

STUDIES OF H I AND D I IN THE LOCAL INTERSTELLAR MEDIUM

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ABSTRACT

We present high-dispersion *IUE* spectra of the hydrogen Ly α chromospheric emission line of two nearby late-type stars, Capella ($d = 13.2$ pc, $l = 163$, $b = 5$) and λ And ($d = 24$, $l = 110$, $b = -15$). Both interstellar H I and D I Ly α absorption can be seen against the chromospheric line, and we have derived the density, velocity dispersion, and bulk velocity of the gas in those lines of sight. We have also placed limits on the D/H ratio. Our results are consistent with the current picture of the local interstellar medium (LISM), as we obtain a total column density of $\sim 10^{18}$ cm $^{-2}$ toward both stars with velocity dispersions of ~ 13 km s $^{-1}$ (10^4 K). We place relatively high lower limits of 2.4×10^{-5} and 3.9×10^{-5} on the D/H ratio toward Capella and λ And, respectively, strongly indicative of variations in $n_{\text{D I}}/n_{\text{H I}}$ on the small scales in the LISM.

Subject headings: interstellar: abundances — stars: individual (α Aur, λ And) — ultraviolet: spectra

I. INTRODUCTION

Most of our knowledge of the local interstellar medium (LISM)—the material within 50 pc of the Sun—has come from absorption line spectroscopy; i.e., the study of interstellar absorption lines in the spectra of nearby stars. This technique is limited primarily by two factors: the relatively short path-lengths, and thus column densities, involved; and the limited number of stars bright enough that absorption lines may be seen in their spectra, and it is only recently, with the advent of space-based observatories such as the *Copernicus* and *International Ultraviolet Explorer* satellites and with better ground-based instrumentation, that the full complexity of the LISM is beginning to be understood.

The current picture of the LISM (see the reviews by Bruhweiler 1984 and Bruhweiler and Vidal-Madjar 1987) is that we are located inside a warm, low-density ($n_{\text{H I}} \sim 0.1$ cm $^{-3}$, $T \sim 10^3$ – 10^4 K) cloud which, in turn, is embedded in a still lower density, hot ($n_{\text{H I}} \sim 10^{-2}$ – 10^{-3} cm $^{-3}$, $T \sim 10^6$ K) substrate. This local cloud is rather asymmetrically distributed around the Sun, extending to a total column depth of 10^{19} cm $^{-2}$ toward the Galactic center, but only 10^{18} cm $^{-2}$ in most other directions. The gas in the cloud has a bulk motion coming from the general direction of the nearby Sco-Oph association, but high-resolution observations reveal that this bulk flow is broken up into several velocity components (Lallement, Vidal-Madjar, and Ferlet 1986), with structure on scales as small as 5 pc, perhaps as a result of shocks from recent supernovae in the Sco-Oph association.

In this work, we will present the results of observations of the chromospheric Ly α emission line of two nearby cool stars made with the short-wavelength prime (SWP) camera aboard the *IUE* satellite in the high-dispersion mode ($\lambda/\Delta\lambda \sim 10,000$). The interstellar H I Ly α absorption line is seen in absorption against the (much broader) stellar line and, from profile fitting, we have determined the density, temperature, and bulk velocity of the H I in the line of sight to the stars. The interstellar D I Ly α line is also seen at its isotopic blueshift of 0.332 Å and we have placed limits on the cosmologically important D/H ratio in the same directions. At present, *IUE* observations of nearby, late-type stars is the only method of directly determining the H I and D I parameters in the LISM.

II. OBSERVATIONS AND DATA ANALYSIS

Our observation log is given in Table 1. We observed the two stars on the two days of observations; λ And required a 16 hr *IUE* shift while Capella was bright enough that we could obtain two useful spectra in an 8 hr shift. All of the observations were made using the SWP camera in the high-dispersion mode with the star centered in the small aperture and the large aperture closed (to minimize geocoronal contamination).

The standard IUESIPS software (Turnrose *et al.* 1984), with one modification, were used to process the raw data. In the IUESIPS procedure, the local background is extracted from between the orders in the *IUE* camera. However, because the orders are very crowded at the short-wavelength end of the camera the point spread function of the instrument is a significant fraction of the interorder separation, and the extracted background may be contaminated by a strong emission line, such as the stellar Ly α line. The end result of this is that the

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TABLE 1
OBSERVING LOG

Star	Image	Date	Exposure Time (minutes)
Capella (α Aur)	SWP 34165	1988 Sep 1	90
	SWP 34166	1988 Sep 1	90
λ And	SWP 32845	1988 Jul 20	800

camera background is overestimated by the IUESIPS procedure, and thus the net signal is underestimated. This problem was easily corrected by replacing the background spectrum used by IUESIPS with one where the affected region was patched over with data from the neighboring wavelength region.

The spectra obtained for each of the two stars are shown as $\pm 1 \sigma$ error bars in Figures 1 and 2, respectively. (Although we obtained two useful spectra for Capella, co-addition did not significantly improve the signal-to-noise ratio, and we have just shown the higher quality spectrum in Fig. 1.) The error bars were derived by adding in quadrature the camera noise, estimated from the rms deviations in a flux-free region near the Ly α line, and the photon noise, assuming a 12:1 signal-to-noise ratio (Joseph 1985).

The modeling procedure was the same for each star and consisted of minimizing the χ^2 goodness-of-fit of an eight-parameter model to the data. The model was comprised of a Gaussian stellar emission profile, with the height and the FWHM as free parameters, multiplied by Voigt absorption profiles for the interstellar H I and D I absorption lines, with the H I column density, the velocity dispersion, the bulk velocity, and the D/H ratio as free parameters. (The two remaining free parameters were the zero level for the spectrum and the shift of the line center from its nominal position [1215.57 Å] to allow for small errors in either the wavelength scale or in the stellar radial velocity.) Before comparison with the data, the model profile was convolved with the instrumental profile (a Gaussian of FWHM 0.1 Å). The best-fit models to the two stars are shown as solid lines in Figures. 1 and 2, respectively.

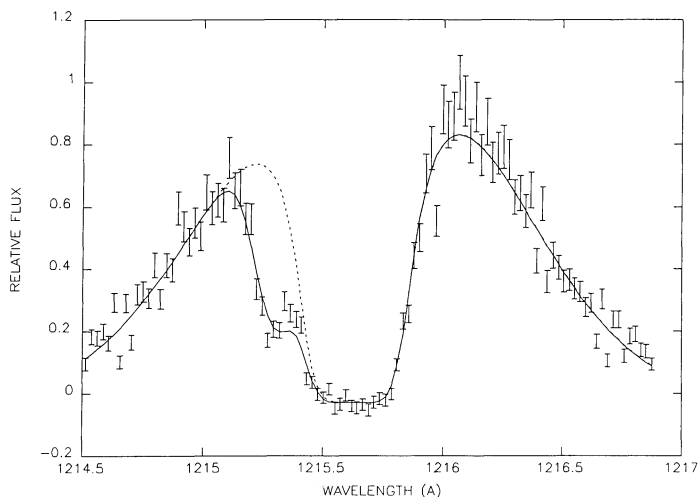


FIG. 1.—The reduced spectrum of Capella (SWP 34166) is shown as $\pm 1 \sigma$ error bars with the best-fit profile (solid line) superposed. Also plotted (dashed line) is a profile with the same parameters as the best-fit model, but with the effects of interstellar D I absorption removed.

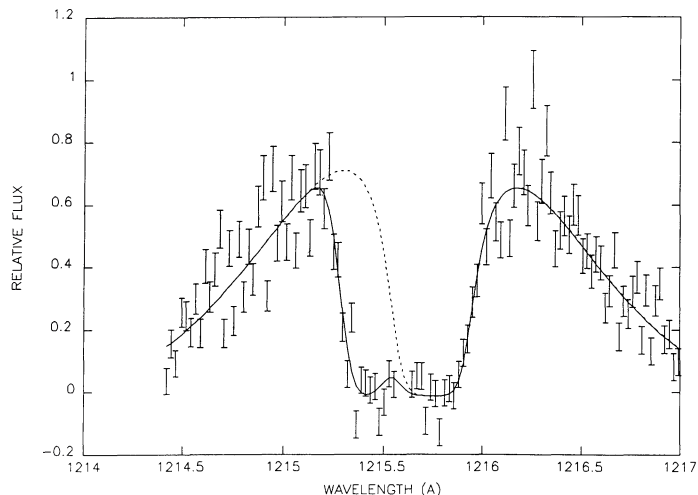


FIG. 2.—The reduced spectrum of λ And is shown as $\pm 1 \sigma$ error bars. As in Fig. 1, the solid line is the best-fit model profile, and the dashed line is a model with the same parameters except that the interstellar D I density was set to zero. The minimal effects of geocoronal Ly α contamination may be seen from the gap in the middle of the H I absorption feature where three points were deleted in the middle of the spectrum.

The best-fit values of the parameters of interest (n_{HI} , b_{HI} , $n_{\text{D I}}/n_{\text{HI}}$, and v_{HI}) are, themselves, of limited utility as there are broad ranges for each parameter which yield almost as good a fit to the data, primarily because both the H I and D I lines fall near the flat part of the curve of growth, where there can be large trade-offs between the column density and the velocity dispersion. All of the above parameters, except for v_{HI} , are closely inter-related and perhaps the most informative presentation of these parameters is in the form of confidence contour plots, as per the method of Lampton, Margon, and Bowyer (1976). These plots, which are shown in Figures 3 and 4, represent the projection onto the plane formed by the two parameters of interest of the eight-dimensional hypersurface bounded by the specified confidence level. The use of the contour plots is best illustrated by example. Figure 3a shows the 50% (dashed line) and 90% (solid line) confidence levels for $n_{\text{D I}}/n_{\text{HI}}$ versus n_{HI} toward Capella. From the figure we can place 90% confidence limits of $2.4\text{--}6.0 \times 10^{-5}$ on $n_{\text{D I}}/n_{\text{HI}}$, regardless of n_{HI} , or if we specify $n_{\text{HI}} = 0.03 \text{ cm}^{-3}$ then we can place the much tighter 90% confidence limits of $2.9\text{--}3.9 \times 10^{-5}$ on $n_{\text{D I}}/n_{\text{HI}}$.

There are two major assumptions implicit in our modeling procedure—that the stellar line may be modeled by a simple Gaussian and that there is but a single velocity component along the line of sight to each of our target stars.

The first assumption may be justified by noting that the interstellar H I Ly α line is always saturated for any line of sight in the LISM and so completely obscures any structure, such as self-reversal, which may be present in the center of the stellar profile. If we do not include too much of the stellar wings, where line-blanketing and other effects may become important, the stellar parameters should be reasonably well fitted by a Gaussian, and the derived interstellar parameters should be virtually independent of stellar type. This has been borne out by Landsman *et al.* (1986), who found similar values of the interstellar parameters toward both components of the α Cen binary system (α Cen A [G2V] and α Cen B [K1V]), despite their very different spectral types.

A complication may arise in the case of spectroscopic binaries, such as Capella, where the observed Ly α profile is

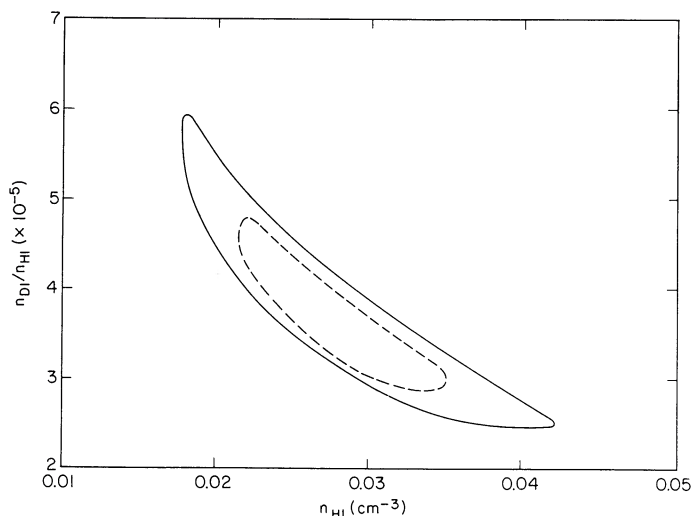


FIG. 3a

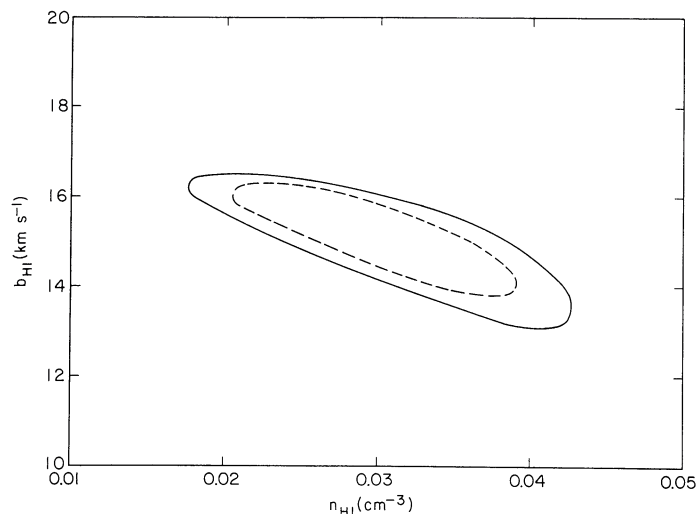


FIG. 3b

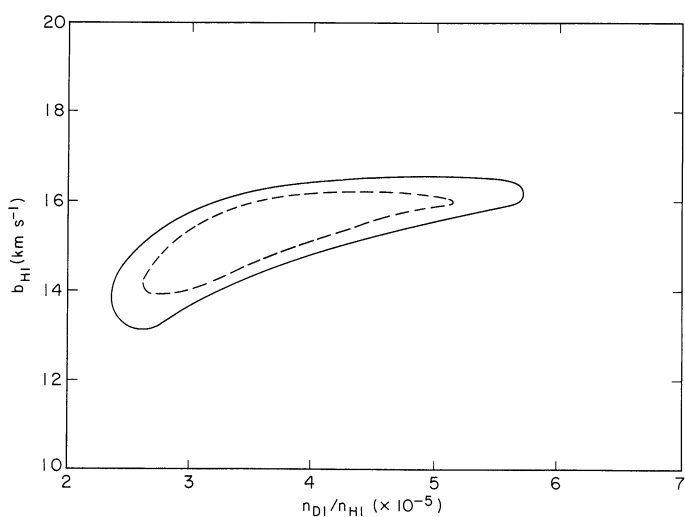


FIG. 3c

FIG. 3.—Confidence contour plots of (a) b_{HI} vs. n_{HI} , (b) $n_{\text{DI}}/n_{\text{HI}}$ vs. n_{HI} , and (c) b_{HI} vs. $n_{\text{DI}}/n_{\text{HI}}$ are plotted for Capella (SWP 34166). The solid line represents the 90% confidence contour, while the dashed line represents the 50% confidence contour. (See the text for an explanation of how to use these plots.)

made up of contributions from both stars, which, if not observed at conjunction, may cause the combined profile to be asymmetric. As interstellar absorption, itself, may give rise to an asymmetry in the observed profile, especially if the difference between the stellar radial velocity and the velocity of the gas in that direction is large, the derived interstellar parameters may be incorrect. For this reason, we attempted to observe Capella as close to conjunction as possible but, due to the constraints of *IUE* scheduling, instead observed it at a phase of 0.10. Fortunately, Ayres and Linsky (1980) found that both components of the Capella binary system have relatively strong Ly α emission lines, and Murthy *et al.* (1987) found little difference in the interstellar parameters derived from observations of Capella at different phases.

The second assumption is perhaps more difficult to justify as we know that there are at least three velocity components toward Altair (Ferlet, Lallement, and Vidal-Madjar 1986), at a

distance of only 5 pc, which are blended together in Ly α to simulate a much hotter, denser medium in the line of sight (Murthy *et al.* 1987). However, the lines of sight in this work are all in the direction of the near edge of our local cloud where the column density is low and there is likely to be no more than one component, whereas Lallement, Vidal-Madjar, and Ferlet (1986) observed multiple velocity components in directions where the H I density was high. In addition, as will be shown later, the data toward the two stars themselves favor the ideal of but a single velocity component in the observed directions.

III. RESULTS AND DISCUSSION

Our results are summarized in Figures 3 and 4 and are tabulated in Table 2. In the following paragraphs, we will discuss the interstellar parameters derived in this work toward each of our stars, and we will place them in the context of previous observations of the same lines of sight.

The first observations of the interstellar Ly α absorption toward Capella were made by Dupree, Baliunas, and Shipman (1977) with the Princeton spectrometer aboard the *Copernicus* satellite. From these observations, they estimated H I densities of 0.02–0.04 cm^{-3} , a velocity dispersion of 10 km s^{-1} , and a D/H ratio of 2.2–9.6 $\times 10^{-5}$, results later confirmed by Murthy *et al.* (1987) through the analysis of three small-aperture *IUE* spectra. (These spectra had originally been taken and analyzed from a stellar point of view by Ayres and Linsky 1980 and Ayres, Schiffer, and Linsky 1983.)

All of the previous observations had been made at phases other than zero which, as discussed in the last section, may lead to an asymmetric observed stellar profile and thus an error in the derived interstellar parameters. We therefore obtained an exposure of Capella near conjunction again obtaining results similar to those previously claimed— $0.014 < n_{\text{HI}} < 0.046 \text{ cm}^{-3}$, $12.6 < b_{\text{HI}} < 17.1$, $2.4 \times 10^5 < n_{\text{DI}}/n_{\text{HI}} < 6.0 \times 10^{-5}$. (These values are based on an analysis of SWP 34166, the much higher quality spectrum. An analysis of SWP 34165 yields consistent, but larger, ranges and we will not list them here.) An examination of Figure 1 shows that we have some problems in fitting the data near the D I feature and the long-wavelength peak, possibly due to deviations of the combined stellar profile from a Gaussian. Nevertheless, the similarity of

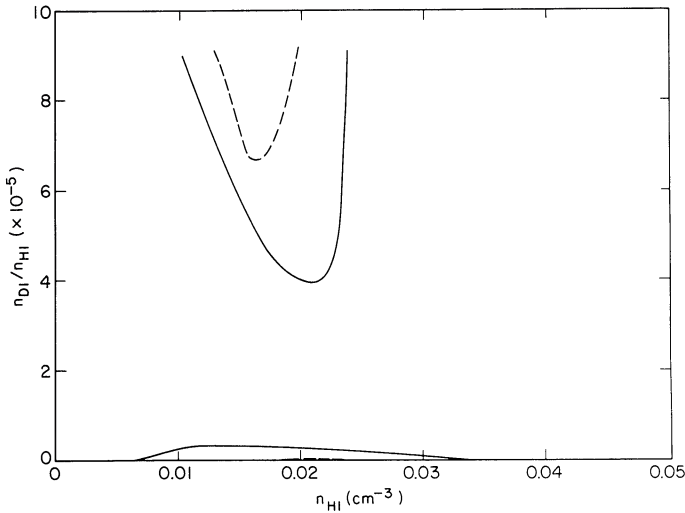


FIG. 4a

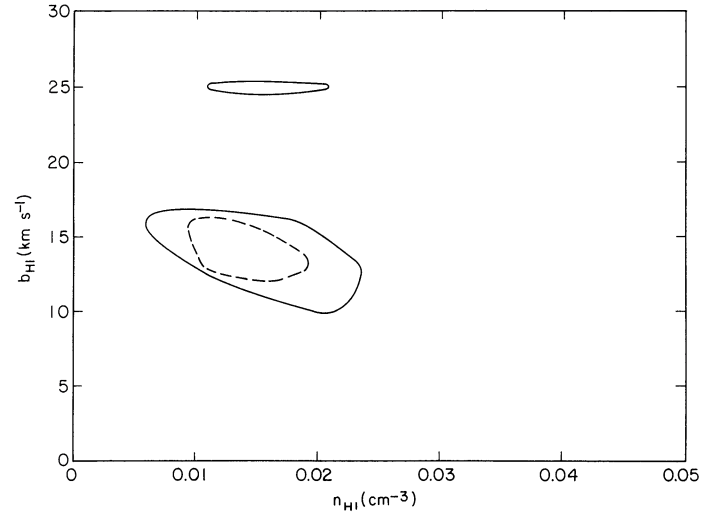


FIG. 4b

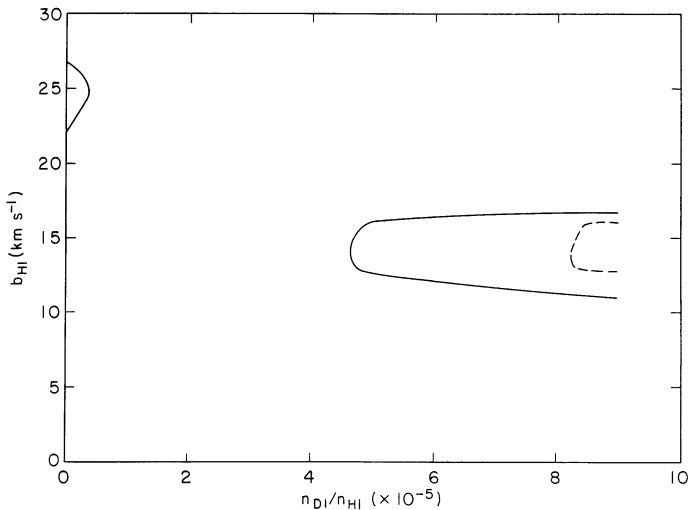


FIG. 4c

FIG. 4.—Confidence contour plots of (a) b_{HI} vs. n_{HI} , (b) $n_{\text{D I}}/n_{\text{H I}}$ vs. $n_{\text{H I}}$, and (c) b_{HI} vs. $n_{\text{D I}}/n_{\text{H I}}$ are plotted for λ And. The solid line represents the 90% confidence contour while the dashed line represents the 50% confidence contour.

our derived parameters to those previously reported is a good measure of the robustness of our procedure.

There is only one previous study of interstellar Ly α absorption toward λ And, by Baliunas and Dupree (1979) using the *Copernicus* satellite. Despite extensive geocoronal Ly α con-

tamination and a rather poor signal-to-noise ratio, they estimated a density of $0.03\text{--}0.08\text{ cm}^{-3}$ for the neutral hydrogen with a velocity dispersion of $10\text{--}12\text{ km s}^{-1}$ and a D/H ratio of $0.13\text{--}0.50 \times 10^{-5}$. Our results are somewhat different— $0.0058 < n_{\text{HI}} < 0.024\text{ cm}^{-3}$; $9.7 < b_{\text{HI}} < 16.8\text{ km s}^{-1}$; and $3.9 \times 10^{-5} < n_{\text{D I}}/n_{\text{H I}}$ —and are probably superior due to the higher quality of our data and the lack of significant geocoronal contamination. Of particular importance is the lower limit of 3.9×10^{-5} on $n_{\text{D I}}/n_{\text{H I}}$, the highest such limit reported in the LISM.

The high deuterium abundance is needed in our model fitting because of the width of the interstellar absorption line, and an examination of Figure 4 reveals that there is another solution, at the 90% confidence level, where we have a large velocity dispersion ($b_{\text{HI}} \sim 25\text{ km s}^{-1}$) and a low D/H ratio. Such a high-velocity dispersion would indicate the presence of at least two velocity components in that line of sight, which could compromise our derived parameters. However, we can exclude this solution at the 50% confidence level, and, in addition, the similarity of the H I density and velocity dispersion (in the lower χ^2 solution) to those found toward other cool stars (Murthy *et al.* 1987) argue for but a single component.

The bulk velocity of the gas in the line of sight is quite well determined from the center of the interstellar absorption line which, itself, can be found with some accuracy because of its boxlike shape. We have listed the bulk velocities (in the heliocentric frame) of the H I in the two lines of sight in Table 2, and these velocities are consistent with the general picture of a wind coming from the direction of the Sco-Oph association, as found by Crutcher (1982).

TABLE 2
SUMMARY OF RESULTS

Star	l	b	d (pc)	$n_{\text{H I}}$ (cm^{-3})	$b_{\text{H I}}$ (km s^{-1})	$N(\text{H I})$ ($\times 10^{17}\text{ cm}^{-2}$)	$n_{\text{D I}}/n_{\text{H I}}$ ($\times 10^{-5}$)	$v_{\text{H I}}$ km s^{-1}
Capella ^a	163	5	13.2	0.016–0.043	13.1–16.8	6.5–17.5	2.8–4.8	28.1–33.1
Capella ^b				0.014–0.046	12.6–17.1	5.7–18.7	2.4–6.0	27.7–33.6
λ And ^a	110	–15	24	0.0068–0.021	10.9–16.0	5.0–15.5	> 6.6	9.0–23.5
λ And ^b				0.0059–0.024	9.7–16.8	4.4–17.7	> 3.9	–1.8–25.8

^a 50% confidence levels.

^b 90% confidence levels.

TABLE 3
INTERSTELLAR PARAMETERS

Star	l	b	d (pc)	$n_{\text{H I}}$ (cm^{-3})	$b_{\text{H I}}$ (km s^{-1})	$N(\text{H I})$ ($\times 10^{17} \text{ cm}^{-2}$)	$n_{\text{D I}}/n_{\text{H I}}$ ($\times 10^{-5}$)	$v_{\text{H I}}$ km s^{-1}
α Cen A	316	-1	1.3	0.03 - 0.21	> 11	1.2-8.4	> 8.1	-11.7 to 17.7
α Cen B	316	-1	1.3	< 0.15	> 14.3	< 6.0	> 1.5	-13.6 to -17.4
ϵ Eri	196	-48	3.3	0.01 - 0.27	3.3-16.6	2.4-28	> 0.6	7.3 to 15.4
Procyon	214	13	3.5	0.09 - 0.2	3.4-14.8	9.7-22	> 0.8	20.8 to 27.2
β Gem	192	23	10.8	< 0.15	15-22
HR 1099	185	-41	33	0.009-0.016	< 13.1	9.1-16	> 0.09	20.4 to 30.4

NOTES.—All values are at the 50% confidence level and are taken from Murthy *et al.* 1987, except for those for β Gem which were from Murthy *et al.* 1989.

IV. SUMMARY AND CONCLUSIONS

This work, in all likelihood, represents the culmination of our small-aperture *IUE* study of the LISM, and it is appropriate at this time to summarize the results of our program (Table 3). We have observed a total of nine late-type stars, ranging in distance from the α Cen system at 1.3 pc to HR 1099 at 33 pc, all of which (except for α Cen A and B and Altair) lie away from the Galactic center toward the near edge of the local cloud (Fig. 5).

Our results confirm much of the picture of the LISM presented in § I. We find very similar column densities ($< 10^{18} \text{ cm}^{-2}$) and velocity dispersions ($\sim 13 \text{ km s}^{-1}$) toward all of our observed stars, except for Altair, implying that there is a single cloud in that quadrant, extending not more than ~ 3.5 pc from the Sun (the distances of ϵ Eri and Procyon) with very little material beyond until at least λ And and HR 1099, at distances of 24 and 33 pc, respectively. We have only observed three stars in the other direction, toward the thick part of the cloud, and of these α Cen A and B are only 1.3 pc away, and the line of sight to Altair has multiple velocity components in it (Ferlet, Lallement, and Vidal-Madjar 1986), rendering it impossible for us to extract any useful information about the H I in that direction (Murthy *et al.* 1987), so we can say very little about the extent of the nearby gas in that direction.

Our bulk velocities are all roughly consistent with the projection into the relevant line of sight of the interstellar wind vector of $(l, b, v) = (25, 10, -28 \text{ km s}^{-1})$ found by Crutcher (1982), but there are deviations, such as toward the α Cen system where we find a bulk velocity of -15 km s^{-1} , considerably more than the projected flow velocity of -9.8 km s^{-1} . There are also some discrepancies within our data set, itself, as the velocity ranges for ϵ Eri and HR 1099, which lie only 11° apart in the sky, do not overlap, perhaps indicative of a non-uniform velocity field, even in the direction of the near edge of the local cloud.

We have placed a stringent lower limit (at the 90% confidence level) of 4.0×10^{-5} on $n_{\text{D I}}/n_{\text{H I}}$ toward λ And, the highest such lower limit reported in the LISM, and 2.4×10^{-5} on $n_{\text{D I}}/n_{\text{H I}}$ toward Capella. Our own results are all consistent with a uniform D/H ratio of 4×10^{-5} (however, Murthy *et al.*

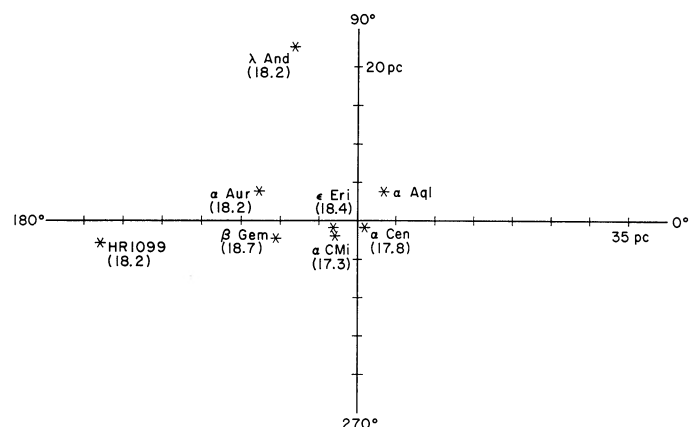


FIG. 5.—The distribution of all our observed stars is shown as a function of Galactic longitude and distance (with projection effects due to latitude ignored). We have also given the log of the maximum column density to each star (from Tables 2 and 3). Note that the column densities are very similar toward each of the stars with the smallest values being toward the more distant stars, showing that the Sun must be near the edge of the local cloud. We were unable to derive a maximum density to Altair because of the multicomponent velocity structure along that line of sight (see Murthy *et al.* 1987).

1987 have presented evidence that the D/H ratio toward HR 1099 is no more than 1.1×10^{-5} if $b_{\text{H I}} > 10 \text{ km s}^{-1}$), but Vidal-Madjar *et al.* (1986) concluded that there was an interstellar cloud with a D/H ratio less than 10^{-5} in the direction of λ Sco, which would imply significant variations in the D/H ratio in the LISM. It is difficult to understand such variations on the small scales in the LISM, unless perhaps as a tracer of shock processing, and one must await *Lyman* or the high-resolution spectrometer (HRS) aboard the *Hubble Space Telescope* with their higher resolution and greater sensitivity for a more detailed probing of the D I in the LISM.

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