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Detection of a variable interstellar absorption component towards δ Orionis A

R. J. Price,★ I. A. Crawford and M. J. Barlow

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT

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ABSTRACT

Observations of δ Ori A made with the UHRF in its highest resolution mode ($R \approx 900\,000$) have revealed the presence of a cool ($T_{\mathrm{k}} \leqslant 350$ K) variable absorption component at a heliocentric velocity of $+21.3\,\mathrm{km\,s^{-1}}$. The component is detected in Na I D_1, where clear hyperfine splitting is seen, and Ca II K. Comparison of our data with existing spectra suggests that the component has consistently increased in strength from 1966 to 1994, and subsequently reduced in intensity by 1999. Following a discussion of the possible origins of this component it is concluded that an interstellar, rather than circumstellar, origin is most likely. This is one of very few detections of variable interstellar absorption reported in the literature, and we suggest an origin within filamentary material associated with the expanding H I shell surrounding the Orion–Eridanus superbubble.

Key words: line: profiles – stars: individual: HD 36486 – ISM: atoms.

1 INTRODUCTION

The O 9.5 II star δ Ori A (HD 36486) is the most westerly of the three stars defining Orion's belt. It gained historical significance when Hartmann (1904) reported the 'quite surprising result that the calcium line at $\lambda 3934$ does not share in the periodic displacements of the lines caused by the orbital motion of the [spectroscopic binary] star', a discovery which launched the study of the interstellar medium (ISM). Here we report the discovery of a variable interstellar (IS) component toward this star, made using Na I and Ca II observations obtained as part of an ultra-high-resolution study of the ISM towards Orion (a full analysis of which will be presented elsewhere).

2 OBSERVATIONS

The observations reported here were obtained with the Ultra-High-Resolution Facility (UHRF) at the Anglo-Australian Telescope during observing runs in 1994 (January 21–22, inclusive) and 1999 (July 31). During 1994, a total of three 1200-s integrations were obtained for the Na I D_1 region at 5895.924 Å, and a single 1200-s integration of the Ca II K region at 3933.663 Å. The detector used was the AAO Thomson CCD (1024×1024, 19-μm pixels). During 1999 a single 1000-s integration of the Na I D_1 region was obtained using the AAO Tektronix CCD (1024×1024, 24-μm pixels).

The spectrograph was operated with a confocal image slicer (Diego 1993), and the CCD output was binned (by factors of either four or eight) perpendicular to the dispersion direction in order to reduce the readout noise. The velocity resolution, measured from the observed width of a stabilized He–Ne laser line, was $0.34 \pm 0.01\,\mathrm{km\,s^{-1}}$ FWHM ($R = 880\,000$) for both sets of observations. Other aspects of the instrument and observing procedures have been described in detail by Diego et al. (1995) and Barlow et al. (1995).

The spectra were extracted from the individual CCD images using the FIGARO data-reduction package (Shortridge 1988) at the University College London (UCL) Starlink node. Scattered light and CCD dark current were measured from the inter-order region and subtracted. Wavelength calibration was performed using a Th–Ar lamp, and normalization achieved by division of low-order polynomial fits to the continuum. Removal of telluric water lines from the Na I spectra was achieved by the division by an atmospheric template spectrum, taken as that observed towards the bright, lightly-reddened star α Vir [note that α Vir actually exhibits a single weak Na I absorption component at a velocity of $-11.2\,\mathrm{km\,s^{-1}}$ (Welsh, Vedder & Vallerga 1990), but this is well clear of the region of interest here]. This atmospheric template was acquired in 1994; small variations in the strength of the atmospheric lines between the different spectra were allowed for by scaling the optical depths of the template atmospheric lines to match those in the δ Ori spectra before division. In any case, we note that no atmospheric absorption was found to coincide with the location of the transient component reported here. The spectra were then converted to the heliocentric velocity frame and the individual 1994 exposures were added. All velocities referred to here are heliocentric unless otherwise stated.

The absorption lines were modelled using the IS line-fitting routines in the DIPSO spectral analysis program (Howarth, Murray & Mills 1993). The oscillator strengths of the Na I and Ca II

★ E-mail: rjp@star.ucl.ac.uk

Table 1. Velocity systems identified toward δ Ori A. Total quivalent widths as measured from UHRF data are shown in column 3, while other published measurements are included for comparison: † Welty et al. (1994); ‡ Hobbs (1974); § Welty et al. (1996); * Frisch et al. (1990); ° Hobbs (1984).

Line	S/N	EW (mÅ)	Comp	$V_\odot$ ($\mathrm{km\,s^{-1}}$)	b ($\mathrm{km\,s^{-1}}$)	$\log N$ ($\mathrm{cm^{-2}}$)
Na I D_1	185	61	1	-5.0 ± 0.4	$0.9^{+0.3}_{-0.4}$	$9.90^{+0.05}_{-0.10}$
(1994)		42.6†	2	$+0.1 \pm 0.5$	$2.5^{+0.4}_{-0.5}$	$10.39^{+0.05}_{-0.05}$
		49‡	3	$+4.6 \pm 0.2$	$1.9^{+0.3}_{-0.3}$	$10.46^{+0.04}_{-0.04}$
			4	$+9.2 \pm 0.2$	$2.7^{+0.2}_{-0.2}$	$10.96^{+0.01}_{-0.03}$
			5	$+15.0 \pm 0.2$	$1.6^{+0.2}_{-0.3}$	$10.67^{+0.04}_{-0.04}$
			6	$+19.6 \pm 0.3$	$1.1^{+0.6}_{-0.5}$	$10.17^{+0.06}_{-0.12}$
			7	$+21.3 \pm 0.1$	$0.50^{+0.05}_{-0.05}$	$11.08^{+0.02}_{-0.02}$
			8	$+23.1 \pm 0.1$	$1.0^{+0.1}_{-0.1}$	$10.84^{+0.03}_{-0.03}$
			9	$+24.0 \pm 0.1$	$0.55^{+0.15}_{-0.10}$	$10.66^{+0.05}_{-0.05}$
			10	$+25.1 \pm 0.1$	$0.53^{+0.03}_{-0.03}$	$11.13^{+0.02}_{-0.03}$
			11	$+26.5 \pm 0.1$	$0.50^{+0.05}_{-0.05}$	$10.76^{+0.03}_{-0.05}$
Na I D_1 (1999)	31	60 ± 3	7	$+21.3 \pm 0.2$	$0.50^{+0.15}_{-0.05}$	$10.85^{+0.05}_{-0.05}$
Ca II K	14	31 ± 4	1	$+10.2 \pm 0.8$	$4.5^{+1.0}_{-1.0}$	$11.12^{+0.08}_{-0.07}$
(1994)		45§	2	$+15.7 \pm 0.5$	$1.6^{+0.6}_{-0.5}$	$10.65^{+0.10}_{-0.10}$
		38 ± 5*	3	$+21.3 \pm 0.1$	$0.7^{+0.1}_{-0.1}$	$11.14^{+0.06}_{-0.06}$
		21‡	4	$+23.5 \pm 0.5$	$1.5^{+0.5}_{-0.3}$	$10.60^{+0.10}_{-0.20}$
		45°	5	$+28.6 \pm 0.6$	$2.5^{+0.5}_{-0.5}$	$10.75^{+0.15}_{-0.10}$

transitions were taken from Morton (1991). The resulting line profile parameters, heliocentric velocity, $v_\odot$, velocity dispersion, b, and column density, N, are listed in Table 1. The best-fitting Voigt profiles for the Na I and Ca II spectra of 1994, after convolution with the instrumental response function, are shown in Figs 1(a) and (b). Fig. 1(c) shows the 1999 Na I spectrum, overplotted with the 1994 line profile parameters (dotted line) and the new component-7 parameters (solid line; Table 1). It is clear from Fig. 1(c) that this component has decreased in strength between the two epochs.

A number of simple checks were performed in order to exclude the possibility that the apparent variation is an artefact of some kind. Each of the three individual 1994 Na I spectra was examined, and found to exhibit the same enhancement in line strength. Moreover, examination of the individual CCD images, and of the flat field frames, revealed no anomalous features at this location in the spectra. In addition, the detection of the transient component in both Na I and Ca II at the same velocity (where the Na I exhibits clear hyperfine splitting with the expected 3:5 ratio) strongly implies the detection to be genuine.

3 COMPARISON WITH EARLIER OBSERVATIONS

Previous observations of IS Na I and Ca II absorption toward this star have been made at a variety of resolutions, and include the studies of Hobbs (1969, 1984); Marschall and Hobbs (1972); Frisch, Sembach & York (1990); Welty, Hobbs & Kulkarni (1994); Welty, Morton & Hobbs (1996). The resolution achieved by the UHRF exceeds that of these earlier observations, although the Na I survey of Welty et al. (1994) did employ a comparable resolution ($R = 6 \times 10^5$). Hobbs (1969) also estimated the resolving power of the PEPSIOS Fabry–Perot interferometer to be about 6×10^5, although a comparison of PEPSIOS and UHRF observations (Barlow et al. 1995) suggested that the resolving power of the former was probably in the range $R \approx (1\text{–}2) \times 10^5$. For the purposes of comparison, we here assume a value of $R = 2 \times 10^5$ for the PEPSIOS data.

In order to check that the line profile changes reported here are not caused by the range of resolving powers employed in these earlier studies, we have used Gaussian convolution to reduce all the observations to an *effective* resolving power of $R = 2 \times 10^5$. Table 2 summarizes the previous high-resolution ($R > 10^5$) observations, and includes the estimated residual line intensity at a velocity of $21\,\mathrm{km\,s^{-1}}$, in both the original spectra and at the common resolving power of 2×10^5. Fig. 2 shows the same comparison graphically. In the case of Na I (Fig. 2a), a clear increase in the strength of the $+21\,\mathrm{km\,s^{-1}}$ component is seen between 1966 and 1994, followed by a reduction in the line intensity by 1999. Since all four spectra plotted in Fig. 2(a) have the same effective resolution, it is clear that resolution effects are not responsible for the line profile variability. In the case of Ca II (Fig. 2b), good agreement is seen between the UHRF and Welty et al. (1996) data, which were both obtained in 1994, but the spectrum of Marschall & Hobbs (1972), obtained in 1970, shows only weak absorption at this velocity. Thus, in agreement with the Na I results, a consistent increase in the Ca II absorption strength is found to have occurred between 1970 and 1994.

4 DISCUSSION

4.1 Location of the transient component

δ Ori is a well-known multiple star system: δ Ori A (discussed below); δ Ori B ($V = 14.0$, separation 33 arcsec); and δ Ori C ($V = 6.85$, separation 52 arcsec). Both B and C are sufficiently distant from A not to contribute to the observed flux from δ Ori A. However, δ Ori A is itself a multiple system: the primary is an

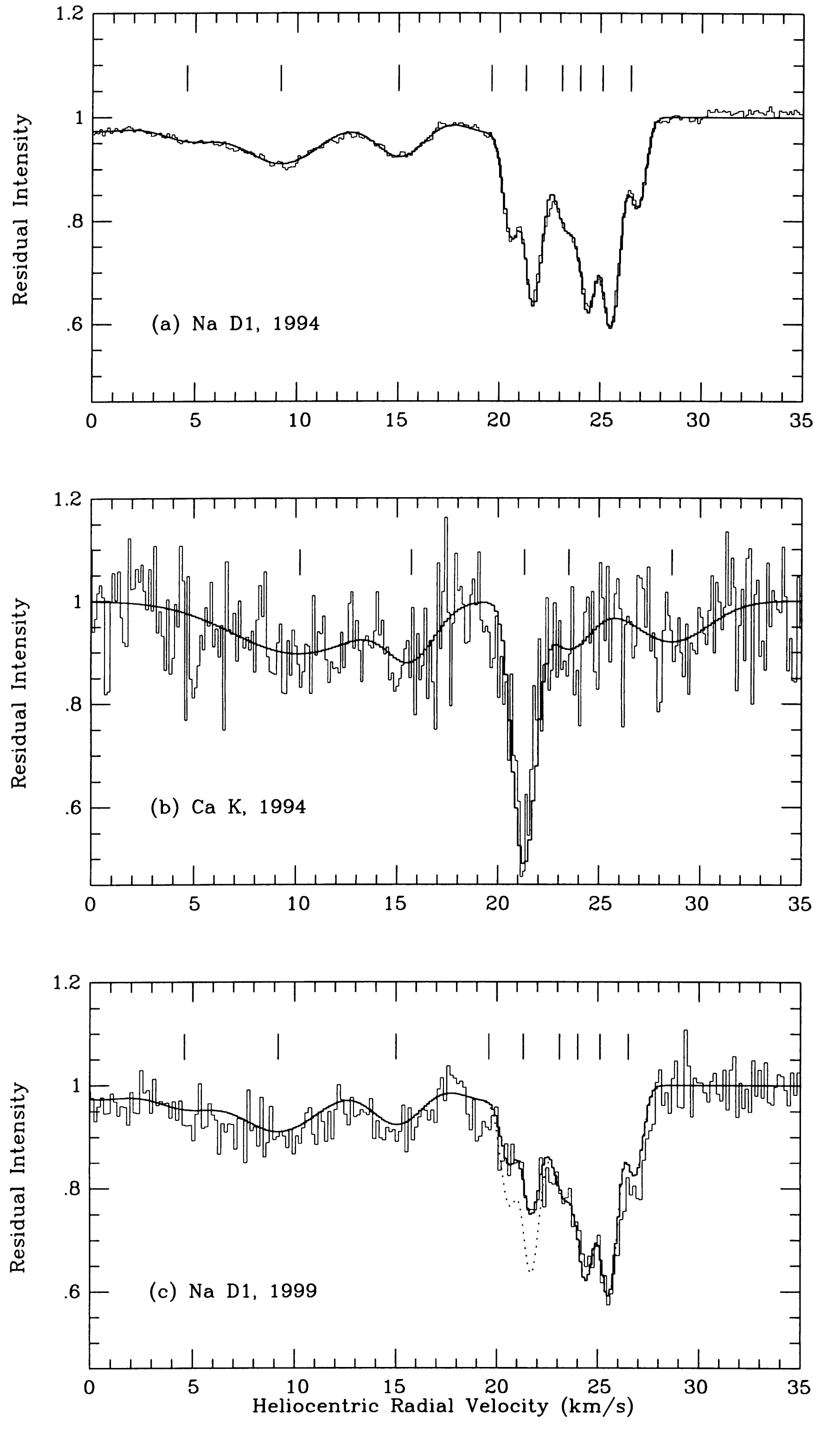

Figure 1. Theoretical line profiles are shown plotted over spectra observed toward δ Ori A in the (a) Na I and (b) Ca II regions, both obtained in 1994, and (c) Na I region, obtained in 1999, with the fit to the 1994 data (dotted line) superposed. The tick-marks indicate the velocities of the individual model components listed in Table 1.

eclipsing spectroscopic binary, with an orbital period of 5.73 d and a velocity amplitude of 97.9 km s^{-1} (Harvey et al. 1987). The two stars are classified as O9.5 II and B1 III/IV (Galkina 1976; Koch & Hrivnak 1981), with somewhat uncertain *V* magnitudes of 2.90 and 4.4 respectively; both stars are significantly evolved from the main sequence. In addition, a third star, δ Ori D, was detected by Heintz (1980) and McAlister & Hendry (1982); the *Hipparcos* survey (ESA 1997) found δ Ori D to be 1.35 magnitudes fainter, and 0.27 arcsec away from, δ Ori A. The small separations of these three stars leads to the observations being a composite of flux from all three.

Given this complex environment, and the evolved nature of the component stars, a circumstellar (CS) origin for the variable absorption component reported here may at first sight appear the most likely. Indeed, δ Ori A is known to be losing a significant amount of mass through a stellar wind ($\dot{M} \approx 10^{-6}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$;

Table 2. A comparison of previous high-resolution ($R > 10^5$) observations of interstellar lines towards δ Ori A. Columns 5 and 6 indicate the residual line intensity of the absorption found at $+21\,\mathrm{km\,s^{-1}}$, as measured from the original observations (R_{orig}), and at the common, effective, resolving power of $R = 2\times10^5$ (R_{2E5}) shown in Fig. 2. The last two columns give the heliocentric radial velocity and equivalent width of the transient component respectively [* estimated from published spectrum; † estimated from published absorption parameters; in the case of Welty et al. (1994) the upper limit is a result of the fact that the component they identify at this velocity is actually a blend of the variable component and the two, presumably stable, adjacent components identified in our higher resolution data].

Region	Reference	Observation date	Resolution	Residual line intensities R_{orig}	R_{2E5}	Velocity of transient	Equivalent width of transient (mÅ)
Na I D_1	Hobbs 1969	1966	2×10^5	0.95	0.95	n/a	≤5.0*
	Welty et al. 1994	1988	6×10^5	0.82	0.85	+21.81	<9.3†
	This study	1994	9×10^5	0.64	0.74	$+21.3 \pm 0.1$	11.0 ± 1.0
	This study	1999	9×10^5	0.80	0.82	$+21.3 \pm 0.2$	6.6 ± 1.0
Ca II K	Marschall & Hobbs 1972	1970	2×10^5	0.85	0.85	$+20.8 \pm 0.4$	4.0 ± 1.0*
	Welty et al. 1996	1994	2.5×10^5	0.62	0.66	+21.19	6.8†
	This study	1994	9×10^5	0.50	0.65	$+21.3 \pm 0.1$	9.4 ± 1.5

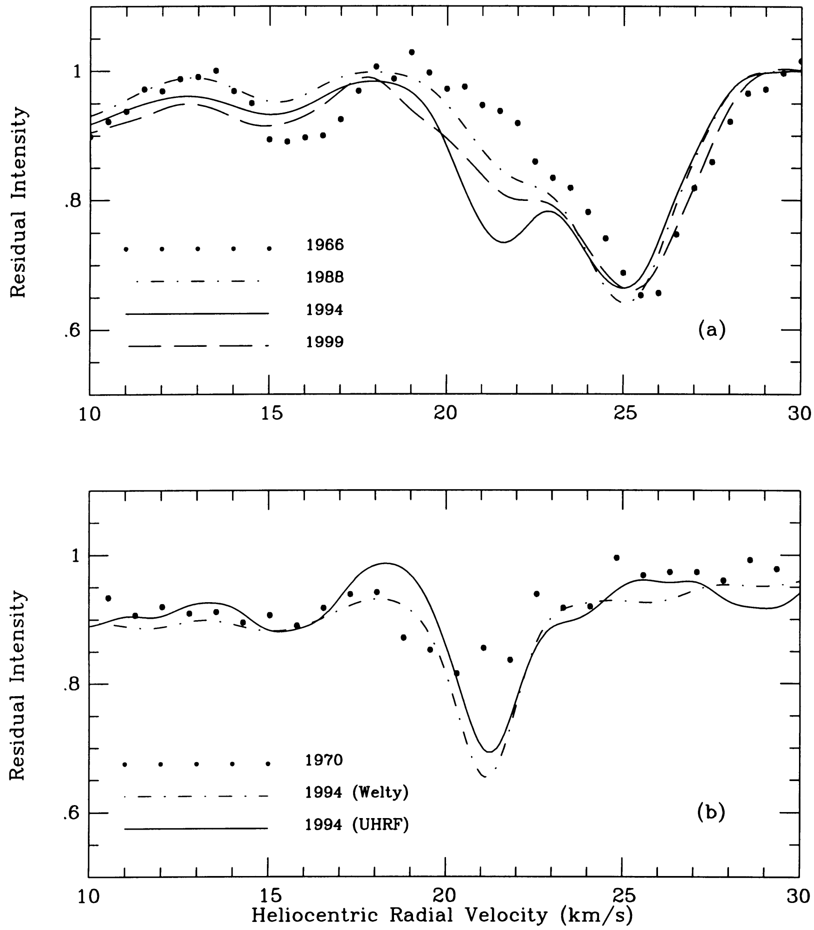

Figure 2. Comparison of (a) Na I and (b) Ca II observations towards δ Ori A on the dates indicated (cf. Table 2). All the spectra have been reduced to a common, effective, resolving power of $R = 2\times10^5$.

Howarth & Prinja 1989). Moreover, there have been various claims for the presence of CS shells and envelopes, with expansion velocities ranging from $50\,\mathrm{km\,s^{-1}}$ (Singh 1982) to $550\,\mathrm{km\,s^{-1}}$ (Galkina 1976). However, the low radial velocity of the transient component is not consistent with an origin in such high-velocity shells. Moreover, a CS origin in the vicinity of one or other of the spectroscopic binary stars is effectively excluded by the fact that that this component has maintained a constant heliocentric velocity ($+21.3 \pm 0.5\,\mathrm{km\,s^{-1}}$; Table 2) for at least 29 yr, rather than sharing in the extreme ($\pm97.9\,\mathrm{km\,s^{-1}}$) orbital velocity of the binary.

Absorption in a common envelope around *both* stars would not show this effect, but might be expected to be centred on the systemic velocity of the system. It is true that the velocity of this component, $+21\,\mathrm{km\,s^{-1}}$, is actually quite close to recent measurements of the systemic velocity (e.g. Harvey et al. 1987). However, there is good evidence that the systemic velocity is in fact changing with time, whereas that of the variable absorption

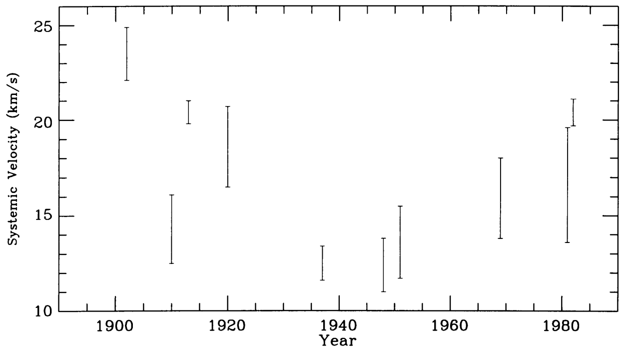

Figure 3. Systemic velocity measurements made of δ Ori A, taken from table II of Harvey et al. (1987).

component is not. The various earlier measurements of the systemic velocity of δ Ori A (V_0) are plotted in Fig. 3 (taken from table II of Harvey et al. 1987). They appear to indicate a velocity variation with a minimum value during the 1940s, and a period of the order of a century (consistent with a value suggested by Koch & Hrivnak 1981), and possibly resulting from orbital interaction with δ Ori D. However, these velocity variations are not echoed by the velocity of our transient component, and this apparent stability suggests it arises either in a common envelope around both δ Ori A and δ Ori D, or within the foreground ISM.

If the variable absorption does indeed arise in the foreground ISM, then the fact that its strength has varied significantly over only three decades indicates either a high tangential velocity, or a small spatial extent, for the absorbing cloud. By assuming a plausible upper limit of $50\,\mathrm{km\,s^{-1}}$ on the transverse velocity, and a transit time of 30 yr, a length-scale of $\lesssim$300 au can be imposed on the cloud. In this respect, it is notable that such small-scale structures have recently been detected in the ISM, on the basis of both pulsar dispersion measures (Frail et al. 1994) and optical absorption lines towards the components of closely spaced multiple star systems (Watson & Meyer 1996). Indeed, both these studies concluded that such small-scale structure in the ISM may be ubiquitous. Thus the small spatial scale implied by the variability of this component towards δ Ori A cannot in itself be used to exclude an IS origin.

4.2 Physical conditions of the transient component

Additional information concerning the physical conditions in the material giving rise to the variable component, and thus constraints on its proximity to the δ Ori system, can be provided by the linewidths and the Na I to Ca II ratio.

4.2.1 Linewidths

The velocity dispersion parameter, b, is related to the kinetic temperature, T_k, and the line-of-sight turbulent velocity, v_t, by the expression

$$b = \sqrt{\frac{2kT_\mathrm{k}}{m} + 2v_\mathrm{t}^2}, \tag{1}$$

where k is Boltzmann's constant and m is the mass of the atom or ion observed. By assuming the case of purely thermal broadening ($v_\mathrm{t} = 0$) it is possible to obtain a rigorous upper limit to the kinetic temperature from the observed b-value. The very low Na I b-value for this component ($b = 0.5\,\mathrm{km\,s^{-1}}$, Table 1), which permitted the clear resolution of the Na I hyperfine splitting, corresponds to a limit of $[T_\mathrm{k}]_{\mathrm{Na\,I}} \leqslant 348\,\mathrm{K}$. This is typical of IS cloud values, and shows no evidence for significant heating from nearby hot stars. The slightly broader line for the heavier Ca II ion yields $[T_\mathrm{k}]_{\mathrm{Ca\,II}} \leqslant 1187\,\mathrm{K}$, although we note that the higher signal-to-noise ratio (S/N) data of Welty et al. (1996) yields $[T_\mathrm{k}]_{\mathrm{Ca\,II}}$ to be $\leqslant$872 K.

Despite the fact that both the Na I and Ca II absorption increased in strength over the same period, and must therefore be physically associated in some way, the fact that the component is broader in the heavier Ca II ion than in Na I means that the two species cannot be well mixed spatially, as no combination of thermal and turbulent processes can reproduce the observed linewidths. This effect is commonly observed in IS clouds, and is attributed to Ca II occupying a warmer and/or more turbulent (presumably outer) region of the cloud than Na I.

By assuming $T_\mathrm{k} = 0$ in equation (1), we may obtain rigorous upper limits to the turbulent velocity. This analysis yields $[v_\mathrm{t}]_{\mathrm{Na\,I}} \leqslant 0.35\,\mathrm{km\,s^{-1}}$, and $[v_\mathrm{t}]_{\mathrm{Ca\,II}} \leqslant 0.49\,\mathrm{km\,s^{-1}}$ (our data) or $[v_\mathrm{t}]_{\mathrm{Ca\,II}} \leqslant 0.42\,\mathrm{km\,s^{-1}}$ (Welty et al. 1996). Moreover, we find that the full, three-dimensional, turbulent velocity, $\sqrt{3}v_\mathrm{t}$, is definitely subsonic, unless the kinetic temperature is very low (<30 K for Na I). These low, sub-sonic, turbulent velocities are more in keeping with the diffuse ISM than with the energetic CS environment of hot stars.

4.2.2 The Na I/Ca II ratio

We obtained a Na I to Ca II ratio of 0.87 ± 0.13 for the transient component in 1994; using the Ca II column density of Welty et al. (1996), where the component is probably better defined, gives a similar ratio of 1.25. As discussed by Crawford (1992, and references therein) these values are typical of values found in diffuse (non-molecular) IS clouds characterized by $n_\mathrm{H} \sim 10\,\mathrm{cm^{-3}}$ and $T_\mathrm{k} \sim 100\,\mathrm{K}$, in which Ca atoms are significantly, although not entirely, depleted on to grain surfaces (specifically, $\delta_{\mathrm{Ca}} \approx -2$, where δ_{Ca} is the logarithmic Ca depletion factor, relative to a gas of solar composition). This significant Ca depletion further suggests an IS location of the absorbing gas, as the energetic CS environment of δ Ori might be expected to lead to partial or total grain destruction, resulting in $N(\mathrm{Na\,I})/N(\mathrm{Ca\,II}) \lesssim 0.1$ (Crawford 1992).

On the other hand, the fact that the observed N(Na I)/N(Ca II) ratio is much smaller than the large values ($\gtrsim$10) typically found in dense ($n_\mathrm{H} \sim 10^3\,\mathrm{cm^{-3}}$) molecular clouds, where essentially all of the gas-phase Ca has become adsorbed on grain surfaces (Crawford 1992, and references therein), is also of interest. As noted by Watson & Meyer (1996), the small spatial extent implied by time-variable IS lines implies an implausibly high cloud density unless the geometry is highly non-spherical. In the present case, taking the empirical relationship between N(Na I) and N(H) obtained by Ferlet, Vidal-Madjar & Gry (1985), and a path length of 300 au (the upper limit to the *transverse* extent of the cloud discussed in Section 4.1), we obtain $n_\mathrm{H} \gtrsim 10^4\,\mathrm{cm^{-3}}$. Unless the material is far from equilibrium for some reason, such a high density is inconsistent with a N(Na I)/N(Ca II) ratio of order unity, as observed. This analysis therefore supports the conclusion of Heiles (1997) that the material responsible for the various manifestations of small-scale structure in the ISM must be distributed as sheets or filaments, rather than in approximately spherical 'clouds.'

4.3 Previous observations of transient clouds

Previously reported variations in IS absorption include those observed toward HD 72127 (Hobbs, Wallerstein & Hu 1982; Hobbs et al. 1991), and HD 72089 and HD 72997 (Danks & Sembach 1995). All three stars lie behind the Vela supernova remnant (SNR), where rapidly moving, small-scale structure might be expected. The very low N(Na I)/N(Ca II) ratio towards HD 72127 (0.11; Hobbs et al. 1982) is certainly consistent with grain destruction resulting from supernova-induced shocks, although Danks & Sembach found larger values towards their stars, which they attributed to less than total grain destruction.

The only other known observation of transient IS absorption is that reported towards HD 28497 by Blades et al. (1997). This star lies behind the Orion–Eridanus superbubble, a roughly spherical structure with a diameter of about 280 pc, thought to have been created by the stellar winds of the Ori OB1 association stars and/or a series of supernova explosions (Reynolds & Ogden 1979; Brown, Hartmann & Burton 1995; Heiles et al. 1999). Blades et al. suggested that this is a plausible location for the variable absorption towards this star. This component was found to be very narrow ($b = 0.31 \pm 0.03\,\mathrm{km\,s^{-1}}$), and has a fairly high N(Na I)/N(Ca II) ratio (>4.5). Thus, the HD 28497 component more closely resembles the δ Ori component reported here than the highly shocked components towards HD 72127.

It is noteworthy that δ Ori is also located behind the expanding shell of H I that marks the boundary of the Orion–Eridanus superbubble (cf. the maps presented in fig. 8 of Brown et al. 1995). It is true that, at the precise velocity range occupied by the transient component, the maps of Brown et al. appear to show a gap in the ring, but this may just reflect a lower (and non-detectable) H I column density, rather than a total absence of gas at this velocity. As for the HD 28497 case, we therefore suggest that edge-on filamentary sheets at the boundary of the Orion–Eridanus shell are the most likely cause of the absorption-line variability observed towards δ Ori.

5 CONCLUSIONS

We have detected clear evidence for a variable absorption component toward δ Ori A. In principle, the variable absorption could occur in either the circumstellar environment or the foreground interstellar medium. However, the fact that the component has remained stable in velocity for many years argues against an origin in the immediate vicinity of this complicated multiple stellar system. This conclusion is further supported by the very narrow linewidths ($b = 0.50 \pm 0.05\,\mathrm{km\,s^{-1}}$ for Na I), which imply low kinetic temperatures ($T_\mathrm{k} < 350\,\mathrm{K}$) and turbulent velocities ($v_\mathrm{t} < 0.35\,\mathrm{km\,s^{-1}}$), and by the moderate N(Na I)/N(Ca II) ratio, which indicates that the IS grains are largely intact.

These observations therefore add to the growing body of evidence for small-scale (∼100 au) structure within the diffuse ISM. However, the observations strongly imply that the absorbing medium must be highly non-spherical, and support the conclusion of Heiles (1997) that it is most likely filamentary in structure. The fact that the line of sight intercepts the expanding H I shell surrounding the Orion–Eridanus superbubble makes this an especially plausible interpretation. We recommend that further high-resolution observations of this sightline, and of the closely neighbouring sightlines to δ Ori B and δ Ori C, should be made in order to constrain further the spatial extent, and physical conditions, of the absorbing medium.

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