative approach velocity, as measured along the line of sight from the Earth, is about 10 km sec^{-1}; allowance for a probable projection effect raises this to about 14 km sec^{-1}. A collision of this kind is supersonic and will produce a strong shock wave; immediately after the collision the kinetic temperature will be raised to about 3000° K, and the material will subsequently cool, in the manner considered by Field *et al.* (1968), to lower temperatures and higher densities than the original material.

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