THE ASTROPHYSICAL JOURNAL, 394:552–564, 1992 August 1

OBSERVATION OF FINE STRUCTURE IN THE COLD PHASE OF THE LOCAL INTERSTELLAR MEDIUM USING K I ABSORPTION

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Received 1991 September 25; accepted 1992 February 10

ABSTRACT

We have observed at high resolution ($\lambda/\Delta\lambda = 5 \times 10^4$) and good signal-to-noise ratio (between 50 and 250, with the majority having S/N $\gtrsim 100$) a group of 18 early-type stars in the solar neighborhood in the region of the K I λ7699 resonance line, to detect interstellar absorptions due to K I. Using our detections, and upper limits, we measure K I column densities and estimate those of H I along these lines of sight. Selecting estimates of interstellar absorption in K I and also in other species, from literature observations in the same angular range centered on $l = 152°$, $b = -9°$, we examine a conical volume of semiangle $\sim 20°$ out to some 200 pc from the Sun, placing constraints on a number of the individual cold clouds ($T \lesssim 100$ K) in this zone. The technique entails estimating the H I number density of a cloud using the H I column density, and combining it with the cloud radius estimated by identifying neighboring lines of sight in which the cloud is or is not present. The interstellar absorptions allow us to "tag" a given cloud via its radial velocity, to within ± 1.5 km s^{-1}. Using the hypothesis of pressure confinement, we find temperatures in these clouds of $\lesssim 100$ K; as a typical cloud mass ranges up to a few hundred solar masses, which is lower than the estimated Jeans mass, pressure confinement is justified. We also show that the mass fraction of the local interstellar medium (LISM) in these cold clouds is high, at least 80% of the total, while the filling factor is low, well below 10% of the total LISM volume. We detect one cloud with higher densities and lower temperatures, which the physical conditions suggest is on the edge of atomic-molecular equilibrium.

Subject headings: ISM: abundances — ISM: atoms

1. INTRODUCTION

The division of the interstellar medium into separate structures with more than one distinguishable phase has been very clear to observers since the realization in the 1970s of the presence of molecular clouds with temperatures of order 10–30 K and densities of order 10^3, as well as the previously widely known and mapped 21 cm H I clouds with temperatures of order a few hundred K, and densities of order 1–10 cm^{-3}. The necessity of including a hot medium had been theoretically predicted as early as 1956 by Spitzer, who cited the need for hot gas in the halo to pressure-confine the high-latitude clouds observable in Ca II. In 1969 the key contribution of Field, Goldsmith, & Habing was to show that in a model of the atomic interstellar medium (ISM) (before the full realization of the importance of the molecular component) heated by cosmic rays, there ought to be two stable phases, the cold clouds around 100 K and warm intercloud material at $\sim 10^4$ K. The realization that hot gas is an important component in the disk came with a launch of the *Copernicus* satellite in 1972. The key observation here was that of absorption in O VI, first reported by Rogerson et al. (1973) and reviewed in two comprehensive papers by Jenkins (1978a, b). in which the increase in O VI column density with path length pointed to the interstellar, not circumstellar, origin of the line. These observations were supported by maps of the sky in soft X-rays (McCammon et al. 1983). Both results imply the pervasive presence of gas at temperatures (1–3) $\times 10^5$ K in the local disk, within ~ 300 pc of the Sun. Theoretical models taking this into account were proposed by Cox & Smith (1974) and McKee & Ostriker (1977), attributing the presence of hot gas to supernova remnants, whose frequency is such that their bubbles merge, allowing the hot medium to fill much of the ISM. In the latter model, the hot ionized medium ($T \gtrsim 4 \times 10^4$ K) fills $\sim 60\%$ of the local volume; inside it float small, cold neutral clouds ($T \sim 80$ K) occupying some 2%–3% of the volume. The interfaces between the cold clouds and the pervasive hot medium are composed of warm neutral and warm ionized shells, both at $T \sim 8 \times 10^3$ K and occupying $\sim 15\%$ and some 22% of the total volume, respectively. Since the individual clouds are not gravitationally bound, they must be in pressure equilibrium with their hotter surroundings. Observational determinations of the mean interstellar pressure (Jura 1975; Jenkins, Jura, & Loewenstein 1983) give a mean value $P/k = nT \simeq 3600$ K cm^{-3} (with which the McKee-Ostriker model gives good agreement) and using this value, one finds densities of 40, 0.37, 0.25, and 3.5×10^{-3} cm^{-3} for the four components in order of increasing temperature. The proportions of the total mass in the four components in the model are $\sim 90\%$, $\sim 5\%$, $\sim 5\%$ and $\sim 0.2\%$, respectively.

The McKee-Ostriker model predicts well many of the observed features of the local interstellar medium (LISM); the electron densities in the warm ionized envelopes, $n_e \sim 0.04$ cm^{-3}, confirmed by pulsar dispersion measures, the cloud velocity dispersion, ~ 8 km s^{-1}, and the local soft X-ray intensities, as well as the value of the interstellar pressure. However, there are several possible objections to the model, which may be summarized as follows: (1) The model assumed spherical clouds, whereas clouds on large scales might be sheet like, since shocks tend to produce sheets, not spheres. (2) Supernovae, assumed random in the model, tend to occur in clusters of tens of stars, affecting the global phenomenology and in particular the filling factor of the hot gas. (3) The H I distribution appears smoother (Paresce 1984; Heiles 1987), at least on large scales, than that predicted from a model with condensed clouds, and the fraction of warm H I appears larger (Kulkarni & Heiles 1987) than that predicted. However, the detailed interpretation of the observations underlying these inferences depends on the morphology of the three-dimensional structures observed, which is not known a priori and not easy to infer. (4) Lockman, Hobbs, & Shull (1986) inferred ratios of Lyα to 21 cm column densities toward halo stars which did not show the degree of variation expected if the individual clouds have such low filling factors. This conclusion, too, is open to interpretational doubts.

The present paper addresses the problem of the properties of the individual cold clouds. We have chosen the LISM for this work, i.e., we have concentrated our attention with 200 pc of the Sun, because this allows us to avoid at least some of the problems associated with multiple clouds along the line of sight. We have employed the 7699 Å resonance absorption of K I for the observation because this line is sufficiently strong to yield measurable absorptions for column densities as low as $N(\text{H I}) \sim 10^{20}$ cm^{-2}, but sufficiently weak not to present major saturation difficulties up to $N(\text{H I}) \sim 5 \times 10^{21}$ cm^{-2}, which is the range required. The approach used is quite straightforward: to observe LISM absorption in K I in a selected cone of directions, over a range of distances, and then, by delimiting the spatial extent of the absorptions, delimit the sizes of the individual clouds producing them. Using velocity as well as column density information as a tag offers a valuable second parameter to distinguish one cloud from another. Although there are multiple components even over these short distances, blending in the weak K I line is generally resolvable, given adequate spectral resolution ($\lambda/\Delta\lambda \gtrsim 5 \times 10^4$) and signal-to-noise ratio ($\gtrsim$100 in the majority of our spectra). In this we follow in the observational tradition pioneered in the 1970s especially by Hobbs (1969a, b, 1974a, b, 1978a, b), both in K I and more extensively in Na I, and by a number of more recent studies in other lines, notably Ca II (Lallement, Vidal-Madjar, & Ferlet 1986), in the visible where high-resolution spectroscopy is practicable. The observations presented here are an early step in a wider and deeper program to explore the LISM. They are restricted in number but, supplemented by literature data for the same part of the LISM, are already yielding very clear results, confirming that the cold component is indeed present in the LISM with properties very similar to those predicted by the models, that the bulk of the mass is in fact concentrated in these clouds, and that there is no clear evidence that they are not spherical. In § 2 we describe the observation and data reduction procedures, in § 3 we detail the results for the lines of sight to each object in turn, and in § 4 we present our deductions about the physical properties of the clouds observed and draw some brief conclusions.

2. OBSERVATIONS AND DATA REDUCTION

We observed the line K I λ7699 toward the 18 stars shown in Table 1. The basic data cited in the table were obtained from the Bright Star Catalogue (Hoffleit & Jaschek 1982), while the parallaxes are spectroscopic, inferred from magnitudes; the colors and luminosity classes are given directly in the catalog. The observations were carried out at the Roque de los Muchachos Observatory during two periods, in 1988 October and 1991 November, using the QUBES echelle spectrograph (McKeith, Dufton, & Kane 1987) at the Cassegrain focus of the 4.2 m William Herschel Telescope and the IACUB echelle (McKeith et al. 1992) at the Cassegrain focus of the 2.5 m Nordic Optical telescope, respectively. The effective resolution in all of the spectra was $\lambda/\Delta\lambda \sim 5 \times 10^4$ (2 pixels) using a CCD detector, which provided the limiting factor in the resolution here.

TABLE 1

STARS OBSERVED

Identifier in Fig. 2	Star (HD)	l	b	d (pc)	Spectral Type	m_V	$v \sin i$ (km s^{-1})
a........	219688	67°62	−61°54	115	B5 V	4.39	332
b........	208108	75.51	−26.41	100	A0 V	5.68	41
c........	210129	79.80	−27.15	170	B7 V	5.78	250
d........	212097	87.03	−23.88	125	B9 III	4.81	81
e........	220599	102.46	−27.02	175	B9 III	5.57	110
f........	220105	106.22	−15.79	65	A5 V	6.13	...
g........	7034	127.84	−31.26	30	F0 V	5.16	80
h........	9100	135.56	−43.57	95	A4 IV	6.02	84
i........	19279	145.59	−9.47	95	A3 V	6.41	...
j........	23552	149.16	−2.90	170	B8 V	6.14	250
k........	21455	148.93	−7.80	200	B7 V	6.24	150
l........	21038	151.58	−12.91	145	A0 V	6.51	91
m........	20995	156.09	−19.30	95	A0 V	5.61	145
n........	27026	158.72	−5.93	150	B9 V	5.12	41
o........	19698	168.40	−38.41	155	B8 V	5.98	350
p........	18883	173.08	−45.39	150	B7 V	5.61	80
q........	26793	183.04	−28.34	95	B9 V	5.22	350
r........	43525	200.16	−2.99	70	A2 V	5.39	192

Data reduction was effected using routines from a standard package (IRAF), in a sequence of steps which included bias subtraction, division by the flat field taken closest in time to the spectrum of the star in question, and calibration in wavelength. The flat fields were obtained using background dome illumination from a tungsten lamp source, supplemented by twilight flat fields from the sky. Wavelength calibration relied on the presence of a well-known set of sharp, strong terrestrial atmospheric absorption lines in the region of the K I interstellar line, ideal for this purpose, which enable us to derive a wavelength scale with an absolute internal precision of 7 mÅ, corresponding to 0.3 km s^{-1}. In Figure 1 we show examples of three calibrated spectra. Figure 1*a* is that of HD 21455, where there is considerable K I along the line of sight. The strongest line here is the K I line itself, at 7699 Å, and we can see three doublets due to atmospheric O_2 which were used in the wavelength calibration. The fact that the half-widths of the atmospheric and IS lines are comparable indicates that the instrumental width is the dominant contributor to the line widths in both cases. In Figure 1*b* we show a weaker K I line, estimated at 7 mÅ, in the spectrum of HD 18883, which allows an indication of the lower limit to a measurable equivalent width in the spectra, and in Figure 1*c* that of HD 26793, an example where any intererstellar K I was below the limit of detection, at 2 mÅ.

In order to derive the velocity and intensity structure of a given K I absorption line, it was fitted by a set of Voigt profiles using an iterative routine. The input parameters to each component consisted of an equivalent width and central wavelength (in fact translated into a column density and a heliocentric velocity) together with a value for the parameter b, governing the width, due to interstellar microturbulence. The routine was designed to be used interactively, and a solution

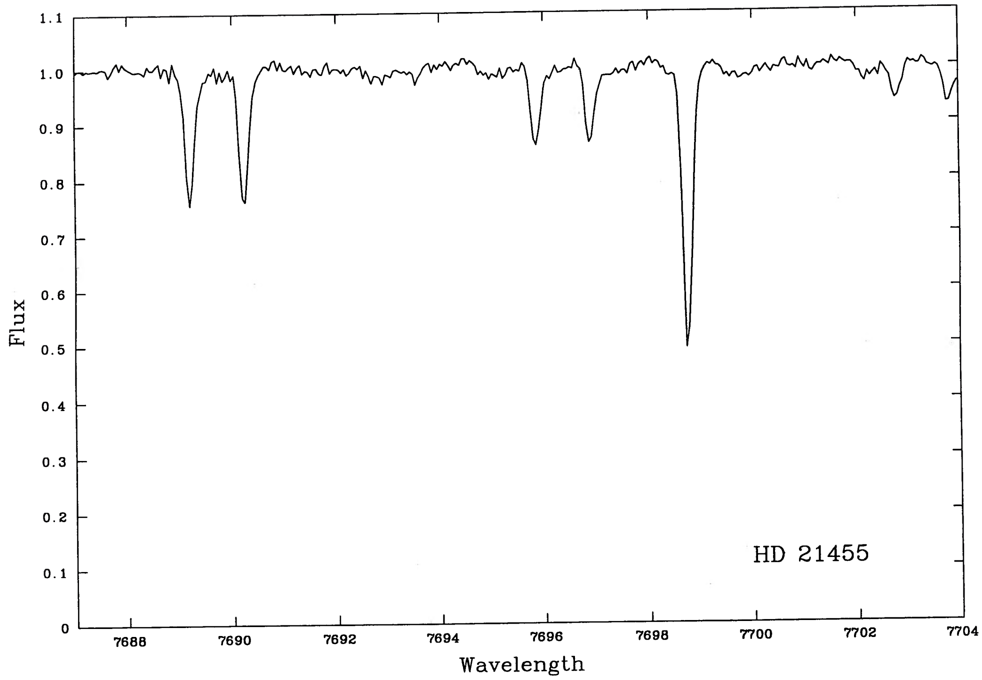

FIG. 1*a*

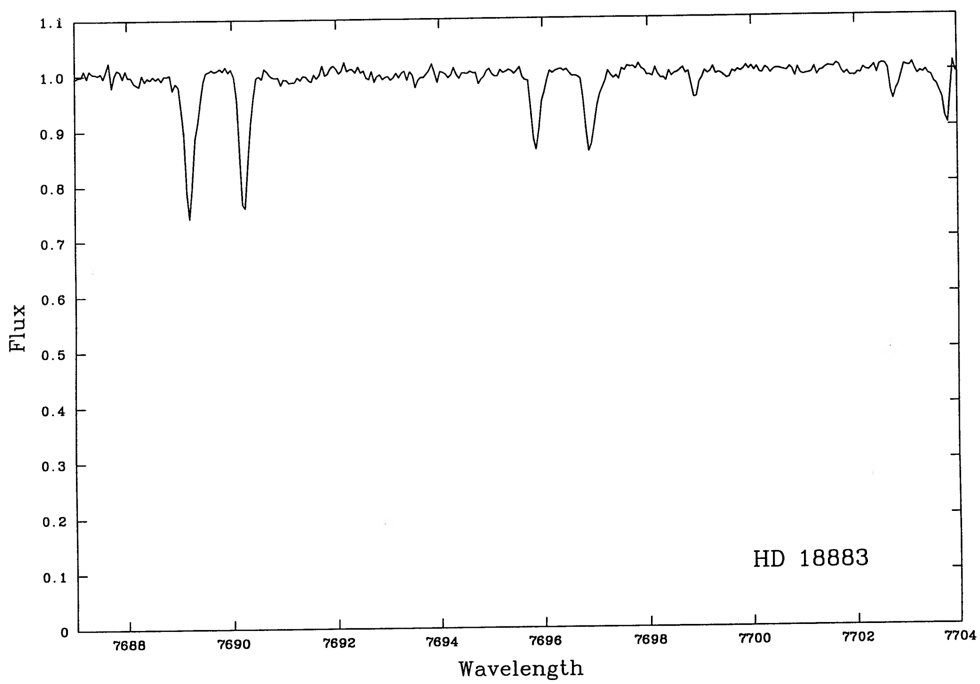

FIG. 1*b*

FIG, 1.—Spectra of three stars: (*a*) HD 21455, (*b*) HD 18883, and (*c*) HD 26793, in the range centered on 7695 Å, including the interstellar K I line at 7699 Å. The spectra illustrates cases of much K I, little K I, and no detectable K I, respectively, and the noise levels indicate limits to detectable equivalent widths.

was achieved when the observed line was fitted with the minimum number of distinguishable components. In general, using values of b in the range 2–4 km s^{-1}, excellent fits were obtained with a single component, or at most two (for two of the stars). The transformation between the equivalent width and column density for any interstellar component was effected using curves of growth calculated for a family of b-values on the basis of Voigt profiles, using a value of 0.339 for the oscillator strength and a value of 0.382×10^8 s^{-1} for the Einstein spontaneous coefficient A_{ki} (both values from Wiese, Smith, & Miles 1969) and using the values tabulated by Finn & Mugglestone (1965) to compute the Voigt function $H(\alpha, v)$. In all but one of our observations the K I line was in fact found to be on the linear part of the curve of growth, so varying the b-value

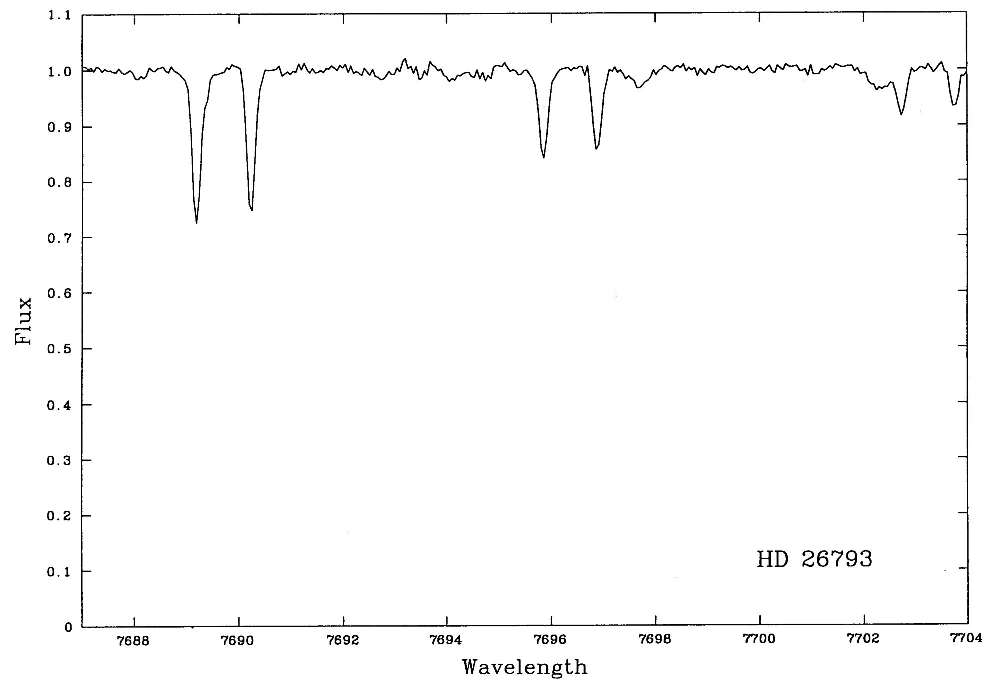

FIG. 1*c*

made very little practical difference to our column density determinations. Given the noise limits to our spectra, the minimum measurable equivalent width in a typical spectrum was 2 mÅ, corresponding to a minimum detectable column density in K I of 10^{10} cm^{-2}. In order to convert from column densities *N*(K I) to column densities in atomic hydrogen, *N*(H I), we used two relations from the literature, based on empirical evidence. This is, of course, necessary given the difficulty in inferring the fractional ionization of potassium in a range of radiation fields and temperature regimes. The initial step was to use the simple observational relation of Hobbs (1976) between K I and Na I column densities, namely, *N*(Na I) = 60 *N*(K I), which implicitly folds the underlying cosmic abundance ratio Na/K with the lower ionization potential of the K atom. The second step used the relation obtained by Ferlet, Vidal-Madjar, & Gry (1985) between *N*(Na I) and $N(\mathrm{H\ I} + H_2)$, based on their own Na I data, those of Hobbs (1976, 1978a, b), and the hydrogen column density measured by Bohlin, Savage, & Drake (1978) and Bohlin et al. (1983) using *Copernicus* Lyα observations. A good fit to most of these data, offered by Ferlet et al., is

$$\log N(\mathrm{H\ I}) = [\log N(\mathrm{Na\ I}) + 9.09]/1.04\ , \qquad (1)$$

where the H_2 contribution can be safely neglected for total column densities less than 10^{21} cm^{-2}, corresponding to total dust extinction in the line of sight, $A_v < 0.5$ (Bohlin et al. 1978), conditions not conducive to the formation of H_2. This linear relation is usable to convert K I to H I column densities up to this same value of 10^{21} cm^{-2}. Above this level, corresponding to $N(\mathrm{Na\ I}) = 7 \times 10^{12}$ cm^{-2} and to $N(\mathrm{K\ I}) = 1.1 \times 10^{11}$ cm^{-2}, we estimated $N(\mathrm{H\ I} + H_2)$ using the observational points of Ferlet et al. (1985) in their Figure 1, without assuming any analytic relation between this quantity and *N*(Na I). In practice this was required for only two or our interstellar spectra in K I, those of HD 21455 and HD 23552; the others corresponded to values up to 10^{21} cm^{-2} for *N*(H I).

The reslts obtained for each interstellar component in each star are tabulated in Table 2, in which we have included the measured equivalent widths and corresponding K I column densities, the conversions to *N*(H I), and the velocity of each component along the line of sight converted to heliocentric coordinates. Where no positive detection was made, the corresponding upper limits are shown. In order to use these measurements to make detailed deductions about the structure of the LISM along our chosen line of sight, we needed to search the literature to find any comparable or complementary studies made at high spectral resolution along neighboring lines of sight, defined somewhat arbitrarily for this purpose as lying within 10° on the sky of our given K I object, and within

TABLE 2

INTERSTELLAR K I LINES OBSERVED

Identifier in Fig 2	Star (HD)	$W_{\mathrm{K\ I}}$ (mÅ)	*N*(K I) ($\times 10^{11}$ cm^{-2})	*N*(K I) ($\times 10^{20}$ cm^{-2})	V_{HEL} (km s^{-1})
a........	219688	<2	<0.1	<1.2	...
b........	208108	<2	<0.1	<1.2	...
c........	210129	16.8	0.99	10.5	−10.5
		16.2	0.94	10.0	−7.4
d........	212097	25.6	1.9	15	−11.5
e........	220599	<2	<0.1	<1.2	...
f........	220105	<5	<0.35	<3.8	...
g........	7034	3.8	0.22	2.4	+0.7
h........	9100	<2	<0.1	<1.2	...
i........	19279	<5	<0.35	<3.8	...
i........	23552	105.6	10	20.0	+2.0
k........	21455	105.3	10	20.0	+3.7
		16.3	0.95	10.1	+9.3
l........	21038	<5	<0.35	<3.8	...
m........	20995	2.1	0.11	1.2	+8.2
n........	27026	<5	<0.35	<3.8	...
o........	19698	<2	<0.1	<1.2	...
p........	18883	7.2	0.41	4.5	+6.1
q........	26793	<2	<0.1	<1.2	...
r........	43525	2.5	0.14	1.6	+29.1

TABLE 3

INTERSTELLAR INFORMATION FROM THE LITERATURE ALONG NEIGHBORING LINES OF SIGHT

Number	Star	l	b	d (pc)	N(H I) ($\times 10^{20}$ cm^{-2})	Ion	V_{HEL} (km s^{-1})	Ion
1	32 Peg	87°	−26°	170	<6.0	Na I[a]	−6.5	Ca II[b]
2	2 And	103	−15	21	0.2	Mg I[c]	−7.7	Ca II[c]
3	o And	102	−16	110	4.4	K I[d]	−8	K I[d]
4	ν Psc	131	−35	47	<0.08	Mg I[c]	...	...
5	ψ Per	149	−6	170	15.5	K I[a,e]	−3	K I[a,e]
					17.0	K I[a,e]	+3	K I[a,e]
					13.6	K I[a,e]	+8	K I[a,e]
6	34 Per	147	−6	125	4.1	Na I[f]	{−3.2, +6}	Na I[f], Na I[f]
7	HD 21278	148	−6	145	>10.0	Na I[f]	{+6, +0.5}	Na I[f], Na I[f]
8	δ Per	150	−6	78	0.37	Na I[a,e]	+6	Na I[a,e]
9	ϵ Per	157	−10	263	3.0	Na I[a,e]	+8	Na I[g]
10	48 Per	154	−3	170	3.0	Na I[c,g]	+9.1	Na I[g]
11	Feige 24	170	−55	90	0.01	N I[c,h]	...	...
12	λ Tau	178	−29	100	0.2	Na I[a,e]	+22	Na I[a,e]
13	μ Tau	184	−29	190	14.7	Na I[f]	+23	Na I[f]
14	λ Ori	195	−12	532	0.6	Na I[a,e]	+8	Na I[a,e]
					1.0	Na I[a,e]	+17	Na I[a,e]
					15.0	K I[a,e]	+26	K I[a,e]

[a] Hobbs 1974a.
[b] Marschall & Hobbs 1972.
[c] Frisch et al. 1990.
[d] Hobbs 1976.
[e] Stokes 1978.
[f] Hobbs 1978b.
[g] Hobbs 1969a.
[h] Dupree & Raymond 1982.

no more than a couple of hundred parsecs from the Sun. In Table 3 we list the 14 stars chosen using these criteria, together with their Galactic coordinates, distances, and the estimated H I column density in each resolved interstellar component. We also include the heliocentric velocity of each component, the atomic species on which the column density and velocity measurements are based, and the original literature references for each object. In this reanalysis of the literature observations, the indirect N(H I) values derived from Na I measurements were obtained by direct use of equation (1). In the case of K I data, the steps followed were the same at those used with our own data. For the stars ν Psc and 2 And observed in Mg I by Frisch et al. (1990), we used the column density N(H I) calculated by Frisch & York (1991) using the ratio log [N(Mg I)/N(H I)] = −7.62 derived from observed values in nearby unreddened stars.

3. LINES OF SIGHT TO INDIVIDUAL STARS

In Table 2 we have the equivalent widths of K I λ7699, or upper limits, for all the stars observed. We also showed our best estimates of the subcomponents in each line, obtained by the Voigt profile fitting routine explained in § 2. Here we examine, star by star, how the K I line seen toward each subject fits into the pattern of interstellar absorptions seen toward that object and its neighbors, with the aim of putting observational limits to the cool interstellar component in the directions observed.

3.1. *HD 219688*

In the star, at 125 pc from the Sun, in the first quadrant, and at high (negative) Galactic latitude, we do not detect measurable K I. A comprehensive literature search did not yield further spectral observations of the LISM in this direction, or of neighboring stars whose lines of sight have been explored. We may simply note that our upper limit of 2 mÅ for the K I line corresponds to an upper limit of 1.2×10^{20} cm^{-2} for N(H I) to this star, well below the global figure of 2×10^{20} cm^{-2} depicted by Paresce (1984) for this Galactic latitude in his in-plane map of H I. There need be no inconsistency, given the difference in Galactic latitude, but the present limit points to fairly low column densities in this direction.

3.2. *HD 208108*

We detect no K I absorption toward this object, which is at 100 pc from the Sun in the direction $l = 76°$, $b = -26°$. We could not find any objects in the literature very close in angle to this star, but it does lie in the same general direction as two of our K I objects, HD 210129 and HD 212097, and serves to constrain the size of the cloud detected toward these two stars described below.

3.3. *HD 210129*

We have a clear detection of the interstellar K I line in the spectrum of this star, situated at 170 pc from the Sun, in the first quadrant, 27° below the plane. In fact, the line shows two virtually equal components, each corresponding to a column density N(H I) ~ 10^{21} cm^{-2}. The velocity of one of these, −10.5 km s^{-1}, corresponds precisely with the global LISM velocity of Crutcher (1982), but the other lies only 3.1 km s^{-1} away, and within the limits of the determination of this global velocity, both components can be identified as belonging to the local flow. A literature search for observations along neighboring lines of sight produced the observation of Na I by Hobbs (1974a) toward 32 Peg. The line of sight to this star passes within 20 pc of HD 210129, and Hobbs (1974a) measured an H I column density greater than 6×10^{20} cm^{-2} with a heliocentric velocity of -6.5 km s^{-1}. If we assume that this column density belongs to the same cloud that produces our component at -7.4 km s^{-1}, we can draw some tentative conclusions about the cloud. In the extreme case that it lay just in front of HD 210129, and assuming sphericity, it would have a diameter of $\gtrsim 25$ pc and a mass of 5×10^3 $M_\odot$ (given here the assumption of uniform density). We will see below that this is very high for a typical cloud, that it is well in excess of the Jeans mass for the temperature and density range observed via K I, and that values of this scale for the majority of the clouds would be much too high for the known local surface density of the Galaxy.

Since the component in K I at -6.5 km s^{-1} does not show up in HD 212097 (see below), we could use this constraint to place the cloud just beyond that object (see dotted circle in Fig. 2) instead of at the difference of HD 210129. In that case, the observations could be satisfied by a cloud of density 33 cm^{-3} in H I, and with a mass of 640 $M_\odot$, a much more reasonable value than the upper limit inferred above.

However, as we will see when examining the line of sight toward HD 220599, there is a further possible observational constraint on this cloud which may allow us to place it much closer to us than HD 210129, and to place a much stronger limit on its mass.

3.4. *HD 212907*

This object lies at 123 pc from the Sun at Galactic longitude 87° and at $-24°$ latitude, along a line of sight very close to 32 Peg but closer to the Sun. In the spectrum of this star we detect a strong single component in K I corresponding to an H I column density of $\sim 1.5 \times 10^{21}$ cm^{-2} at a radial velocity of -11.5 km s^{-1}. This strong detection can be grouped together with our measured column density of 10.5×10^{20} cm^{-2} for H I in front of HD 210129, and a measurement in Hobbs (1974a) of a component of somewhat lower column density in the direction of 32 Peg at velocities of -10.5 and -10.6 km s^{-1}, respectively. These stars lie within a narrow cone on the sky, and it is reasonable to claim that we are seeing the effects of a single cloud in the direction defined by these three stars, and limited in the direction toward HD 208108 where no K I absorption could be detected. Taking the limiting case, in which the cloud lies just within the distance of HD 212097, the observational conditions implying a radius of at least 6 pc for a spherical cloud, and for the line of sight to the star to contain 1.5×10^{21} cm^{-2} in H I, the average cloud density would be 70 cm^{-3} and the total mass some 780 $M_\odot$. This is quite large, as we will see in the detailed discussion of HD 21455 (§ 3.11), where we will show that many clouds with masses greater than 1000 $M_\odot$ are unlikely to be present in the LISM. However it should certainly be taken as an upper limit. If, for example, we place the cloud at half the distance to HD 212097, the corresponding density and mass would be 140 cm^{-3} and 195 $M_\odot$, respectively. This, however, can be taken as a lower limit, since the general condition of pressure equilibrium would imply a temperature of only 25 K for such a cloud. While this cannot be totally excluded, it is low for a cloud of this column density, where the total dust extinction A_V should not be more than 0.75 mag (Bohlin et al. 1978); this cloud has a rather lower column density than the cloud we find in front of HD 21455 (see below). Thus our observations serve to limit the mass of the cloud to 780 $M_\odot$ and place a temperature upper limit of 50 K, while a rather more tentative lower limit of some 200 $M_\odot$ corresonding to a cloud temperature of 25 K represents the other permitted extreme. Better limits would require more lines of sight, nearer stellar sources in the same direction, or complementary methods.

3.5. *HD 220599*

This star, which lies in the second quadrant, at 175 pc from the Sun and some 30° below the plane, does not show measurable interstellar K I. Using Na I, however, Hobbs (1978b) made positive detections toward two other stars with lines of sight very close to HD 220599. In both 2 And, at a distance of 21 pc, and o And, at 110 pc from the Sun, he detected the Na I doublet in absorption with typical LISM characteristics. Using Hobb's (1976) observations, we infer a heliocentric velocity of -8 km s^{-1} for o And, and from Hobbs (1974a) we obtain -7.7 km s^{-1} s^{-1} for 2 And. We can make a trial assumption that the cloud which produces these absorptions is that which gives rise to our component at -7.4 km s^{-1} toward HD 210129, and probably that detected by Hobbs at -6.5 km s^{-1} toward 32 Peg. In that case the proximity of 2 And to the Sun would enable us to constrain the cloud parameters quite well. It would lie at a distance of $\lesssim 20$ pc, intersect the lines of sight to the four stars named above, but not impinge on the line of sight to HD 220599, which passes 4.4 pc away from 2 And, or to HD 220105 (see § 3.6), which passes only 1.2 pc from 2 And, or to HD 212097, which lies 4.6 pc above the line of sight to 32 Peg. Although we cannot limit the cloud in all directions with these assumptions, we can set an estimate of its linear scale at ~ 16 pc. In that case, the column density of 10^{21} cm^{-2} obtained in the -7.5 km s^{-1} component of HD 210129 would correspond to an H I density n_H of 20 cm^{-3}, and the cloud would have a mass of 600 $M_\odot$. A quick check on these numbers is provided by the condition that the total pressure, P/k, should be 3600 K cm^{-3}, which, for the value of n_H inferred, here corresponds to a cloud temperature of 180 K. This implies that we are dealing with a cloud whose parameters lie in the $T \lesssim 100$ K space defined in the three-phase model of McKee & Ostriker (1977). This conclusion cannot be definitive in the case of this cloud, whose boundaries are not well defined. In fact, it could not be spherical if its signature appears in the spectra of the four stars named above while avoiding the lines of sight to HD 220599 and HD 212097. An alternative explanation for the observations could be the presence of two neighboring small, separate spherical clouds in comparable masses (100–200 $M_\odot$) and with radii ~ 4 pc, which have virtually identical heliocentric radial velocities. We have no observational means, as yet, to distinguish these two solutions. However, we will see that the cumulative evidence of our different lines of sight, showing similar parameters for other clouds, supports the basic picture, in which the K I lines are produced in discrete cool cloudlets. It is clear from the results in the present section that closely neighboring lines of sight can pass through very different column densities of H I, which is at variance with models which assume much smoother distributions.

3.6. *HD 220105*

For this star, situated at 67 pc from the Sun, we make no detection of interstellar K I, which puts an upper imit to the H I column density of 3.8×10^{20} cm^{-2}. As explained in the section on HD 220599 (§ 3.5), this puts a geometrical limit on the cloud detected along the line of sight to 2 And and o And. Given the moderate signal-to-noise ratio for this object, we cannot exclude the passage of this line of sight through the edge of the

1992ApJ...394..552T

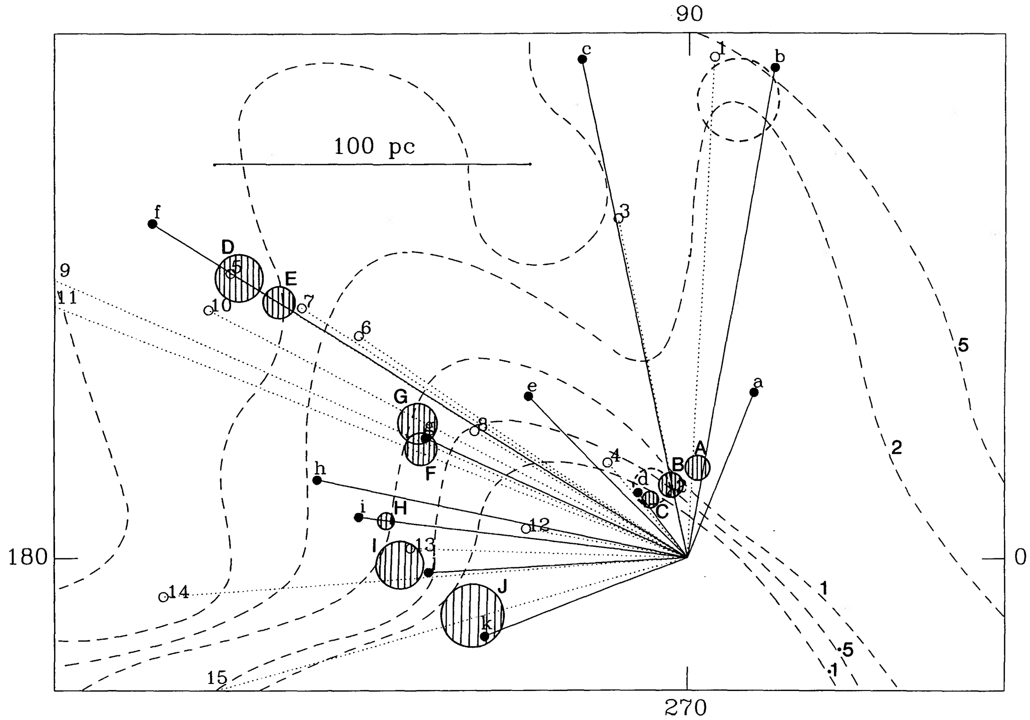

FIG. 2*a*

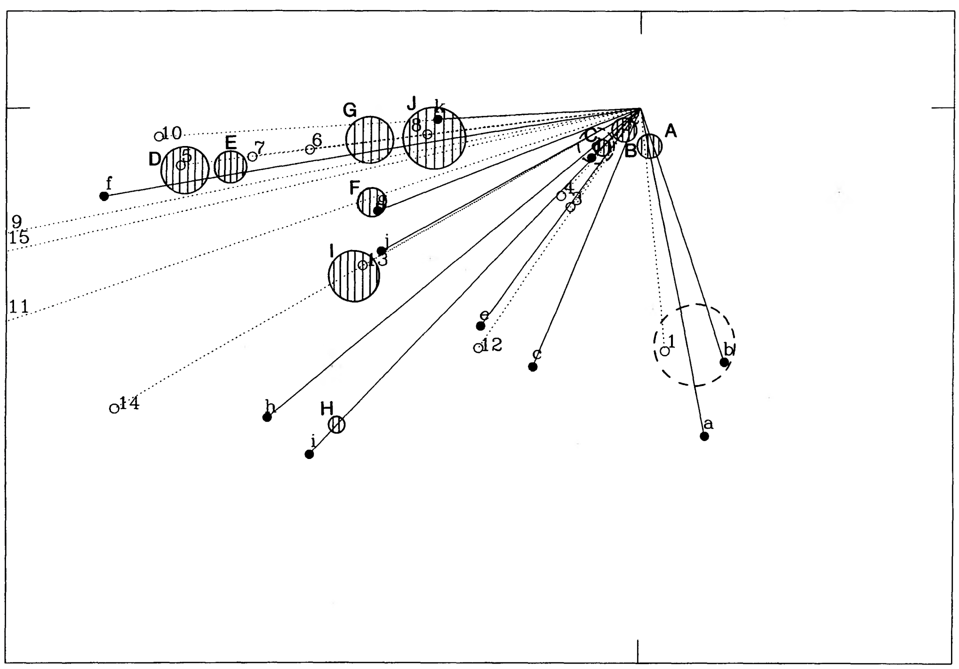

FIG. 2*b*

FIG. 2.—Three cross sections of the local interstellar medium passing through the Sun, (*a*) in the Galactic plane, (*b*) perpendicular to the plane along the direction $l = 0°$–$180°$, and (*c*) perpendicular to the plane along the direction $l = 90°$–$270°$. Shown are (1) the stars employed in the present K I survey (*filled circles*, lettered *a*–*r* (2) radius vectors to these stars (*continuous lines*); stars on neighboring lines of sight, from the literature (*open circles*, numbered 1–14); (4) radius vectors to these stars (*dotted lines*); (5) estimated positions and sizes of local cold interstellar clouds (*shaded large circles*); (6) less probable hypothetical positions of interstellar clouds (where more probable parameters are indicated shaded) (*dotted large empty circles*). The dashed lines in (*a*) are contours of iso–column density in H I, from Paresce (1984), in units of 10^{20} cm^{-2}.

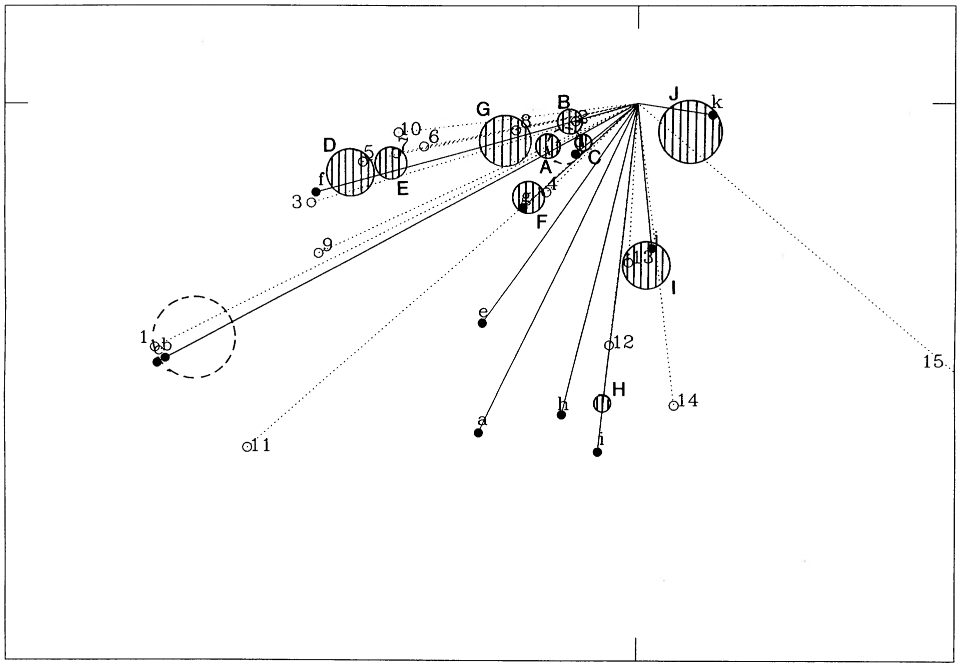

FIG. 2c

cloud, at levels of absorption below our detection limit. The constraint provided by this star makes little difference, however, to the cloud parameters inferred from the other lines of sight discussed.

3.7. *HD 7034*

Along the line of sight toward this star, situated at 300 pc from the Sun, in the direction $l = 127\overset{\circ}{.}26$, $b = -31\overset{\circ}{.}26$, we detect a K I component which corresponds to a cloud with column density $N(\text{H I}) = 2.4 \times 10^{20}$ cm^{-2} and a heliocentric veocity of $+0.7$ km s^{-1}.

The line of sight to ν Psc, observed by Frisch et al. (1990), which passes within 2.4 pc of HD 7034 in the sense of increasing Galactic longitude is apparently free of measurable absorption (an upper limit of 8×10^{18} cm^{-2}) due to H I. Our own observation of HD 220599, discussed in § 3.5, shows no measurable K I absorption, which in our case corresponds to an upper limit of $\sim 10^{20}$ cm^{-2}. The line of sight to HD 220599 passes within 11 pc of HD 7034, in the sense of decreasing Galactic longitude. These nondetections enable us to limit the size of the cloud producing the observed K I feature in HD 7034 to a radius of ~ 6 pc. The column density in the cloud, if it were spherical and in the position shown in Figure 2, would be produced by a column of length 4.8 pc, implying a number density n_{H} of 17 cm^{-3} and a total cloud mass of 100 $M_{\odot}$. However, this number density, combined with a canonical LISM pressure of 3600 cm^{-3} K, would correspond to a temperature of 210 K. This value is rather high for stability, so we conclude that n_{H} is a lower limit and that the diameter of the cloud must in fact be less than 12 pc. If we do not want to constrain the temperature in this way, we could let the cloud fill the line of sight to the star, i.e., 30 pc; this would imply an equilibrium temperature of 360 K, but this is not realistic because the cloud would then cut many more of the lines of sight in its hemisphere. None of our physical constraints is complete. One could adjust the geometry of the cloud in an arbitrary way to get around them. However, the simplest solution of a single small cloud near HD 7034 with mass less than 100 $M_{\odot}$ and temperature well below 200 K satisfies all the observations.

3.8. *HD 9100*

We can place an upper limit for $N(\text{H I})$ of 1.2×10^{20} cm^{-2} along the line of sight to this star, which is at 100 pc from the Sun in the direction $l = 135\overset{\circ}{.}56$, $b = -34\overset{\circ}{.}57$, given that we see no measurable K I in its spectrum. This limit is not particularly severe; it is in fact compatible with the "canonical" value, given in the map by Paresce (1984), of 10^{20} cm^{-2} for $N(\text{H I})$. As there are no measurements in the literature along neighboring lines of sight, we are not in a position to back up any conclusion about the LISM distribution; clearly further observations in this range of directions are needed.

3.9. *HD 19279*

We make no detection of K I in this star, but the signal-to-noise ratio in the spectrum does not permit a better upper limit for $N(\text{H I})$ than 4×10^{20} cm^{-2}. Since the line of sight to this object lies further away in angle from our detections, reported below toward HD 21455 and HD 23552 than the null measurements toward 24 Per and HD 21278 (Hobbs 1978b) at the velocity we detect in K I, and since the column density constraint is weaker, this star does not serve to limit the cloud responsible for the detections. This nondetection is, however, consistent with the nondetections toward 34 Per and HD 21278, confirming the general inhomogeneity.

3.10. *HD 23552*

In the spectrum of this star, which is at 170 pc from the Sun, at $l = 149°$, $b = -3°$, we detect by far the strongest K I LISM feature, matched, however, by a feature of similar strength seen in the neighboring star HD 21455 (see § 3.11), at similar velocity. The equivalent width in HD 23552 is 105.6 mÅ, and the detected radial velocity is +2 km s^{-1}. This line is so strong compared with the other detections we make toward stars which include objects at greater distances that our first reaction was to check whether or not it could be of stellar origin. However, its FWHM of 0.35 Å, even before deconvolving the slit function, is too small by an order of magnitude for this object, which has a $v \sin i$ of 250 km s^{-1}. We conclude that it is due to a LISM cloud. Apart from our strong K I detection in HD 21455, absorption features of various atomic species with closely matching heliocentric velocity corresponding to N(H I) of 1.7×10^{21} cm^{-2} appear in the spectrum of ψ Per, which lies at 170 pc from the Sun along a line of sight only 3° (which translates to some 9 pc) away from that to HD 23552. This reinforces the idea that we are observing a single LISM cloud. The conversion of the observed column densities of K I along the line of sight to HD 23552, 10^{12} cm^{-2}, to a column density in H I via the empirical calibration N(Na I)/N(K I) of Ferlet et al. (1985) yields a much lower ratio N(H I)/N(K I) for this high range of equivalent widths than for the other detections in the present sample (apart from that toward HD 21455), which are of order 20 mÅ or less. However, the value of the H I column density derived, 2×10^{21} cm^{-2}, corresponds to an extinction A_V of 1.25 mag (see Bohlins et al. 1978), which means that the opacity of the cloud to UV photons is in the range ~2 mag or greater. This is certainly consistent with an ionization ratio K II/K I much lower than in the optically thiner clouds, so that the lower N(H I)/N(K I) conversion factor used is justified, As the stronger absorption in this star is so closely similar to that in HD 21455, we will discuss the details of the LISM cloud causing them in the next subsection, where the line of sight to this latter star is examined.

3.11. *HD 21455*

The sharp K I absorption line in this star at 200 pc from the Sun, in direction $l = 149°$, $b = -8°$, comprises two components, a strong one with equivalent width 105 mÅ and heliocentric velocity +3.7 km s^{-1}, and a weaker one, of 16.3 mÅ at +9.3 km s^{-1}. The coincidence in position, velocity, and strength of the strong component with the single K I absorption seen in HD 23552 lends clear support to its interstellar origin. In this star also, which has a measured $v \sin i$ of 150 km s^{-1}, any stellar line would be an order of magnitude broader than the measured 0.22 FWHM of the detected feature. Converting the observed equivalent width to the K I column density, and thence, to an H I column density, involved exactly the same considerations as for HD 23552, giving an essentially identical result of 2×10^{21} cm^{-2}. We can make an estimate of the properties of the cloud causing this strong absorption, noting that it intercedes between ourselves and the three stars HD 21455, ψ Per, and HD 23552, with the column densities described above. The three stars are well aligned in Galactic longitude; the line of sight to HD 21455 passes 5 pc in latitude below ψ Per and 14 pc away from HD 23552. An additional, though weak, constraint is the absence of any feature at the observed velocity in the spectrum of HD 21278, some 25 pc in front of ψ Per. The presence of three almost equal H I column densities at the same velocity for HD 21455, HD 23552, and ψ Per, enabling us to say that the cloud lies across their lines of sight, sets a minimum cloud radius of some 7.5 pc to the cloud. The maximum-sized spherical cloud that could fit between ψ Per and HD 21278 without overlapping the other cloud component which we detect there with a distinct velocity is 10 pc. Thus we can make a trial estimate of the properties of the present cloud assuming a radius of 9 pc. This radius yields a mean cloud density of 60 cm^{-3} (corresponding to $T = 60$ K, if we use pressure equilibrium and $P/k = 3600$ K cm^{-3}) and a total mass of 2500 $M_\odot$. This is, by the standards of the LISM within 200 pc from the Sun, a very massive cloud. Obtaining a statistical number count of clouds in the cylinder around the Sun from our own and literature measurements, we can convert to a projected surface density of order 0.1 clouds pc^{-2}. Estimates of the total mass surface density above the Galactic plane in the form of interstellar gas (e.g., Kulkarni & Heiles 1987) set an upper limit to the average cloud mass of 1000 $M_\odot$ per cloud, assuming conservatively that all the mass in the LISM is in these cold clouds and that there are no major unknown contributors. Although a single cloud of mass 2500 $M_\odot$ is not excluded by this reasoning, it is rather high. It is also high compared with the Jeans mass M_J of the medium in this state, which we can estimate using $M_J \approx 6(T/20)^2 A_V$, which yields $M_J \sim 220$ $M_\odot$. Changing the geometry of the cloud, we can go some way to reducing the overall mass. For example, a cylindrical cloud with radius 5 pc and length 15 pc lying in front of the stars observed would give a mass of 1060 $M_\odot$ with a particle density of 67 cm^{-3}. This would not affect the physics in any fundamental way, however, because the cloud mass would still be 5 times greater than the Jeans mass at the corresponding temperature.

This cloud is considerably more opaque than the others observed in the present set, and a lower temperature is a reasonable consequence, as a result of dust shielding. Further, in this relatively dense object the magnetic field is almost certainly more concentrated than in the warm, diffuse LISM. This is not quantifiable without the required observations, but can offer a qualitative explanation for an apparent super–Jeans mass in a case of this sort.

We can conclude that we are dealing with a relatively dense, cool, opaque massive cloud, where it would be of considerable interest to look for enhanced field strength and for molecular line emission, as well as to map the object in H I. A virtue of the present technique is that it places much firmer limits on the distance to the cloud than would be feasible using radio observations alone.

The weaker K I component in HD 21455 with heliocentric velocity +9.3 km s^{-1} shows up in the lines of various species (Stokes 1978) in the spectrum of ψ Per. Using the K I data Hobbs (1974a) for this star, Stokes (1978) obtains a column density N(H I) of 1.36×10^{21} cm^{-3}, compared with 1×10^{21} for HD 21455 along an almost identical line of sight but 30 pc further away. We conclude that the cloud causing this component lies between us and ψ Per, but, as there is no absorption at this velocity in the spectrum of HD 21278 (Hobbs 1978b), we conclude that the cloud can be placed between 145 and 170 pc from the Sun, along a line having $l \approx 150°$, $b \approx -8°$. We also note that this component is not detected along the line of sight to HD 23552, which passes 9 pc above ψ Per, so that the cloud cannot extend as far as this line in the direction specified. Applying the canonical pressure equilibrium value of $P/k = 3600$ K cm^{-3} and assuming a temperature of 100 K, we find for N(H I) $= 10^{21}$ cm^{-2} a radius for the (spherical) cloud of 5 pc, and a mass of 185 $M_\odot$. This size constraint coincides with that imposed by the condition that this cloud cannot overlap with the cloud we have just considered (at velocity +3.7 km s^{-1}). We cannot, however, exclude the possibility that the present cloud is flattened, extending across the line of sight to 48 Per, where a weak component is observed in Na I

(Hobbs 1969a) at a similar velocity. With a reasonable assumption about temperature, a cloud mass of $\sim 350\ M_\odot$ is found. We cannot distinguish on general physical grounds between these cloud geometries; the Jeans mass, for example, in this temperature range would be of order 500 $M_\odot$, nor do we have any further lines of sight to assist us. However, we can be reasonably sure that we are dealing with a cloud with a mass of 200–300 $M_\odot$, a scale size of order 5 pc, and density of order $n_H = 30\ cm^{-3}$.

3.12. *HD 21038*

Along the line of sight to this star, at 150 pc from the Sun, with Galactic coordinates $l = 152°$, $b = -13°$, we find no measurable K I absorption, although with an upper limit which is not particularly low, $3.8 \times 10^{20}\ cm^{-2}$, due to the relatively modest signal-to-noise ratio in the observed spectrum. This absence of a detection here serves as a possible though weak constraint on the extent of the LISM clouds detected in the direction of HD 20995, as is explained below.

3.13. *HD 20995*

This star lies at 100 pc from the Sun, in the direction $l = 156°$, $b = -19°$, and from our weak K I detection, at a heliocentric veocity of $+8.2\ km\ s^{-1}$ we find an H I column density N(H I) of $1.2 \times 10^{20}\ cm^{-2}$. We note from the literature the detection of components along neighboring lines of sight to ϵ Per (Hobbs 1969a) and 48 Per (Hobbs 1974a) with comparable velocities of $+8$ and $+9.1\ km\ s^{-1}$, respectively, and with N(H I) of $3 \times 10^{20}\ cm^{-2}$ in both cases (Stokes 1978). We also note in Stokes (1978) the absence of a detection in δ Per. In addition, we note the absence of detections in the spectrum of HD 21038 and HD 27026 with limits given in the respective sections dealing with those objects. It is not easy, geometrically, to find a single cloud that satisfies all of these detection conditions, and also the temperature and pressure criteria we have been applying generally, viz., $P/k = 3600\ K\ cm^{-3}$ and $T \sim 100$ K, but it could be done just possibly using a bent "cigar-shaped" cloud somewhat flattened perpendicular to the direction of flow. This cloud would have a total mass of 350 $M_\odot$, a long axis of 30 pc, and a thickness of 3 pc, and its mean atomic hydrogen density n_H would be $36\ cm^{-3}$, if it were close to HD 20995, and with a lower mass and reduced length of the long axis if it were nearer to the Sun. There is no proof, however, that we are really dealing with such an elongated cloud, and a solution with two small separate clouds, one covering the line of sight to HD 20995 and the other the lines of sight to 48 Per and ϵ Per, is also possible. Solutions at somewhat higher or lower temperatures with correspondingly higher or lower masses are also possible. Whatever the precise morphology, we can again conclude that we are deaing with a cold ISM component, with typical cloud structure on the scale of a few parsecs.

3.14. *HD 27026*

We obtain only an upper limit to the K I absorption along the line of sight to this star, which is at 150 pc from the Sun and at $l = 159°$, $b = -6$. This limit, as for the case of HD 21038 (§ 3.12), is $3.8 \times 10^{20}\ cm^{-2}$, not a very low value, and can be used only as a very weak limit on the extent of the clouds detected toward HD 20995.

3.15. *HD 19698*

Toward this star, at $l = 168°$, $b = -38°$, at a distance of 150 pc we do not detect K I. The only literature object we have found, along a reasonably nearby line of sight, is Feige 24 at $d = 90$ pc observed by Dupree & Raymond (1982), whose N I detection was converted to an H I column density of $1.1 \times 10^{18}\ cm^{-2}$ by Frisch & York (1991). Our upper limit and this measurement are entirely consistent, and show that there is no important cold condensed H I cloud along the line of sight to HD 19698.

3.16. *HD 18883*

There is a good detection of K I toward this object, 150 pc distant from the Sun, in the direction $l = 173°$, $b = -45°$. The corresponding H I column density is $4.5 \times 10^{20}\ cm^{-2}$. The literature here does not allow us any very useful geometrical constraints perpendicular to the line of sight. There are no detected interstellar components in HD 19698 (the previous star in this sample), whose line of sight passes within 20 pc of HD 18883 to one side, while to the other side Stokes (1978) using Na I data from Hobbs (1974a) did note an interstellar absorption in the spectrum of λ Tau, but at a heliocentric veocity of $+22\ km\ s^{-1}$, very different from the $+6.1\ km\ s^{-1}$ we detect for the present object. These nondetections set an upper limit for the radius of a supposedly spherical cloud of 13 pc, and this would yield an H I density n_H of $6\ cm^{-3}$. Combining this with a pressure of $3600\ K\ cm^{-3}$ would yield a cloud of mass 750 $M_\odot$ with a temperature of 560 K, well above the limit for temperature stability of cool clouds. Although Frisch, York, & Fowler (1987) claim the presence of one cloud in this temperature range in the direction of α Oph, it is preferable to consider this size, and hence mass and temperature, as upper limits. We are in fact unable to set more exact values to the parameters of the cloud, but if we go on to assume that its temperature T is equal to 100 K, we find an object of 4 pc in diameter and a mass of 20 $M_\odot$. Clearly more detailed observational evidence is required here.

3.17. *HD 26793*

We are not able to detect K I in the spectrum of this star, which leaves us with an upper limit of 1.2×10^{20} for N(H I) along the line of sight to the object. We are able to compare this limit with the weak detection of H I in the neighboring star λ Tau, given in Stokes as a column density N(H I) of $1.3 \times 10^{20}\ cm^{-2}$, obtained from measurements of Na I (Hobbs 1974a) with a heliocentric velocity of $+22\ km\ s^{-1}$. This star is some 10 pc away from HD 29793 and some 7 pc further away from us. We also find in the literature (Hobbs 1978b) a LISM component in the spectrum of μ Tau, corresponding to a column density N(H I) of $14.7 \times 10^{20}\ cm^{-2}$. We derive from Hobbs's (1978b) Na data a heliocentric velocity of near $+23\ km\ s^{-1}$ for this component, which is confirmed in the older though less reliable observation of Adams (1949). Since μ Tau is almost precisely along the same line of sight as HD 26793, and at a heliocentric distance of 190 pc, we infer that there is a cloud producing this component which extends from just this side of λ Tau to a few pc beyond it, cutting the line of sight to μ Tau but not extending as near to us as HD 26793. Although the sensitivity of our K I derived upper limit would allow a column density of up to $10^{20}\ cm^{-2}$ in N(H I) to go undetected, the geometry suggests that a cloud surrounding both HD 26793 and λ Tau, and going on to give a strong component in μ Tau, would yield a much stronger component in λ Tau than the column density observed. If we use the "canonical" values of $P/k = 3600\ K\ cm^{-3}$ and $T \approx 100$ K, implying a cloud density n_H of $36\ cm^{-3}$, the implied diameter and mass of the cloud would be 14 pc and 700 $M_\odot$, respectively. These values are perhaps on the high side for both Jeans mass and local surface density considerations, but we have no further observational constraints on the cloud. If it were a little cooler, or not spherical, then the size and mass would be correspondingly reduced, but these considerations are speculative.

3.18. *HD 43525*

In this star, situated at 68 pc from the Sun, and at $l = 2000^\circ.16$, $b = -2^\circ.99$, we obtain a K I detection which corresponds to an N(H I) of 1.6×10^{20} cm^{-2}. This star lies within the low-density region mapped by Paresce (1984) and verified to very low limits of neutral hydrogen column density by Welsh, Vedder, & Vallerga (1990), by Vladilo et al. (1985), and by Molaro, Vladilo, & Beckman (1986). In keeping with the findings in the present paper, the inhomogeneity of the LISM is such that it is not a complete surprise to find a neutral cloudlet in this low-density region. The only possible corroborative evidence is found in Stokes (1978), quoting measurements of K I and Na I by Hobbs (1974a) in the star λ Ori. In the spectrum of this object there appear three separate interstellar absorptions in Na I, the strongest of which (also detected in K I) appears complex, covering a velocity range from +26.6 to +32.5 km s^{-1}, compared with our detection in HD 43525 at +29.1 km s^{-1}. As λ Ori is at 500 pc from the Sun, it is legitimate to infer that a part of the complex seen could correspond to the cloudlet near HD 43525. The line of sight to λ Ori passes within 10 pc of HD 43525 and, taking the column density of the component in λ Ori, N(H I) $= 1.5 \times 10^{21}$ cm^{-2}, an upper limit, we find an upper limit to the density $n_{\rm H}$ of 50 cm^{-3}, a lower limit to the cloud temperature of 70 K, and a rough mass estimate of 700 $M_\odot$. This is a fair upper limit for a neutral cloud, being somewhat above the Jeans mass, but the discrepancy of less than a factor of 2 would be reconciled by a somewhat flattened geometry, or by modest temperature and density adjustments, all within reasonable error limits. An alternative interpretation ignoring λ Ori, and using only our own detection to obtain a total column density, would yield a cloud diameter of 1.5 pc and mass of $\lesssim 1\ M_\odot$. It is, of course, possible that we are seeing the last traces of a neutral cloud about to evaporate finally into the high-temperature low-density region surrounding it, although statistical arguments suggest that the cloud of a few hundred solar masses is the more probable solution. Here again, further examination of neighboring lines of sight would be required for a definitive answer.

4. THE INHOMOGENEITY OF THE COLD LOCAL INTERSTELLAR MEDIUM

In Figure 2 we show the approximate position and sizes of the clouds whose individual properties we have detailed above. The shaded circles are the projection of the clouds in the three principal planes in Galactic coordinates with the Sun as origin. The dotted circles represent initial guesses at the positions and sizes of particular clouds whose more probable sites are presented as closer to the Sun, shaded, and with a corresponding letter of identification. The diagram gives a fair idea of the distribution of the more important cold clouds within 200 pc of the Sun in the directions of observation. It illustrates the strongly inhomogeneous texture of the LISM and the low filling factor of the cold medium (in reality even lower than it appears in these two-dimensional representations). Although the inhomogeneity of the LISM is implicit in many of the studies showing the multiplicity of interstellar absorption components in, especially, Na I, it is striking to map in detail the microstructure shown clearly in Figure 2 which underlies the macrostructure shown in a map such as that of Paresce (1984) (who in fact stated clearly that he expected clumpiness to be found and that his map was the result of an averaging process). We have superposed Paresce's contours on our cross section in the Galactic plane (Fig. 2*a*), to bring out this point. Given the incompleteness of the present study in parameter space, in the angular range covered, in the number of lines of sight, and in the lower limit of H I column density, here we can only point the way to the need for more complete work along the same lines. The use of LISM absorptions in stellar spectra offers the advantage of being able to plot three-dimensional structure, but we must note the uncertainties in all such work implicit in the present limits to the accuracy of stellar distance measurement. The qualitative effect on an individual cloud will, in general, over these short distances, not be greater than 50% in estimated cloud masses. There might exist cases, however, where an error in distance could lead to the misidentification of a component and a consequently incorrect estimate of a cloud size. Detailed examination of the clouds in this study which fall between stars closely separated in angle suggest that reversing the distance order to these stars (ψ Per and HD 21278, for example) would make a reasonable interpretation much more difficult than the one adopted here. While raising a flag of caution, therefore, we see no reason here to change any conclusion about homogeneity.

5. GENERAL DISCUSSION AND CONCLUSIONS

We have seen in the previous section that the LISM in the directions observed is very inhomogeneous: the column densities in K I or Na I vary very sharply from one line of sight to a neighboring line of sight, when these are known to be separated by only a few parsecs at the distance of a given observed star. Characteristically, there are changes of order 10^{21} cm^{-2} in the observed column densities of H I in distances of ~ 5 pc perpendicular to the line of sight. Given the variation of our direction of observation with respect to any local flow direction (e.g., that of Crutcher 1982) and the fact that this characteristic scale length of column density variation does not change from one direction to another, the simplifying assumption of sphericity for the clouds giving rise to the observed K I and Na I absorption is not likely to be far from the true situation (and in any case, no qualitative conclusion we draw depends on absolute sphericity; flattened clouds with axial ratios up to 4 would give similar physics). A spherical cloud of column density N(H I) $= 1 \times 10^{21}$ cm^{-2} and radius, say, 3 pc has a number density $n_{\rm H}$ of 50 cm^{-3} and a mass of $\sim 150\ M_\odot$. These values do not depend on any further assumption about the temperature of the cloud; they should be taken as typical rather than as any type of mean.

It is instructive to see to what extent our observational errors, and other uncertainties, might produce fundamental changes in our conclusions about these clouds. In the majority of our detections we have equivalent width uncertainties (due to signal-to-noise ratio considerations and the need to estimate correctly the continuum level) of ~ 1.5 mÅ. Taking the cloud detected toward HD 7034 as an extreme example, in which the detected equivalent width was only 3.8 mÅ, imposition of our uncertainty limits yields a range for the number density, of between 9 and 24 cm^{-3} (our best estimate was 17 cm^{-3}) and for the resulting cloud mass of between 109 and 293 $M_\odot$ (our best estimate was 210 $M_\odot$). For a more massive cloud, that toward HD 210129, with individual components of ~ 16.5 mÅ, the ranges would be from 30 to 37 cm^{-3} (our best value was 33 cm^{-3}) for the number density, and the cloud mass limits from

580 to 720 $M_\odot$, bracketing our best estimate of 640 $M_\odot$. Thus our own internal errors give rise to significant but not qualitative uncertainties in the detailed numerical conclusions reached about the mass fraction of the cool component of the LISM, described below. A better estimate of these effects would require a good mass function for the clouds, which is, at this stage, beyond our scope.

A cloud with a number density of 50 cm^{-3} in pressure equilibrium in the LISM will have a temperature of $\sim$70 K, assuming that the general pressure is a uniform 3600 K cm^{-3}. At this temperature, the Jeans mass would be a few hundred solar masses, so the mass of the cloud as inferred will indeed be less than the Jeans mass, and therefore in pressure equilibrium with its warmer surroundings: the physical picture is self-consistent. Although the general pressure will not in fact be uniform, it would require departures from the literature value of more than a factor of 3 to change this picture, and there is no observational reason to believe that such major variations are common. The K I clouds that we have detected here fall, with one exception, into this regime. Their densities, masses, and temperature of course vary somewhat compared with this example. However, the two basic observations of column density and geometrical extent (the latter supported by the kinematic "tagging" of a given cloud) are sufficient to fix the parameters of the clouds and, in particular, their temperature range, within reasonable limits. There is one further, global, constraint that we can use to put an approximate upper limit on this temperature range. A count of the number density of separate clouds using the present sample as representative, but supplementing this from the observational literature sources quoted in the section on the individual clouds, gives us $\sim$1000 clouds within a 200 pc radius of the Sun. Using the conservative approach of assuming that there are no major interstellar contributions to the surface density from outside this sphere, and that the local gaseous surface density limit of 5 $M_\odot$ pc^{-2} (Kulkarni & Heiles 1987) is due entirely to these clouds, we can set a statistical upper limit to the mass of a single cloud of $\sim$1000 $M_\odot$. Combining this value with a typical column density of 10^{21} cm^{-2}, we would find a cloud density n_H of 20 cm^{-3}, and this would corresond to a pressure equilibrium temperature of 180 K. Thus, although an individual cloud could have a mass higher than 1000 $M_\odot$, the generic cloud with a column density measured in the range N(H I) = 10^{21} cm^{-2} could not exceed this mass, and hence $\sim$180 K marks a broad upper limit to the temperature of these clouds We can add that the radius of this typical hypothetical 1000 $M_\odot$ cloud would be $\sim$8 pc, and that this, too, can be considered large compared with a "typical" observation-limited radius of around half this value. Thus, without the need to invoke directly considerations of temperature stability limited by interstellar heating and cooling rates, we can see that the clouds we have detected in this way are a cool population, with characteristic temperatures around 100 K. They correspond to the stable cold phase predicted in models such as that of McKee & Ostriker (1977). While it clearly is not possible to set a lower limit to the cloud temperatures by the same style of physical reasoning we have used to set this upper limit, the fact that an individual cloud does typically span lines of sight separated by some 5 pc (as tagged by its velocity), together with the argument of approximate symmetry, can be used to associate a minimum radius, and hence a maximum density and minimum temperature, with its measured column density. In fact, the minimum radius would be just a little less than the 3 pc used as our example above, so that for N(H I) = 10^{21} cm^{-2}, lowest limit temperatures of 60–70 K can be set. There is one exception to this among the observed clouds, namely, the cloud toward HD 21455 and HD 23552, which has a measured N(H I) of 2×10^{21} cm^{-2} and an estimated temperature of 60 K. It was clear in discussing this cloud, however, that it is exceptional in several respects, notably in exceeding its own thermal Jeans mass (and therefore probably requiring magnetic support) and because its opacity is sufficiently high that the linear relation between hydrogen column density and K I column density does not hold. This must be a cloud on the verge of "going molecular," and we have recommended observational tests of this prediction.

Naturally, all the quantities described here would be altered if the empirical relation we have used between N(K I) and N(H I) were changed. From the references used (Hobbs 1976; Ferlet et al. 1985) we can place a rather firm upper limit of 2 on the dispersion of the slope of the linear part of this relation, where all but one of our clouds lie. This would correspond to changes in densities and masses by a corresponding factor of 2, but would leave our qualitative conclusions unchanged.

We can estimate the number of these cold clouds within 200 pc of the Sun, based on the present data and literature data, at some 1000, so that their total volume is some 5×10^5 pc^3, which is some 1.5% of the total volume. In site of the low filling factor, we find a value of 96% for the mass fraction in this cold component, assuming that the rest of the volume is filled with warm gas with number density 0.1 cm^{-3}, ignoring the fact that a notable fraction of the gas is hot and at much lower density, and ignoring the contribution from cold clouds with column densities less than 1.2×10^{20} cm^{-2} which are not picked up using the K I line. In the small sector of the immediate solar neighborhood observed here, we have found only one cold cloud with a possible molecular component, but, as the present sample is small, we can draw no statistical conclusions from this.

The estimates of mass and volume fractions presented here are indeed still subject to serious uncertainties as detailed in the test. However, even with the unrealistic assumption that all uncertainties are combined linearly, an extreme error of a factor of 5 in the masses of the clouds ensues. This would lead to a highly conservative lower limit to the mass fraction of the cold clouds of 80%. The extreme upper limit to the volume fraction if the clouds were 5 times more, rather than less, massive than our best estimate would be some 8%. Thus the present study already strongly constrains these parameters, and these constraints will clearly tighten with time as more precise individual parameters are measured.

The use of K I for these observations has avoided the interpretational problems due to the complexity of the underlying stellar spectra, and the specific range of interstellar temperatures sampled by the resonance lines of Ca II and Mg II, and due to multiple blending. The price paid is the raised lower limit to the cloud column density sampled. Measurements of small cloud masses corresponding to column densities below 10^{20} cm^{-2} need Na I data. An adequate overall approach will require combination of the information from these and other species for the same volume of local space.

We are grateful to E. Barnett and R. J. García López for considerable help with the echelle instrumentation. We thank the observatory staff for their assistance in the use of the

William Herschel Telescope operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The anonymous referee's comments have helped us to make quantitative improvements to this paper.

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