Birkbeck
UNIVERSITY OF LONDON

BIROn - Birkbeck Institutional Research Online

Crawford, Ian and Dunkin, S.K. (1995) Ultra-high-resolution observations of Ca+ ions in the local interstellar medium. Monthly Notices of the Royal Astronomical Society 273 (1), pp. 219-224. ISSN 0035-8711.

Ultra-high-resolution observations of Ca⁺ ions in the local interstellar medium

I. A. Crawford and S. K. Dunkin
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT

ABSTRACT

We present ultra-high-resolution (0.3 km s^{-1} FWHM) spectra of the interstellar Ca K line towards the nearby stars α Oph, α Gru and α Eri. These are the highest resolution absorption-line spectra yet obtained of clouds located within the local interstellar bubble. They have enabled us to resolve the line profiles fully, and reveal structure within components which have, until now, been considered as arising in single clouds. The velocity dispersions (b-values) of the identified components all have well-determined values in the range 1.4-2.3 km s^{-1}, consistent with thermal broadening at temperatures in the range 5000-13 000 K.

Key words: line: profiles – ISM: atoms – ISM: bubbles – ISM: structure.

1 INTRODUCTION

It is now generally agreed that the Sun lies within a warm ($T \sim 7000$ K) low-density ($n_H \sim 0.1$ cm^{-3}) interstellar cloud (the Local Interstellar Cloud; LIC), which is itself located within the very hot ($T \sim 10^6$ K) and empty ($n_H \sim 0.005$ cm^{-3}) Local Bubble in the interstellar medium (e.g. Cox & Reynolds 1987; Bertin et al. 1993; Frisch 1994). In recent years our knowledge of the interior of the Local Bubble has improved dramatically, largely owing to the ability of modern high-resolution ($R \equiv \lambda/\Delta\lambda \approx 10^5$) spectrographs to detect the weak absorption lines, having equivalent widths of a few mÅ, arising from low-density clouds located within it. This work has revealed that, at least within a few tens of parsecs of the Sun, the Local Bubble contains several small clouds with characteristics apparently similar to the LIC.

From Ca K line observations of a number of nearby stars, Lallement & Bertin (1992) have deduced that the LIC is moving past the Sun with a heliocentric velocity of 25.7±0.5 km s^{-1} in the direction $l = 186°.1$, $b = -16°.4$. The projected LIC velocities towards the three stars observed here are listed in Table 1. The temperature of the LIC, in the immediate vicinity of the Solar system, has been determined from observations of back-scattered solar Lyα and He I 584-Å lines, yielding values of 8000±1000 K (Bertaux et al. 1985) and 7000±2000 K (Chassefière, Dalaudier & Bertaux 1988), respectively. An essentially identical value (6700± 1500 K) has been measured directly for interstellar He atoms in the outer Solar system from the *Ulysses* spacecraft (Witte et al. 1993). Although, strictly speaking, these measurements relate only to that part of the LIC actually impinging on the Solar system, they agree very well with the value of 7000±200 K measured by Linsky et al. (1993) from *HST* observations of an apparently single deuterium (D I) velocity component towards Capella (α Aur; distance $D = 12.5$ pc). Moreover, by comparing their D I linewidth with those of Mg$^+$ and Fe$^+$, Linsky et al. were able to estimate an rms turbulent velocity in the LIC of $v_t = 1.17$ km s^{-1}. [The velocity dispersion, b, is given by $b = (2kT/m + 2v_t^2)^{0.5}$, where T is the kinetic temperature, k is Boltzmann's constant, and m is the mass of the ion observed; in their paper, Linsky et al. characterize the turbulence by the parameter ξ, where $\xi = \sqrt{2} \times v_t$.]

In addition to the LIC, Lallement & Bertin (1992) and Bertin et al. (1993) have drawn attention to a nearby cloud located in the direction of the Galactic Centre, which these authors designate as the 'G' cloud. It is not yet clear whether the G cloud is entirely separate from the LIC, or is contiguous with it, although it does seem to have a slightly different heliocentric velocity vector (moving at 29.4±0.5 km s^{-1} towards $l = 184°.5$, $b = -20°.5$; Lallement & Bertin 1992). Further evidence for the prevalence of small clouds within the local interstellar medium (LISM) comes from the discovery of two velocity components towards Sirius ($D = 2.7$ pc; Lallement et al. 1994) and three towards Altair ($D = 5$ pc; Ferlet, Lallement & Vidal-Madjar 1986), where in each case one component can be identified with the LIC. Examples of multiple velocity structure towards slightly more distant stars are given in table 1 of Bertin et al. (1993).

Here we report observations of the interstellar Ca K line towards three nearby stars obtained with the Ultra-High-Resolution Facility (UHRF) at the Anglo–Australian Tele-

scope. The UHRF is an echelle spectrograph capable of a resolving power of up to $R \sim 10^6$, and has been described in detail elsewhere (Barlow et al. 1995; Diego et al. 1995). The use of a resolving power an order of magnitude higher than that used in previous studies of the LISM has the following advantages: (1) it enables the resolution of discrete, but closely spaced, velocity components and therefore separation of the LIC component from those of other nearby clouds; and (2) it enables us to measure reliable intrinsic linewidths (*b*-values), something only marginally possible before because previous instrumental widths of about 3 km s^{-1} ($R = 10^5$) were comparable to the expected intrinsic widths of the LISM absorption lines.

2 OBSERVATIONS

The observations were obtained with the UHRF in 1994 April (α Oph, α Gru) and June (α Eri). Table 1 gives some basic stellar information and details of the individual exposures. The detector was the AAO Tektronix CCD (1024×1024 24-μm pixels). The spectrograph was used in conjunction with an image slicer (Diego 1993), and the CCD output was binned by a factor of 8 perpendicular to the dispersion in order to reduce the readout noise associated with extracting the very broad spectrum which results. The resolution, measured from a stabilized He-Ne laser line, was determined to be 0.32 km s^{-1} (FWHM), corresponding to two CCD pixels.

The spectra were extracted from the CCD images using the FIGARO data reduction package (Shortridge 1988), and all further analysis was performed with the DIPSO program (Howarth & Murray 1988) at the UCL Starlink node. Background light was measured from either side of the echelle order and subtracted. [Note that, as discussed in section 7.3 of Diego et al. (1995), steps have now been taken to ensure that the interorder light is recorded by the detector, so the background uncertainties which affected the very earliest UHRF observations (see Barlow et al. 1995 and Crawford et al. 1994 have now been eliminated.] Wavelength calibration was performed by means of a Th-Ar lamp, and linear fits to five Th-Ar lines were found to yield rms residuals of 4×10^{-4} Å (0.03 km s^{-1}). Following wavelength calibration, the spectra were converted to the heliocentric velocity frame. The spectra are shown in Fig. 1.

3 DISCUSSION

As one of the primary aims of the present work was to determine the intrinsic Ca K linewidths in the LISM, a line-profile analysis was performed using the DIPSO spectrum analysis program (Howarth & Murray 1988). The best-fitting theoretical line profiles are compared with the observed spectra in Fig. 1, and the resulting line-profile parameters (heliocentric velocity, velocity dispersion and column density) are given in Table 2. Table 2 also gives the values of the kinetic temperature corresponding to the observed linewidths; these have been derived by assuming that there is no turbulent contribution to the line profiles, so they are upper limits to the true kinetic temperature in these clouds. All of the components observed here are quite broad, with *b*-values in the range 1.4 to 2.3 km s^{-1}. These correspond to gas temperatures in the range 5000 to 13 000 K in the absence of turbulence, and are therefore consistent with other estimates of temperatures prevailing in the low-density clouds within the Local Bubble (Section 1).

The individual line profiles are discussed briefly below.

3.1 α Oph

The presence of a strong interstellar Ca K line in the spectrum of α Oph was discovered by Münch & Unsöld (1962). The equivalent width (≈ 20 mÅ) is the largest known for any star within about 30 pc of the Sun and, as α Oph itself has a distance of only 15 pc, the sightline has long held special relevance for studies of the LISM (e.g. Frisch 1981; Paresce 1983; Frisch, York & Fowler 1987).

From high signal-to-noise data obtained at a resolving power of 10^5, Lallement, Vidal-Madjar & Ferlet (1986) identified two velocity components: a main component at -25.3 km s^{-1}, and a much weaker component at -31.0 km s^{-1}. Our higher resolution data confirm the presence of the latter, but reveal that the strongest component is, in fact, multiple (a possibility already noted by Marschall & Hobbs 1972 on the basis of their $R \approx 3 \times 10^5$ PEPSIOS data). It is immediately obvious from the asymmetric line profile (Fig. 1a) that the line is a blend of at least two components, and detailed modelling indicates that an additional component is required to fit the blue wing properly. Thus our final model for the interstellar Ca$^+$ absorption towards α Oph contains a total of four discrete velocity components (Table 2).

We would expect one of these components to arise in the local cloud. The projected heliocentric velocity of the LIC towards α Oph is -22.5 ± 0.5 km s^{-1} (Table 1), so the component observed at -23.6 ± 0.5 km s^{-1} may reasonably be assigned to this source. The *b*-value of this component is also consistent with what is known about the temperature and turbulence of the LIC (Section 1): a temperature of 7000 K corresponds to a Ca *b*-value of 1.7 km s^{-1} in the absence of turbulence, which falls within the range of $2.0^{+0.3}_{-0.5}$ km s^{-1} measured for this component (Table 2). The turbulent velocity deduced by Linsky et al. (1993) for the LIC ($v_t = 1.17$ km s^{-1}) would broaden this to an expected *b*-value of 2.4 km s^{-1}; this is only marginally above the estimated upper limit, but might nevertheless suggest either that Linsky et al.'s turbulent velocity has been somewhat overestimated, or that the LIC is slightly less turbulent towards α Oph than it appears to be towards α Aur (Section 1).

However, there remains a difficulty in confidently assigning the -23.6 km s^{-1} component to the LIC: while this component accounts for only about one-third of the total Ca$^+$ column density towards α Oph, it is still almost an order of magnitude higher than the column densities inferred for the LIC towards other nearby stars (cf. table 1 of Bertin et al. 1993). Thus the suggestion of Bertin et al. (following Frisch et al. 1987) that previously unresolved velocity structure might explain the unusual strength of the Ca K line towards α Oph is only partly sufficient: additional components *are* present, but even allowing for these, the LIC component remains anomalously strong. There appear to be only three possible explanations: (1) the LIC is more extended (by roughly a factor of 10) towards α Oph than it is towards other nearby stars so far studied; (2) it contains a significant density enhancement in this direction; or (3) there remains unresolved velocity structure in the line profile, and the LIC
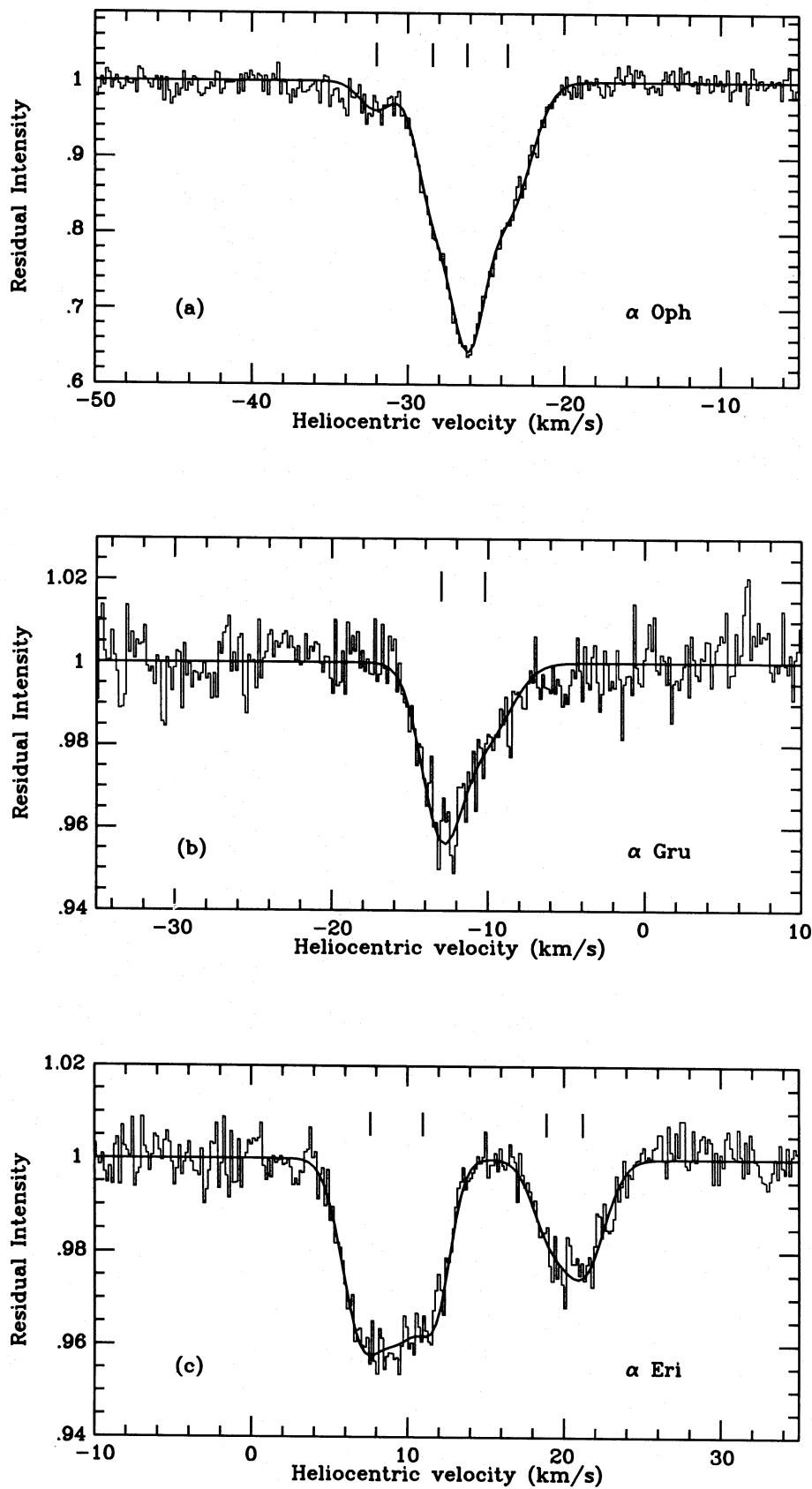
Figure 1. The interstellar Ca K lines observed towards α Oph, α Gru and α Eri with the UHRF. The observed data are plotted as histograms. The smooth curves are theoretical models with the parameters given in Table 2. The locations of the different velocity components are indicated by vertical tick marks.

Table 1. Stellar and exposure details for the UHRF observations of interstellar Ca^+ towards three nearby stars. Stellar data are reproduced from Hoffleit & Jaschek (1982); v_{LIC} is the projected heliocentric velocity (± 0.5 km s^{-1}) for the local interstellar cloud towards each of the three stars (Lallement & Bertin 1992; see text for discussion).

Star	l (deg)	b (deg)	V	Sp. Type	Dist. (pc)	v_{LIC} (km s^{-1})	Exps.	Counts (e$^-$)
α Oph	35.9	+22.6	2.08	A5 III	15	−22.5	2 × 1200s	7.8×10^3
α Gru	350.0	−52.5	1.74	B7 IV	18	−8.7	1 × 1000s	3.2×10^4
α Eri	290.8	−58.8	0.46	B3 Vpe	38	+3.0	1 × 1200s	3.7×10^4

Table 2. Line-profile parameters for the interstellar Ca K lines shown in Fig. 1; w_λ(tot) is the total equivalent width (i.e. summed over all velocity components) of the interstellar Ca K line, and T_k^{ul} is the upper limit to the kinetic temperature (derived under the assumption that there is no line-of-sight turbulence contributing to the observed linewidths).

Star	w_λ (tot) (mÅ)	v_{helio} (km s^{-1})	b (km s^{-1})	$\log N$ (cm^{-2})	T_k^{ul} (K)
α Oph	24.5 ± 0.6	-32.0 ± 0.5	$1.5^{+1.0}_{-0.5}$	$10.20^{+0.20}_{-0.20}$	5450^{+9690}_{-3030}
		-28.4 ± 0.3	$1.4^{+0.2}_{-0.2}$	$10.80^{+0.15}_{-0.20}$	4750^{+1450}_{-1260}
		-26.2 ± 0.2	$1.5^{+0.3}_{-0.3}$	$11.20^{+0.13}_{-0.15}$	5450^{+2400}_{-1960}
		-23.6 ± 0.5	$2.0^{+0.3}_{-0.5}$	$11.00^{+0.10}_{-0.20}$	10000^{+2810}_{-4550}
α Gru	2.7 ± 0.2	-13.0 ± 0.5	$1.8^{+0.2}_{-0.2}$	$10.30^{+0.05}_{-0.15}$	7850^{+1840}_{-1650}
		-10.2 ± 1.0	$2.3^{+0.4}_{-0.4}$	$10.05^{+0.20}_{-0.35}$	12800^{+4860}_{-4060}
α Eri	5.4 ± 0.2	$+7.6 \pm 0.4$	$2.2^{+0.2}_{-0.3}$	$10.40^{+0.07}_{-0.10}$	11700^{+2250}_{-2960}
		$+11.0 \pm 0.4$	$2.0^{+0.3}_{-0.2}$	$10.27^{+0.11}_{-0.09}$	10000^{+2810}_{-2150}
		$+18.9 \pm 0.4$	$1.5^{+0.2}_{-0.5}$	$9.70^{+0.20}_{-0.30}$	5450^{+1550}_{-3030}
		$+21.2 \pm 0.4$	$1.9^{+0.3}_{-0.4}$	$10.10^{+0.05}_{-0.20}$	8740^{+2980}_{-3290}

contributes only a fraction of the absorption seen at -23.6 km s^{-1}.

The line of sight to α Oph might also be expected to intercept the G cloud of Lallement & Bertin (1992), which has a projected heliocentric velocity in this direction of -25.7 ± 0.5 km s^{-1}. This is sufficiently close to that observed at -26.2 ± 0.2 km s^{-1} that we may plausibly identify the two. The b-values of the -23.6 and -26.2 km s^{-1} components are similar, although (assuming that the cloud identification is accepted) the slightly lower value for the latter may indicate that the G cloud is somewhat cooler and/or less turbulent than the LIC. The presence of additional velocity components at -28.4 and -32.0 km s^{-1} implies the existence of two more discrete clouds along the 15-pc line of sight to α Oph; the similarity in the b-values suggest similar temperatures/turbulent motions as the G cloud.

Frisch et al. (1987) have drawn attention to a wisp of H I emission close to the position of α Oph in the sky, visible in the 21-cm maps of Colomb, Pöppel & Heiles (1980). This feature is most prominent in Colomb et al.'s heliocentric velocity bin which extends from -28.6 to -24.6 km s^{-1} (i.e. -8 ± 2 km s^{-1}, LSR), and which includes the velocity range occupied by both the -28.4 and -26.2 km s^{-1} components. Thus, if Frisch et al. are correct in their assumption that the H I wisp lies in front of the star, it may have contributions from the clouds giving rise to both these velocity components (indeed, Frisch et al. state that the emission can actually be traced over the much larger range -43.6 to -22.6 km s^{-1}, so it may have contributions from all of the velocity components identified here, rather than being due to a single discrete condensation in the LISM).

Our ultra-high-resolution data are able to place some constraints on the suggestion that much, or even most, of the

material towards α Oph is located in a cold ($T \sim 70$ K; Paresce 1983), or cool ($T \sim 500$ K; Frisch et al. 1987), interstellar cloud. These temperatures correspond to Ca b-values of 0.17 and 0.45 km s^{-1}, respectively, and it would be immediately obvious in the present data if such narrow components, containing an appreciable fraction of the total column density, were present towards the star. However, it is true that any of the components identified here (b-values ~ 1.5 km s^{-1}; Table 2) could be as cold as 70–500 K if their internal rms turbulent velocities were of the order of 1 km s^{-1}. The fact that Linsky et al. (1993) have deduced a turbulent velocity of $v_t = 1.17$ km s^{-1} for the LIC towards α Aur might lead one to expect turbulent motions of this order in the LISM. However, we note that at the temperature of the LIC (7000 K) the sound speed, C_S, is 6.7 km s^{-1} and turbulent velocities of ~ 1 km s^{-1} are therefore definitely subsonic; the hydrodynamical conditions would be rather different if the cool clouds envisaged by Paresce (1983) and Frisch et al. (1987) were turbulent to the same extent (the turbulence would be supersonic at 70 K, for which $C_S = 0.67$ km s^{-1}, and comparable to the sound speed at 500 K, where $C_S = 1.8$ km s^{-1}).

3.2 α Gru

Lallement et al. (1986) identified three components towards α Gru on the basis of their $R = 10^5$ observations, although it is not clear from a visual inspection of their fig. 1(b) that three components are really justified. Indeed, our higher resolution (but admittedly lower signal-to-noise ratio) observations can be fitted adequately with two components (Fig. 1b; Table 2). The central velocity we obtain for the strongest component (-13.0 ± 0.5 km s^{-1}) agrees well with that obtained by Lallement et al. (-12.6 km s^{-1}), but the -6.9 and -3.8 km s^{-1} components of Lallement et al. fall within the blue wing of what we identify as a single component centred at -10.2 ± 1.0 km s^{-1}.

The LIC velocity projects to -8.7 ± 0.5 km s^{-1} towards α Gru (Table 1); so, allowing for the uncertainties in the velocities, the -10.2 ± 1.0 km s^{-1} component may reasonably be identified with the LIC. We see that the velocity dispersion of this component (2.3 ± 0.4 km s^{-1}) is very similar to that obtained for the putative LIC component towards α Oph, and is likewise consistent with a temperature of about 7000 K and moderate turbulence ($v_t \sim 1$ km s^{-1}). In this case, the column density is an order of magnitude lower, in much better agreement with other determinations of typical LIC column densities (e.g. Bertin et al. 1993, their table 1). However, it should also be noted that the projected velocity of the G cloud of Lallement & Bertin (1992) for this line of sight (-8.1 ± 0.5 km s^{-1}) is very similar to that of the LIC, so both may contribute to this component without them having been individually resolved. The -13.0 km s^{-1} component almost certainly arises in an entirely separate cloud, unconnected with either the LIC or the G cloud, although having a very similar b-value (and hence temperature/turbulence regime) and column density.

3.3 α Eri

α Eri is much the most distant of the three stars studied here, being more than twice as far away as α Oph and α Gru

(Table 1), and this is reflected in a more complicated absorption-line spectrum. Lallement et al. (1986) identified four components: a very weak one (which we do not see in our data) at about -5 km s^{-1}, a relatively strong, unresolved blend with components at about $+5$ and $+9$ km s^{-1}, and a fourth component at $+20$ km s^{-1} (cf. their fig. 1d). Our data confirm that the absorption feature at approximately $+10$ km s^{-1} contains contributions from at least two discrete clouds (although, as these have internal velocity dispersions comparable to their separation, they are almost as blended in our data as they are in those of Lallement et al., obtained with a resolving power a factor of 10 lower). We also note that, while, on grounds of economy, we have chosen to present a model with two components at this velocity (Fig. 1c), a somewhat better fit to the line core could be obtained by introducing two components in place of that at $+11.0$ km s^{-1} (having velocities $+9.4$ and $+11.7$ km s^{-1}, and b-values of 1.80 and 1.55 km s^{-1}, respectively), so our data are certainly consistent with the presence of additional unresolved velocity structure. Our observations also show that the apparently single $+20$ km s^{-1} feature of Lallement et al. is composed of at least two discrete components (Table 2).

All the identified velocity components towards this star have velocity dispersions ($b \approx 2$ km s^{-1}) consistent with a gas temperature in the range 5000 to 12 000 K, and the column densities ($\approx 10^{10}$ cm^{-2}) are comparable to that ascertained for the LIC (excluding the still anomalous direction to α Oph) and other nearby clouds (e.g. Bertin et al. 1993).

It is noteworthy that none of the components observed towards α Eri coincides with the projected velocities of either the LIC ($+3.0$ km s^{-1}; Table 1) or the G cloud ($+4.8$ km s^{-1}). Line-profile modelling yields conservative upper limits of $N(\text{Ca}^+) \lesssim 3 \times 10^9$ cm^{-2} for components assumed to be present at either of these two velocities. If the assumption that the Sun is actually embedded in the LIC is correct, it follows that the cloud must have a relatively small extent towards α Eri (there is other evidence that the LIC has a small extent, probably $\lesssim 1$ pc, in this galactic longitude range; see Bertin et al. 1993 and Crawford 1994). The non-detection of the G cloud is rather more surprising, as it has been detected in the neighbouring sightline towards α Hyi ($l = 289°.5$, $b = -53°.8$) at the expected velocity and with a column density $(4.6 \pm 1.5) \times 10^{10}$ cm^{-2} (Bertin et al. 1993). Either this cloud is very inhomogeneous, with an unusually small extent and/or low density towards α Eri, or the line of sight has just missed the cloud. Clearly, more observations are required in order to sort out these uncertainties.

4 CONCLUSIONS

We have used the UHRF at the AAT to obtain the highest resolution absorption-line spectra yet acquired of clouds located within the Local Bubble in the interstellar medium. The UHRF resolution (0.3 km s^{-1} FWHM) was sufficient for us to resolve the line profiles fully, and to resolve structure within the LISM components which have, until now, been considered as arising in single clouds. Our principal conclusions are as follows.

(1) The 'main' (-26 km s^{-1}) component towards α Oph, which was well fitted by a single Gaussian in the $R = 10^5$ data of Lallement et al. (1986), is in fact a blend of at least three components (Table 2). Similarly, the apparently single com-

ponent at $+20$ km s^{-1} towards α Eri (Lallement et al. 1986) is at least double.

(2) All of the components observed towards the three stars have well-determined b-values in the range 1.4 to 2.3 km s^{-1}. These correspond to gas temperatures in the range 5000 to 13 000 K in the absence of turbulence, and are therefore consistent with other estimates of temperatures prevailing in low-density clouds within the Local Bubble (Section 1).

(3) The absence of any narrow ($b < 1$ km s^{-1}) components rules out the presence of significant quantities of cold gas towards any of these stars (as suggested, for example, by Paresce 1983 and Frisch et al. 1987), unless this gas has a turbulent velocity of $\gtrsim 1$ km s^{-1}.

(4) On velocity and linewidth considerations it is possible to identify plausibly both the LIC and Lallement & Bertin's (1992) G cloud towards α Oph, and a possible unresolved LIC/G cloud blend towards α Gru. However, in the former case, the column density at the predicted LIC velocity is still anomalously strong (even allowing for the fact that this component is now shown to contribute only about a third of the total column density towards the star). Neither the LIC nor the G cloud is detected towards α Eri, and further work is required to determine why this is so.

ACKNOWLEDGMENTS

REFERENCES

Barlow M. J., Crawford I. A., Diego F., Dryburgh M., Fish A. C., Howarth I. D., Spyromilio J., Walker D. D., 1995, MNRAS, in press

Bertaux J. L., Lallement R., Kurt V. G., Mironova E. N., 1985, A&A, 150, 1

Bertin P., Lallement R., Ferlet R., Vidal-Madjar A., 1993, A&A, 278, 549

Chassefière E., Dalaudier F., Bertaux J. L., 1988, A&A, 201, 113

Colomb F. R., Pöppel W. G. L., Heiles C., 1980, A&AS, 40, 47

Cox D. P., Reynolds R. J., 1987, ARA&A, 25, 303

Crawford I. A., 1994, Observatory, 114, 288

Crawford I. A., Barlow M. J., Diego G., Spyromilio J., 1994, MNRAS, 266, 903

Diego F., 1993, Appl. Opt., 32, 6284

Diego F. et al., 1995, MNRAS, in press

Ferlet R., Lallement R., Vidal-Madjar A., 1986, A&A, 163, 204

Frisch P. C., 1981, Nat, 293, 377

Frisch P. C., 1994, Science, 265, 1423

Frisch P. C., York D. G., Fowler J. R., 1987, ApJ, 320, 842

Hoffleit D., Jaschek C., 1982, The Bright Star Catalogue, 4th edn. Yale University Observatory

Howarth I. D., Murray J., 1988, Starlink User Note, No. 50

Lallement R., Bertin P., 1992, A&A, 266, 479

Lallement R., Vidal-Madjar A., Ferlet R., 1986, A&A, 168, 225

Lallement R., Bertin P., Ferlet R., Vidal-Madjar A., Bertaux J. L., 1994, A&A, 286, 898

Linsky J. L. et al., 1993, ApJ, 402, 694

Marschall L. A., Hobbs L. M., 1972, ApJ, 173, 43

Münch G., Unsöld A., 1962, ApJ, 135, 711

Paresce F., 1983, Nat, 302, 806

Shortridge K., 1988, Starlink User Note, No. 86

Witte M., Rosenbauer H., Banaszkiewicz M., Fahr H., 1993, Adv. Space Res., 13, (6) 121