OBSERVATIONS OF SMALL-SCALE INTERSTELLAR STRUCTURE IN DENSE ATOMIC GAS

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ABSTRACT

We present high-resolution (R ~ 170,000) Kitt Peak National Observatory coude feed telescope observations of the interstellar K I λ7698 line toward five multiple star systems with saturated Na I components. We compare the K I absorption-line profiles in each of the two (or three) lines of sight in these systems and find significant differences between the sight lines in three out of the five cases. We infer that the small-scale structure traced by previous Na I observations is also present in at least some of the components with saturated Na I absorption lines, and thus the small-scale structures traced by the neutral species are occurring at some level in clouds of all column densities. We discuss the implications of that conclusion and a potential explanation by density inhomogeneities.

Subject headings: ISM: clouds — ISM: structure

1. INTRODUCTION

There is convincing evidence from recent radio and optical observations that the diffuse interstellar medium (ISM) exhibits significant subparsec-scale variations down to limits of a few AU (Frail et al. 1994; Davis, Diamond, & Goss 1996; Meyer & Blades 1996; Watson & Meyer 1996). On somewhat larger scales, strong variations in interstellar Na I profiles are observed toward multiple late-type stars in globular clusters (Langer, Prosser, & Sneden 1990; Bates et al. 1995). In some cases, the inferred densities of these structures far exceed the nominal diffuse cloud values and approach those of molecular cloud cores. For example, Frail et al. (1994) found pervasive variations in the H I opacity on scales of 5–100 AU utilizing multiechelle observations of 21 cm absorption toward high-velocity pulsars, which implied densities of n_H ~ 10^4–10^5 cm^-3. It is not clear how such small, dense structures can arise or be maintained in the low-pressure environments of diffuse clouds.

One difficulty with using the Na I D lines as a tracer of small-scale structure is the increasing saturation of these lines as one goes to larger H I column densities. Thus, the bulk of the gas in heavily reddened sight lines cannot be sampled using the D lines, and one is generally limited to identifying variations in the weaker wings of the line. A potential probe of these sight lines is the K I λ7698 line. The lower cosmic abundance of K I coupled with differences in density in the clouds using the observed K I column variations.

2. OBSERVATIONS

The observations were obtained in 1998 June with the 0.9 m coude feed telescope and spectrograph at KPNO using camera 6 in echelle mode and a Ford 3000 × 1000 pixel CCD chip. The resolution of the data was measured using the ThAr lamp emission lines and is ≈1.75 km s^-1 at the location of the K I λ7698.974 line. A total of five systems were observed: four binaries or common proper motion doubles and one triple system (see Table 1). Observations of the stars α Aql and α Leo were obtained as a template for dividing out telluric absorption in the vicinity of the K I λ7698 line. For the majority of the stars, exposures were taken on different nights at different grating tilts to reduce the effect of any flaws in the CCD chip. However, because of poor weather conditions, observations of ρ Oph were limited to a single night and only a single exposure was obtained for HD 206267D.

Reduction of the data was done with the NOAO IRAF echelle data reduction package. The individual frames were first bias-subtracted and flat-fielded, then the scattered light was removed. For all stars except ρ Oph, the individual orders were then extracted and cleaned of cosmic-ray hits. Since both members of the binary ρ Oph were in the slit, only the portions of the combined stellar profile that were dominated by either one of the two stars were extracted. All of the resulting one-dimensional spectra were then wavelength calibrated, shifted to heliocentric coordinates, summed, and finally continuum fitted using low-order polynomials. Figures 1 and 2 show the final K I line profiles. The resulting signal-to-noise (S/N) ratios for these observations vary widely, from as low as ~20 for the faint star HD 206267D to as high as ~130 for β^3 Sco. Column densities, bvalues, and relative velocities of the various components were derived by profile fitting with the programs XVOIGT (Mar & Bailey 1995) and FITS6P (Welty, Hobbs, & York 1991). The wavelength and oscillator strength of the

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2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
K λ7698 line were taken from Morton (1991); the inclusion of hyperfine splitting (Welty, Hobbs, & Kulkarni 1994) in the fits does not significantly alter the derived columns or \( b \)-values. The column density, \( b \)-value, and velocity of the various components were free parameters in the initial fits, while in the final fits the velocities of the components were fixed, since the velocity differences between members of a system were smaller than the uncertainties. The resulting column densities are listed in Table 2; the listed uncertainties include contributions due to signal fluctuations, continuum placement errors, and the errors induced by uncertainty in the \( b \)-values. It must be noted that if there is unresolved component structure, the column density may be higher than that listed. In particular, higher resolution observations of \( \rho \) Oph A suggest that there are at least three distinct components making up what is fit here as a single main component along this line of sight (D. E. Welty 1998, private communication).

3. DISCUSSION

As seen in Figures 1 and 2, significant differences in the absorption profile were seen between the interstellar K lines toward the stars in three of the five systems. The detection of significant variation in the profiles of the K lines within the saturated cores of the (previously observed) Na I profiles shows that the small-scale structures occur even in regions of high column density. It should be noted that the detection of widespread variation in Na I and K I in multiple components makes a circumstellar origin for the observed small-scale structures significantly less tenable. For example, toward \( \beta \) Sco variations in Na I are observed at \( v \sim -24 \) km s\(^{-1}\) and in K I in the main component at \( v \sim -10 \) km s\(^{-1}\), with the enhancements in Na I and K I columns occurring toward different members of the binary. One also sees variations in multiple K I components toward the HD 206267 system, but one must note that the HD 206267 system bears a striking resemblance to the Trapezium (Abt 1986) and like the Trapezium is in a region of recent, active star formation. Thus, much of the variation toward this system may be in gas that is located relatively near the stars (although not circumstellar) and may be the result of interactions between the surrounding medium and stellar winds and/or associated with the H II region IC 1396 centered on HD 206267A (O’Dell et al. 1993). While large differences were not detected toward \( \rho \) Oph (HD 147933/4) or HD 161270/89, it is possible that significant variation could be hidden in the strong (possibly saturated) cores of these lines. In any case, the observed K I variations suggest that the small-scale structures previously identified using Na I are truly ubiquitous and occur even in highly reddened sight lines.

We can use the observed variations in the K I to infer the corresponding Na I variations for comparison with previous optical studies of small-scale structure. Hobbs (1974) identified a relationship between the total line-of-sight column densities of K I and Na I:

\[
N(\mathrm{K I}) \sim 0.012 N(\mathrm{Na I})^{1.2},
\]

where \( N(\mathrm{K I}) \) and \( N(\mathrm{Na I}) \) are in units of \( 10^{15} \text{ cm}^{-2} \). Assuming the above “typical” relationship between \( N(\mathrm{K I}) \) and \( N(\mathrm{Na I}) \), we see that the observed K I variations correspond to Na I variations as large as \( \sim 1.3 \times 10^{15} \text{ cm}^{-2} \). Thus, small-scale variations occur over 3 orders of magnitude in Na I column density (Meyer & Blades 1996; Watson & Meyer 1996; this Letter) and therefore represent more than a population of small, low column clouds. Furthermore, if we assume the “typical” relationship between \( N(\mathrm{K I}) \) and \( N(\mathrm{H I}) \) from Hobbs (1974), we can estimate the density \( n_\text{H}(\text{cm}^{-3}) \) in the structures responsible for the observed profile variations using the binary separation by assuming that variations in K I trace variations in H I. Then the observed \( N(\mathrm{K I}) \) differences imply \( n_\text{H} \gtrsim 10^4 \text{ cm}^{-3} \), similar to the densities inferred for a number of components in previous Na I studies (Meyer & Blades 1996; Watson & Meyer 1996). Such densities are also only slightly less than the densities \( n_\text{H} \sim 10^4 \text{ cm}^{-3} \) inferred by Frail et al. (1994) in their study of 21 cm absorption toward high-velocity pulsars.

The lack of observable changes in the Zn II column density in components in which the Na I column varies toward the binary \( \mu \) Crucis suggest that at least some fraction of the variation detected in the Na I studies is due to density, temperature, or ionization fraction fluctuations and is thus not indicative of variations in the hydrogen column density between the lines of sight (Lauroesch et al. 1998). If we assume that the observed K I variations are due to similar fluctuations, we can use the measured column density differences to estimate (albeit somewhat crudely) the difference in density and temperature in these structures. The recombination rate for potassium is proportional to \( \sim n_\text{H}T^{-0.7} \) (Péquignot & Aldrovandi 1986); if we assume a neutral ideal gas in pressure equilibrium, then the recombination rate will go roughly as \( \sim n_\text{H}n_\text{e}^{-2} \). Typically it is assumed that the \( n_\text{H}/n_\text{e} \) ratio is roughly constant in neutral interstellar clouds, with the dominant source of electrons being carbon atoms. Under this assumption we can then estimate required density contrast from the observed columns since \( N(\mathrm{K I}) \propto n_\text{H}^{17} \). We must note that as the density increases and/or the

| System | Alternate ID | \( V^b \) (mag) | \( E(B-V)^b \) (mag) | Separation\(^a\) (arcsec) | Separation\(^b\) (AU) |
|--------|--------------|----------------|----------------|----------------|----------------|
| HD 1442178 | \( \beta \) Sco | 2.64/9.9 | 0.21 | 13.6 | 2720 |
| HD 145502/1 | \( r \) Sco | 4.0/6.3 | 0.25 | 41.1 | 7200 |
| HD 147933/4 | \( \rho \) Oph | 5.0/5.9 | 0.48 | 3.2 | 740 |
| HD 161270/89 | ... | 6.2/6.6 | 0.07 | 20.6 | 2880 |
| HD 206267A/C/D | ... | 5.6/8.4/8.0 | 0.52 | ... | ... |

\(^a\) From the Yale Bright Star Catalog (Hoffleit & Jaschek 1982).
\(^b\) Derived using the observed \( (B-V) \) and spectral type from the Yale Bright Star Catalog (Hoffleit & Jaschek 1982) and the intrinsic colors from Mihalas & Binney 1981.
\(^c\) Projected separation between primary and secondary(s) based on the spectroscopic parallax using the spectral types given in the Yale Bright Star Catalog (Hoffleit & Jaschek 1982).
\(^d\) Triple system with separations of \( A-C \) 11.7, \( A-D \) 19.9, and \( C-D \) 31.76. These angular separations correspond to projected separations of 14,300, 24,300, and 38,550 AU, respectively.
temperature decreases in these clouds there will be a corresponding increase in the \( \frac{N(C\,\text{i})}{N(C\,\text{ii})} \) ratio and thus a corresponding decrease in the \( \frac{n}{n_{\text{H}}} \) ratio. However, if \( N(C\,\text{i}) \ll N(C\,\text{ii}) \) in both clouds, then the \( n_{\text{e}}/n_{\text{H}} \) ratio will be roughly constant. In any case, we will initially assume \( n_{\text{e}}/n_{\text{H}} \) is constant and then identify (if necessary) any cases in which a correction is required.

Table 2 lists the column densities from our profile-fitting analysis of these lines of sight. Based on the measured differences in the column densities for the various components, we have estimated the density contrast \( \delta n_{\text{H}} \) assuming an ideal gas with a constant \( n_{\text{e}}/n_{\text{H}} \), then

\[
\delta n_{\text{H}} = \left[ \frac{N(K\,\text{i})_{\text{strong}}}{N(K\,\text{i})_{\text{weak}}} \right]^{0.6},
\]

where we have defined the strong and weak components such that \( N(K\,\text{i})_{\text{strong}} > N(K\,\text{i})_{\text{weak}} \). Thus, all values of \( \delta n_{\text{H}} \) will be \( \geq 1 \). Looking at Table 2, we note that the estimated density differences are generally quite small, generally less than a factor of 2. This shows how relatively small density and temperature fluctuations can give rise to large differences in the column densities of neutral species.

There have been a number of simplifying assumptions made in the preceding argument that may not be correct. First, we have assumed that the observed column density differences reflect density and temperature fluctuations and not \( \text{H}\,\text{I} \) column variations. Despite the lack of \( \text{Zn}\,\text{II} \) column density variations along the lightly reddened \( \mu \text{Cru} \) line of sight (Lauroesch et al. 1998), the radio observations of pervasive variations in the 21 cm opacity toward pulsars and extragalactic radio sources imply that some (or even all) of these structures may be associated with \( \text{H}\,\text{I} \) column density variations. In addition, these structures may not be in pressure equilibrium with the sur-

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**Fig. 1.**—Observed interstellar \( K\,\text{i} \) profiles for both members of the binary star systems HD 144217/8 (\( \beta \text{Sco} \)), HD 145502/1 (\( \nu \text{Sco} \)), HD 147933/4 (\( \rho \text{Oph} \)), and HD 161270/89 taken using the KPNO coude feed telescope. Note that the vertical scale varies between plots. There are significant differences in the (relatively weak) profiles toward \( \nu \text{Sco} \) and \( \beta \text{Sco} \) and a lack of apparent variation in the strong (possibly saturated) lines toward \( \rho \text{Oph} \) and HD 161270/89.

**Fig. 2.**—Comparison of the Na \( \text{i} \) D line profiles and \( K\,\text{i} \) profiles observed toward the HD 206267 multiple star system. Note in particular the large number of variable components in the \( K\,\text{i} \) profile that are hidden within the broad saturated Na \( \text{i} \) profile. This shows the importance of \( K\,\text{i} \) as a probe of small-scale structure in regions of high column density.
Another possibility is that there are pervasive fluctuations in the nature of these structures be fully explored. Such ultraviolet observations will also enable the identification of any sight lines with H I column density enhancements similar to those inferred from radio studies. However, it must be noted that optical studies remain an efficient probe of small-scale structures and can be used to trace such structures on a variety of scales.

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### REFERENCES

Abt, H. A. 1986, ApJ, 304, 688
Bates, B., Shaw, C. R., Kemp, S. N., Keenan, F. P., & Davies, R. D. 1995, ApJ, 444, 672
Davis, R. J., Diamond, P. J., & Goss, W. M. 1996, MNRAS, 283, 1115
Frail, D. A., Weisberg, J. M., Cordes, J. M., & Mathers, C. 1994, ApJ, 436, 144
Hobbs, L. M. 1974, ApJ, 191, 381
Hoffleit, D., & Jaschek, C. 1982, The Bright Star Catalogue (New Haven: Yale Univ. Obs.)
Langer, G. E., Prosser, C. F., & Sneden, C. 1990, AJ, 100, 216
Lauroesch, J. T., Meyer, D. M., Watson, J. K., & Blades, J. C. 1998, ApJ, 507, L89
Mar, D. P., & Bailey, G. 1995, Proc. Astron. Soc. Australia, 12, 239
Meyer, D. M., & Blades, J. C. 1996, ApJ, 464, L179
Mihalas, D., & Binney, J. 1981, Galactic Astronomy: Structure and Kinematics (2d ed.; San Francisco: Freeman)
Morton, D. C. 1991, ApJS, 77, 119
O’Dell, C. R., Valk, J. H., Wen, Z., & Meyer, D. M. 1993, ApJ, 403, 678
Péquignot, D., & Aldrovandi, S. M. V. 1986, A&A, 161, 169
Watson, J. K., & Meyer, D. M. 1996, ApJ, 473, L127
Welty, D. E., Hobbs, L. M., & Kulkarni, V. P. 1994, ApJ, 436, 152
Welty, D. E., Hobbs, L. M., & York, D. G. 1991, ApJS, 75, 425

### TABLE 2: COLUMN DENSITIES

| System                  | Velocity (km s\(^{-1}\)) | \(n(K)\) \(t\) \((\times 10^{19} \text{ cm}^{-2})\) | \(b\)-values \((\text{km s}^{-1})\) | \(\delta n_{i,j}\) \((\text{cm}^{-2})\) |
|-------------------------|--------------------------|-----------------------------------------------|-----------------------------------|----------------------------------|
| HD 1442178              | −9.9                     | 12.3 ± 1.0/16.6 ± 2.4                         | 0.4 ± 0.1                         | 1.2                              |
| HD 145502/1             | −9.3                     | 11.5 ± 0.8/13.1 ± 1.3                         | 0.7 ± 0.1                         | 1.1                              |
| HD 147933/4             | −7.8                     | 7.1 ± 1.0/2.6 ± 1.1                           | 0.3 ± 0.1                         | 1.8                              |
| HD 161270/89            | −16.5                    | 6.1 ± 1.0/4.4 ± 2.3                           | (0.2)                             | 1.2                              |
| HD 206267A/C/D         | −18.9                    | 117 ± 18/118 ± 22                             | 1.3 ± 0.1                         | <1.3                             |
| HD 206267A and C        | −12.5                    | 1.7 ± 0.5<1.3                                | 0.9 ± 0.3                         | >1.0                             |
| HD 206267A and C due to the relatively large uncertainties in the fits to the lower S/N ratio data for HD 206267D. |