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κ Velorum: another variable interstellar sightline?

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ABSTRACT

We present ultra-high-resolution ($R = 900\,000$) observations of interstellar Na I and K I absorption lines towards κ Vel (HD 81188) which show clear evidence for temporal variation between 1994 and 2000. Specifically, the column densities of K^0 and Na^0 in the main velocity component have increased by 40 and 16 per cent, respectively, over this period. Earlier work had suggested that this component actually consists of two unresolved sub-components; this result is confirmed here, and the overall line profile is found to be consistent with only one of these sub-components having increased in strength since 1994. We argue that this variation is consistent with the line of sight gradually probing a cold, dense interstellar filament of the kind recently proposed by Heiles to explain other observations of small-scale structure in the interstellar medium.

Key words: stars: individual: κ Vel (HD 81188) – ISM: atoms – ISM: structure.

1 INTRODUCTION

An earlier paper, by Dunkin & Crawford (1999, hereinafter Paper I) presented high-resolution ($R \approx 900\,000$) observations of interstellar lines towards the bright southern star κ Velorum (HD 81188). These observations were obtained using the Ultra-High-Resolution Facility (UHRF: Diego et al. 1995) at the Anglo-Australian Telescope (AAT) in 1994. The interstellar λ7698.974 K I line towards κ Vel was re-observed on 2000 January 17 as part of a series of throughput tests performed because of a reported drop in UHRF sensitivity. To our surprise, we found that the interstellar K I line appeared to be approximately 50 per cent stronger than it had been in 1994 April (Fig. 1a).

We stumbled across this surprising observation just after completing a paper on a variable interstellar absorption component towards δ Orionis, discovered with the same instrument (Price, Crawford & Barlow 2000). The δ Ori observation is certainly more secure, as only one component out of several was seen to have changed in strength, a circumstance which eliminates most possible instrumental or reduction artefacts. Nevertheless, as documented cases of variable optical interstellar absorption are quite rare (see section 4.3 of Price et al.), it was considered worthwhile to follow up this observation of κ Vel. The results of this exercise are reported here.

2 ADDITIONAL CHECKS AND OBSERVATIONS

The throughput tests carried out in 2000 January revealed a loss of UHRF efficiency resulting from a misalignment of the image slicer with the collimator (see Diego et al. 1995), and this was subsequently corrected. There is no indication that anything other than the efficiency of the instrument was compromised by this misalignment and, in particular, the resolution was not affected (see below). Nevertheless, in order to be sure that the apparent variability in the K I line was not an artefact of instrumental problems, or a result of reduction artefacts, a number of additional checks were carried out.

2.1 Re-extraction of the 1994 data

In order to check that there were no anomalies associated with the 1994 observations, the raw K I and Na I D_1 CCD images were re-extracted using the FIGARO data reduction package (Shortridge et al. 1998). This was a completely independent reduction, in that it was performed by a different person – the data were originally reduced by Dr S. K. Dunkin (the lead author of Paper I), whereas the re-extraction was performed by IAC. The re-extracted spectra were found to be essentially identical to those presented in Paper I, with the exception of a very small ($0.06\,\mathrm{km\,s^{-1}}$) velocity shift, which presumably arises from a different choice of Th–Ar comparison lines, and/or order of polynomial fit, in the two independent wavelength calibration procedures.

It is also important to note that the K I spectrum obtained in 1994 April consisted of two 600-s integrations (Table 1). The grating angle was moved between these two integrations, causing the interstellar line to fall on two different regions of the CCD, approximately 70 pixels apart. Comparison of the two profiles, once wavelength calibrated to allow for this shift, revealed them to be identical within the limits imposed by the signal-to-noise ratio (SNR). This agreement effectively excludes the possibility of

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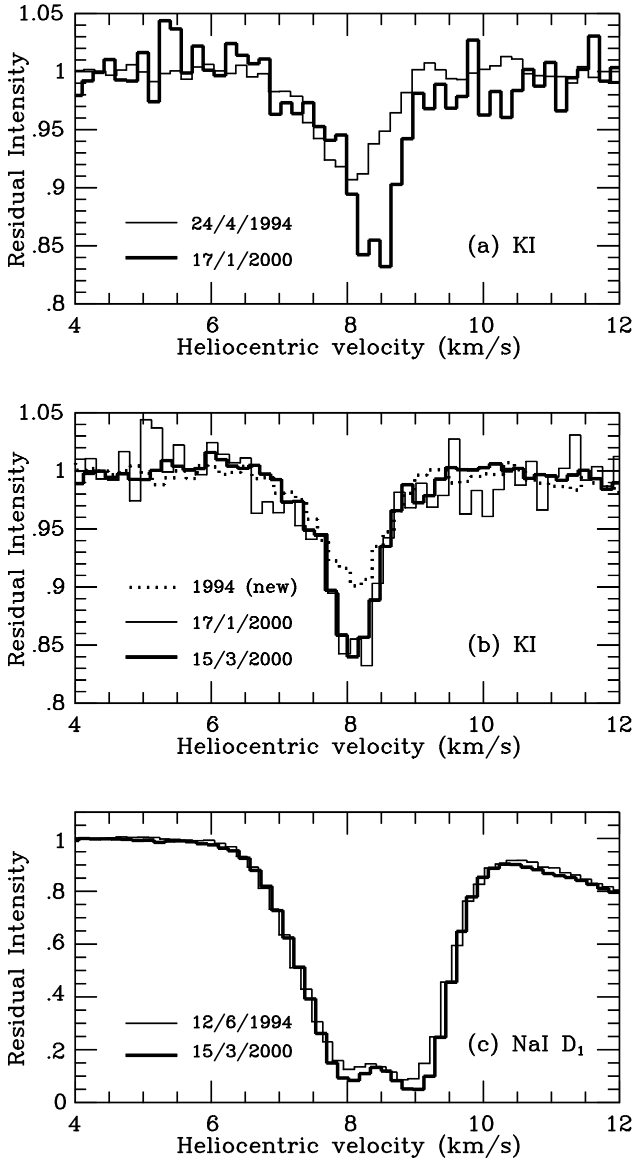

Figure 1. Comparison of interstellar lines observed towards κ Vel. Panel (a) compares the K I line observed on 2000 January 17 with that observed on 1994 April 24; the line has strengthened considerably in this time (the apparent velocity shift is discussed in the text). Panel (b) compares the K I line observed on 2000 March 15 with the re-extracted 1994 data (dotted line), which is essentially identical to the original extraction shown in (a), except for a small ($0.06\,\mathrm{km\,s^{-1}}$) velocity shift; the observation of 2000 January 17, shifted by $0.28\,\mathrm{km\,s^{-1}}$, is also plotted, showing that its profile agrees well with the higher SNR spectrum of March 15. Panel (c) compares the 2000 March 15 Na D_1 spectrum with that obtained on 1994 June 12; the line appears marginally stronger.

pixel-dependent detector or background artefacts affecting the profile of the interstellar line. We conclude that as careful a check as is now possible reveals no reason to doubt the reliability of the observations obtained in 1994 April and published in Paper I.

2.2 New observations

New observations of the interstellar K I line, together with the Na I D_1 (λ5895.924) line, towards κ Vel were obtained on the nights of 2000 March 15 and 16. By this time the UHRF throughput problem had been fixed, and the instrument was working normally. These spectra have a much higher SNR than the spectrum of 2000 January. In addition, observations of the K I line were obtained towards the star HD 110432, which had also been observed in 1994 April, to provide an independent check of the instrument performance.

These additional observations, together with those of 1994 and 2000 January, are listed in Table 1. They were obtained with the same spectrograph configuration, and the same detector (Tektronix CCD with 1024×1024 24-μm pixels), as used in 1994. The data reduction procedure was also identical to that described in Paper I (including the additional 4 per cent background correction there described).

There are several points to be made regarding the information displayed in Table 1.

2.2.1 Instrumental resolution

The column headed Δv(laser) gives the FWHM of the stabilized λ6328 He–Ne laser line, as measured during each of the observing runs. A glance at these values shows that the resolution of the instrument was 'nominal' for all these observations, in spite of its reduced efficiency in 2000 January. Because of the need to re-focus the UHRF at different wavelengths (see Diego et al. 1995), there remains the possibility that the instrument had been badly focused for the K I wavelength in 1994 April, which would have decreased the apparent depth (although not the equivalent widths) of the absorption lines. This can be checked by measuring the widths of the Th–Ar comparison lines obtained at the wavelength of observation immediately before or after the observations of κ Vel. This information is also given in Table 1 [Δv(arc)]. The Th arc lines are broader than the laser line, because they have been resolved by the instrument. Nevertheless, it is clear that there was no significant difference in the instrumental resolution, measured at the observed wavelengths, between 1994 April (both nights), 2000 January 17 and 2000 March 16.

The arc lines for 2000 March 15 are somewhat broader than obtained on the other nights, which at first sight would seem to indicate that the resolution was degraded somewhat (from $R =$ 910 000 to 480 000), possibly owing to less than optimal focus. However, this possibility seems to be excluded by two further considerations. (1) The instrument was focused using a Hartmann test, and the cross-correlation of the focus spectra indicates that it was essentially perfectly focused for all these observations (for example, the focus shifts at Na D_1 on March 15 and 16 were 0.04 and 0.07 pixel, respectively). (2) The *measured* FWHM of the interstellar K I line towards κ Vel on both nights are essentially identical [Δv(obs), Table 1], which is inconsistent with a 50 per cent degradation in resolution. For these reasons we conclude that the UHRF was correctly focused for the March 15 observations, and that the discrepancy in the arc linewidths has some other cause, presumably relating to the functioning of the Th–Ar lamp on that night.

2.2.2 Velocity shifts

The seventh column in Table 1 lists the heliocentric velocities obtained for the strongest interstellar velocity component (there is strong evidence, discussed in Paper I and again below, for unresolved structure within these lines, but we ignore that for the time being). Looking at both the κ Vel and HD 110432 velocities,

Table 1. Summary of the observational data: Exp. and SNR give the exposure times and resulting continuum signal-to-noise ratios, respectively; W_λ and $v_{\rm helio}$ give the total equivalent widths (i.e. summed over all velocity components, and assuming a 4 per cent zero-level uncertainty) and the heliocentric velocity of the strongest absorption component (obtained by a least-squares Gaussian fit); Δv(laser) gives the FWHM of the λ6328 stabilized He–Ne laser line on the given dates; Δv(arc) gives the FWHM of thorium comparison lines obtained with the same setup as used for the interstellar lines; and Δv(obs) gives the observed FWHM of the narrow interstellar K I line towards κ Vel (which can be well fitted by a single Gaussian); these three columns provide a check on the instrumental resolution (see text, Section 2.2.1). All errors are 1σ values.

UT date	Star	Line	Exp. (s)	SNR	W_λ (mÅ)	$v_{\rm helio}$ (km s^{-1})	Δv(laser) (km s^{-1})	Δv(arc) (km s^{-1})	Δv(obs) (km s^{-1})
24-04-94	κ Vel	K I	2 × 600	180	2.8 ± 0.2	8.09 ± 0.02	0.32 ± 0.01	0.57 ± 0.01	1.05 ± 0.10
	110432	K I	2 × 1200	60	78.3 ± 3.2	6.47 ± 0.02	0.32 ± 0.01	0.57 ± 0.01	
12-06-94	κ Vel	Na I	4 × 600	175	57.7 ± 2.3	8.42 ± 0.01	0.32 ± 0.01	0.59 ± 0.01	
17-01-00	κ Vel	K I	1 × 1200	50	4.4 ± 0.4	8.37 ± 0.04	0.35 ± 0.01	0.59 ± 0.01	0.93 ± 0.26
15-03-00	κ Vel	K I	2 × 1200	120	4.0 ± 0.3	8.09 ± 0.02	0.33 ± 0.01	0.79 ± 0.01	0.90 ± 0.08
	κ Vel	Na I	2 × 1200	180	58.9 ± 2.4	8.46 ± 0.01	0.33 ± 0.01	0.67 ± 0.01	
	110432	K I	1 × 1200	40	78.5 ± 3.3	6.48 ± 0.02	0.33 ± 0.01	0.79 ± 0.01	
16-03-00	κ Vel	K I	2 × 1200	180	4.0 ± 0.2	8.31 ± 0.01	0.33 ± 0.01	0.58 ± 0.01	0.93 ± 0.06
	110432	K I	1 × 1200	50	76.7 ± 3.2	6.61 ± 0.02	0.33 ± 0.01	0.58 ± 0.01	

it is clear that small (~0.2 km s^{-1}) velocity differences exist between observations of the same line towards the same star. While it is possible in principle that a variation in line strength would be accompanied by a change in velocity (especially if the profile contained unresolved velocity structure), there are good reasons for believing these apparent velocity shifts to be spurious. In particular, while the velocities measured on 2000 March 15 agree well with those obtained in 1994 April, the ~0.2 km s^{-1} discrepancy between the consecutive nights of 2000 March 15 and 16 indicates that the velocity calibration is not reliable at this level, even though the formal least-squares velocity errors are an order of magnitude smaller. Inspection of the individual Th–Ar calibration frames reveals no evidence for wavelength calibration errors at this level, so the discrepancy is presumably caused by something moving in the spectrograph between the Th–Ar and stellar exposures. In any case, it seems certain that the small velocity shifts recorded in Table 1 cannot be attributed to actual changes in the velocity of the interstellar absorption.

2.2.3 Line strengths

Equivalent widths were measured using the DIPSO spectral analysis package (Howarth et al. 1998). In contrast to the small velocity discrepancies discussed above, there is unambiguous evidence for an increase in the K I equivalent width between 1994 ($W_\lambda = 2.8 \pm 0.2$ mÅ) and 2000 ($W_\lambda = 4.0 \pm 0.2$ mÅ). Note that all three 2000 observations yield essentially identical equivalent widths. The increase in strength is clearly seen in Figs 1(a) and (b), which compare the 1994 April observation with those obtained on 2000 January 17 and March 15.

Fig. 1(c) compares the Na D_1 spectrum obtained on 2000 March 15 (heavy line) with that obtained on 1994 June 12 (light line), and it seems clear that the line has marginally increased in depth since 1994. Although the total equivalent width (summed over all velocity components, Table 1) shows little change over this period, a detailed line profile analysis (Section 3, below) does indicate a significant increase in Na I column density in the main absorption component.

Table 1 also lists the equivalent widths obtained for the

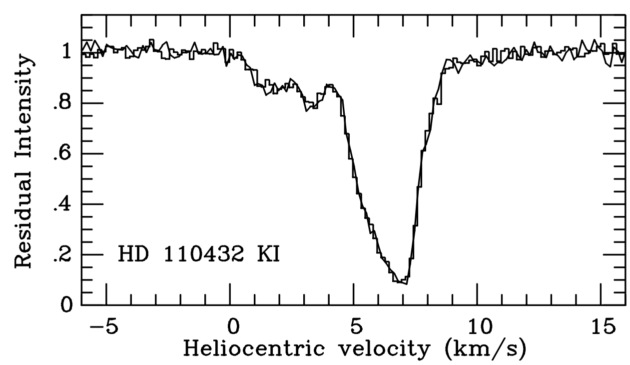

Figure 2. Comparison of two observations of interstellar K I towards HD 110432 obtained on 1994 April 24 (histogram) and 2000 March 15 (smooth curve). To all intents and purposes the two line profiles are identical, giving confidence that the change in line strength found for κ Vel over this period is a real effect.

interstellar K I line towards HD 110432, which was observed as an independent check. It is clear that there has been no significant change in the strength of this line between 1994 and 2000. This conclusion is reinforced by Fig. 2, which directly compares the line profiles obtained on 1994 April 24 and 2000 March 15. Within the limits imposed by the SNR, these two observations are to all intents and purposes identical, lending further support to the conclusion that a real change has occurred towards κ Vel over the same period.

3 LINE PROFILE ANALYSIS

Given that in Paper I we found that two closely spaced velocity components were required to fit the main ($v_{\rm helio} \approx +8.5$ km s^{-1}) Na I absorption feature towards this star, it is of interest to determine whether the temporal changes reported here are consistent with variability in only one of these two components. In order to explore this possibility, we have modelled the newly acquired 2000 observations, and re-analysed the earlier 1994 observations, using a χ-squared minimization routine, ISFIT (Howarth, in preparation). ISFIT returns the optimum values of column density (N), velocity dispersion (b) and central velocity for a specified number of absorption components fitted to the observed data. We took the necessary atomic data from Morton (1991), and have explicitly included the effect of hyperfine structure in both species. Fig. 3 and Table 2 show the results of this analysis. We have concentrated on the apparently variable absorption near $8.5\,\mathrm{km\,s^{-1}}$, but for completeness have also included results for two weaker Na I velocity components near $+12$ and $+15\,\mathrm{km\,s^{-1}}$ (we could find no statistically significant evidence for an additional weak component near $+17\,\mathrm{km\,s^{-1}}$, such as was identified in Paper I).

The first point to note is that these new results unambiguously confirm the suggestion made in Paper I, on the basis of a less rigorous line profile analysis, that two closely spaced components are required to model the main Na I absorption feature. The dotted lines in Figs 3(a) and (c) show the best-fitting single-component fits to the 1994 and 2000 data, respectively, and it is quite clear that in neither case is the core of the line profile modelled adequately. The solid curves in Figs 3(a) and (c) show the best two-component fits with the parameters listed in Table 2. Formally, an F-test indicates that the improvements in χ-squared resulting from the additional component are significant with >99 per cent confidence.

In the case of K I, there is no particular statistical justification for more than one absorption component. However, as discussed in Paper I, given that two Na I components are certainly present, and that the ionization potentials, and grain-surface binding energies, of K I and Na I are so similar (e.g. Barlow 1978), we fully expect two velocity components to be present within the observed K I absorption feature even though these are not explicitly resolved. We have therefore modelled the 1994 and 2000 K I lines using ISFIT under the *assumption* of two velocity components with a velocity separation fixed at that found for the

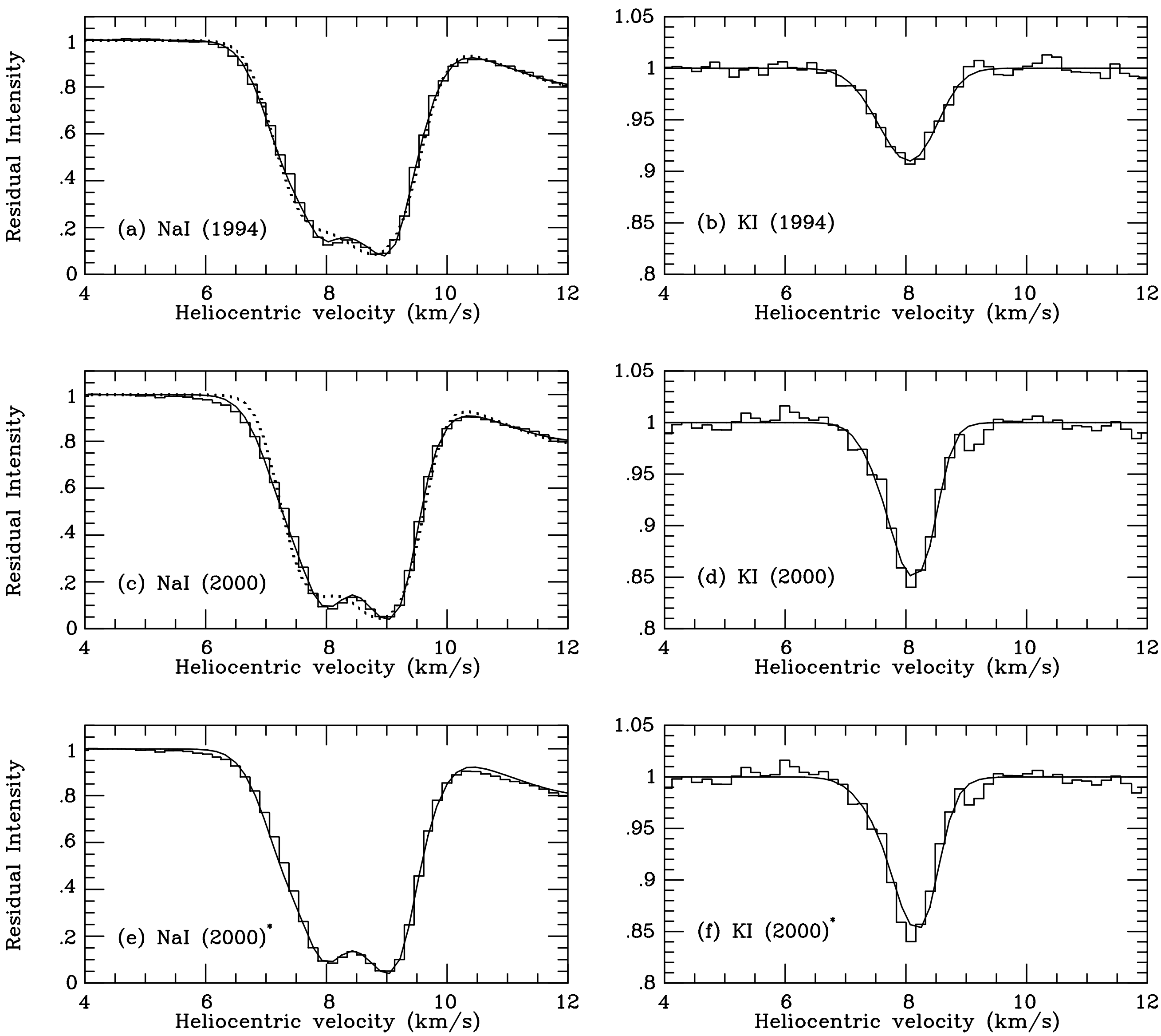

Figure 3. Results of the line profile analysis. The observed line profiles are plotted as histograms, while the best-fitting theoretical profiles (Table 2) are over-plotted. The dotted lines in (a) and (c) show the best-fitting single-component fits to the main absorption component in Na I, and it is clear that in neither 1994 nor 2000 does a single component fit the line core adequately. Panels (e) and (f), marked 2000*, show the fits obtained for the 2000 data if the other component parameters are fixed at their 1994 values.

Table 2. Results of the line profile analysis: v_{helio}, b and $\log N$ are the heliocentric velocity, velocity dispersion and column density of the interstellar Na I and K I absorption components towards κ Vel. The resulting line profiles are compared with the observations in Fig. 3. The last column gives the K^0/Na^0 column density ratio discussed in the text. The last row, marked 2000*, gives the results obtained for the redward of the two strongest components in that year if the other components are fixed at their 1994 values (see text).

Year	Na I v_{helio} (km s^{-1})	Na I b (km s^{-1})	Na I $\log N$ (cm^{-2})	K I v_{helio} (km s^{-1})	K I b (km s^{-1})	K I $\log N$ (cm^{-2})	$N(K^0)/N(Na^0)$
1994	8.40 ± 0.01	0.69 ± 0.01	11.88 ± 0.01	7.95 (fixed)	0.60 ± 0.04	10.14 ± 0.04	0.018 ± 0.002
	8.65 ± 0.01	0.21 ± 0.03	11.16 ± 0.04	8.20 (fixed)	0.37 ± 0.21	9.40 ± 0.23	0.017 ± 0.010
	12.28 ± 0.05	1.49 ± 0.13	11.08 ± 0.07	…	…	…	…
	15.61 ± 0.98	3.34 ± 0.96	10.77 ± 0.15	…	…	…	…
2000	8.42 ± 0.01	0.68 ± 0.01	11.84 ± 0.02	7.95 (fixed)	0.49 ± 0.06	10.20 ± 0.06	0.023 ± 0.003
	8.68 ± 0.01	0.28 ± 0.02	11.55 ± 0.03	8.21 (fixed)	0.21 ± 0.11	9.85 ± 0.11	0.020 ± 0.005
	12.21 ± 0.05	1.66 ± 0.14	11.15 ± 0.05	…	…	…	…
	15.75 ± 0.84	2.48 ± 0.88	10.62 ± 0.18	…	…	…	…
2000*	8.68(fixed)	0.24 ± 0.01	11.49 ± 0.01	8.21 (fixed)	0.26 ± 0.07	9.99 ± 0.04	0.032 ± 0.003

Na I components (0.26 ± 0.01 km s^{-1} : Table 2). The resulting fits are shown in Figs 3(b) and (d), and the best-fitting parameters are given in Table 2.

Interestingly, the results presented in Table 2 do suggest that most, and perhaps all, of the temporal variation has occurred in only one of the two closely spaced velocity components near +8.5 km s^{-1}. Specifically, whereas the column densities of both Na I and K I for the blueward component ($v_{\mathrm{helio}} = +8.40$ km s^{-1} in Na I) obtained in 1994 and 2000 agree, or almost agree, within the 1σ errors, a much more significant column density increase is found for redward component. Given this hint, we decided to determine whether the observed line profiles are in fact consistent with assuming no change at all in the blueward absorption component. This was achieved by using ISFIT to model the 2000 Na I and K I line profiles with the parameters for the blueward component (and the components near +12 and +15 km s^{-1}) *fixed* at their 1994 values, but with the b and $\log N$ values of the redward component allowed to vary. The results are shown in Table 2 (labelled 2000*), and also in Figs 3(e) and (f). It seems clear that plausible fits can be obtained under these assumptions. We conclude that the observations are consistent with only the redward of the two closely spaced absorption components identified in Paper I having varied between 1994 and 2000.

4 DISCUSSION

Recently, Heiles (1997) has reviewed the evidence for structure in the interstellar medium (ISM) on scales of tens to hundreds of astronomical units. Much of the evidence comes from 21-cm observations of H I, including very long baseline interferometry (VLBI) observations of extragalactic sources (Dieter, Welch & Romney 1976; Diamond et al. 1989; Davis, Diamond & Goss 1996), and temporal variations of H I absorption towards high proper motion pulsars (Frail et al. 1994). In addition, observations of optical interstellar absorption lines towards components of closely spaced binary stars have revealed significant differences on scales of hundreds to thousands of astronomical units (Meyer & Blades 1996; Watson & Meyer 1996). Finally, the small number of temporal variations of optical interstellar absorption lines reported in the literature (briefly summarized by Price et al. 2000) also imply the presence of such small-scale structure in the ISM.

It is true that most of the previously reported variations of interstellar absorption lines have been towards stars lying behind interstellar structures such as the Vela supernova remnant (Hobbs, Wallerstein & Hu 1982) and the Orion–Eridanus superbubble (Blades et al. 1997; Price et al. 2000), where such variability might perhaps be expected. At first sight κ Vel seems a less likely candidate for such variability, for, although the line of sight does pass through the Sco–Cen shell (e.g. Crawford 1991; de Geus 1992), the velocities, column densities and moderately large $N(Na^0)/N(Ca^+)$ ratios (Paper I) are more consistent with an origin in denser interstellar clouds in the background.

However, the implication of Heiles' (1997) work is that small-scale structure should be *ubiquitous* in such cold interstellar clouds, and he specifically suggested [his section 8.3(4)] that changes should be observed in absorption lines towards single stars as they move across the sky. The proper motion of κ Vel is quite modest (15.5 mas yr^{-1}: ESA 1997), and for a stellar distance of 165 pc (ESA 1997) results in the line of sight sweeping out a maximum tangential distance of only 15 au between 1994 and 2000. Nevertheless, such a small scale is of the same order as the size of the structures discussed by Heiles (1997), and the present observations may therefore constitute a detection of them at optical wavelengths.

Heiles (1997) has argued persuasively that the small-scale structure must consist of cold ($T \sim 15$ K) and dense ($n_{\mathrm{H}} \sim 10^3$ cm^{-3}) sheets or filaments embedded within warmer, less dense material. When such structures are aligned along the line of sight it is possible to achieve large variations in column density over small transverse scales, without requiring implausibly high spatial densities. Moreover, as Heiles points out, within such filaments the column density of trace neutral species such as Na^0 and K^0 is likely to be further enhanced as a result of increased recombination from their dominant ionization stages. Thus one possible interpretation of the present results is that the line of sight to κ Vel is gradually entering one of the cold, dense sheets or filaments proposed by Heiles (1997).

Interestingly, if this interpretation is correct we might expect an increase in the $N(K^0)/N(Na^0)$ ratio, as is found under the assumption that only one of the two closely spaced velocity components has varied (model 2000* in Table 2). For a photoionized gas in equilibrium, the $N(K^0)/N(Na^0)$ ratio is given by

$$\frac{N(K^0)}{N(Na^0)} = \frac{N(K)}{N(Na)} \frac{1 + \Gamma(Na)/\alpha(Na)n_e}{1 + \Gamma(K)/\alpha(K)n_e}, \qquad (1)$$

where N(Na) and N(K) are the total Na and K column densities (i.e. summed over the neutral and first ionization stages); Γ(Na) and Γ(K) are the photoionization rates for Na^0 and K^0, respectively; α(Na) and α(K) are the corresponding recombination rates for the first ions; and n_e is the electron density.

We have used equation (1) to determine the behaviour of the $N(K^0)/N(Na^0)$ ratio as a function of density and temperature, taking the photoionization and recombination rates from Péquignot & Aldrovandi (1986). We have further assumed that n_e equals the spatial density of C^+ (here taken to be the undepleted carbon abundance), and that Na and K are equally depleted on to grains (as is expected from their similar chemical properties and adsorption binding energies: e.g. Barlow 1978); we have taken the cosmic abundances from Anders & Grevesse (1989). With these assumptions we find that increasing the density, and/or decreasing the temperature, results in an increase in the $N(K^0)/N(Na^0)$ ratio. For example, at $T = 15$ K, increasing the density from $n_H = 1000$ to $5000\,cm^{-3}$ causes $N(K^0)/N(Na^0)$ to increase from 0.019 (close to the 1994 value) to 0.032 (the 2000* value: cf. Table 2), while decreasing T from 150 to 15 K for $n_H = 5000\,cm^{-3}$ yields essentially the same result (which is insensitive to inclusion of charge-exchange reactions; cf. fig. 1 of Péquignot & Aldrovandi 1986). Clearly, these interpretations are not unique. Nevertheless, the trend is clear: if we accept the argument that only one of the velocity components has increased in strength since 1994, the resulting increase in $N(K^0)/N(Na^0)$ is consistent with the line of sight entering a denser and/or colder region.

5 CONCLUSIONS

The main conclusions of the present work are as follows.

(i) We have found clear evidence for an increase in interstellar K I and Na I column density in the line of sight to κ Vel between 1994 and 2000.

(ii) A line profile analysis confirms the suggestions made in earlier work (Paper I) that two closely spaced, unresolved, velocity components are required to fit the main interstellar absorption feature near $v_{helio} = +8.5\,km\,s^{-1}$, and that the data are consistent with only the redward of these two components having increased in strength between 1994 and 2000. Moreover, the $N(K^0)/N(Na^0)$ ratio of this component appears to have increased, consistent with the line of sight entering a region of enhanced recombination.

(iii) We argue that these results are consistent with the line of sight to κ Vel gradually entering a cold, dense sheet or filament of the kind proposed by Heiles (1997) to explain other observations of small-scale strucure in the ISM.

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