Crawford, Ian (1991) Further thoughts on the interstellar spectrum of HD 174632. Monthly Notices of the Royal Astronomical Society 250 (4), pp. 707-711. ISSN 0035-8711.

Mon. Not. R. astr. Soc. (1991) **250**, 707–711

Further thoughts on the interstellar spectrum of HD 174632

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Accepted 1991 January 24. Received 1991 January 21; in original form 1990 November 30

SUMMARY

High-resolution observations (3.6 km s^{-1} FWHM) of interstellar Ca II towards the star HD 174632 are presented. This spectrum complements the Na I spectrum presented in a previous paper (Crawford 1988), and enables additional conclusions to be drawn as to the origin of the observed absorption components. Of the three components observed in both Ca II and Na I, that at -4.3 km s^{-1} is now attributed to diffuse gas associated with the R CrA dark cloud, and that at -22 km s^{-1} is interpreted as arising in the local interstellar medium; the origin of the component at -18 km s^{-1} is unclear, but it appears to exist beyond the local interstellar bubble and has a Na I/Ca II ratio suggestive of an origin in relatively dense gas.

1 INTRODUCTION

In an earlier paper (Crawford 1988, hereafter Paper 1) observations of the interstellar Na I (D_2) line towards the southern sixth magnitude star HD 174632 ($l=5\overset{\circ}{.}2$, $b=-13\overset{\circ}{.}7$) were presented. (Note that, owing to a typographical error, the sign of the galactic latitude given for this star in Paper 1 is incorrect.) Two strong Na I velocity components were found to be present with heliocentric velocities of about -4 and -18 km s^{-1}, with an additional, much weaker, component ($v_{\rm helio} \sim -22$ km s^{-1}) being blended with that at -18 km s^{-1}. The discovery of these strong Na I lines was considered to be of interest owing to the relatively low reddening of the star [$E(B-V)=0.12$] and the fact that, for a stellar distance of 180 pc (Paper 1), the line-of-sight passes through the relatively empty Sco-Cen (or 'Loop I') and Local interstellar bubbles (*cf.* fig. 2 of Paper 1). In Paper 1 it was speculated that the observed absorption components arise in the 'wall' of neutral gas thought to separate the Local and Loop I bubbles. Here I present a spectrum of interstellar Ca II towards HD 174632 which, together with the maps of galactic CO emission presented by Dame *et al.* (1987), suggests a different interpretation for the origin of these components.

2 OBSERVATIONS AND LINE PROFILE ANALYSIS

The spectrum of the Ca II *K* line was obtained using the coudé échelle spectrograph of the Mt Stromlo 74-inch telescope in 1989 June. The 130-inch focal length camera was used, resulting in a dispersion of 0.4 Å mm^{-1}; the slit width was 300 μm, giving a velocity resolution of 3.6 km s^{-1} (FWHM). The data reduction and calibration procedures employed were as described in Paper 1. All measurements were made using the DIPSO program (described by Howarth & Murray 1988) on the UCL Starlink node. We note that, in spite of the rather late spectral type (B8V, Garrison, Hiltner & Schild 1977), no sign of the stellar Ca II *K* line was observed, which implies a large rotational velocity ($v \sin i \gtrsim 50$ km s^{-1}), and/or a large radial velocity ($|v_{\rm helio}| \gtrsim 140$ km s^{-1}).

The Ca II spectrum, and the Na I spectrum reported in Paper 1, are compared in Fig. 1. In this figure the observed spectra are plotted as histograms, where each bin is the mean of two recorded data points; this binning has not degraded the resolution as the 130-inch camera results in there being eight detector pixels across the instrumental FWHM. Superimposed on the observed spectra are theoretical line profiles. These have been convolved with the instrumental response function to enable direct comparison with the observed data and, in the case of Na I, include the effect of hyperfine structure. The oscillator strengths were taken from Morton & Smith (1973), i.e. 0.655 for Na I and 0.688 for Ca II. Table 1 gives the measured equivalent widths (w_λ; 2σ errors), heliocentric radial velocity ($v_{\rm helio}$; determined from a least-squares Gaussian fit, 1σ errors), column density (N) and velocity dispersion (b) of the theoretical profiles shown in Fig. 1, together with the range in these values (ΔN, Δb) which gives a satisfactory fit to the observed spectra. For lines which may be unresolved an upper limit to b is given in Table 1; in such cases it is necessary to assume a lower limit for b in order to obtain an upper limit to N, and here values of 0.3 km s^{-1} (Na I) and 0.2 km s^{-1} (Ca II) have been adopted (these b values correspond to a temperature of about 100 K in the absence of turbulence). Differences between the Na I parameters given here and those given in Paper 1 are due to the use of a least-square fit for the determination of velocities (those given in Paper 1 being eye estimates), adoption of a slightly larger oscillator strength, and a reappraisal of the

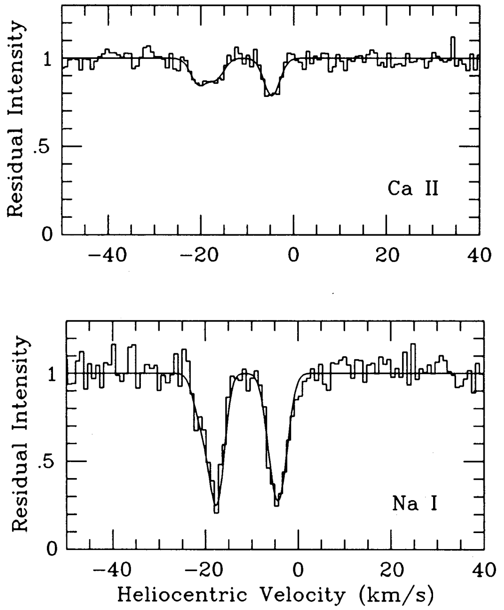

Figure 1. The spectra of interstellar Ca II *K* and Na I D_2 towards HD 174632. The observed intensities are plotted as histograms. The solid curves are theoretical line profiles with the parameters given in Table 1.

Table 1. Equivalent widths and line profile parameters for the absorption lines shown in Fig. 1. Powers of 10 are given in brackets; Δb and ΔN are the ranges of b and N that give acceptable fits to the line profiles. For unresolved lines, the upper limit to N has been obtained by assuming $b_{\min} = 0.2$ km s^{-1} for Ca II and 0.3 km s^{-1} for Na I (see text for discussion).

Line	v_{helio} (km s^{-1})	w_λ (mÅ)	b (km s^{-1})	Δb (km s^{-1})	N (cm^{-2})	ΔN (cm^{-2})
Ca II	-20.0 ± 3.4	}14 ± 3	1.0	≤ 2.5	1.0 (11)	0.8 – 2.0 (11)
	-16.2 ± 2.4		1.0	≤ 1.5	0.8 (11)	0.6 – 1.5 (11)
	-4.7 ± 0.7	11 ± 2	1.0	≤ 2.0	1.6 (11)	1.5 – 10 (11)
Na I	-22.0 ± 0.8	}72 ± 10	1.0	≤ 2.0	1.1 (11)	0.8 – 2.0 (11)
	-18.0 ± 0.5		1.0	≤ 1.2	0.8 (12)	0.6 – 20 (12)
	-4.3 ± 0.5	79 ± 11	1.6	1.0 – 2.2	0.7 (12)	0.5 – 1.0 (12)

permitted ranges of b and N (especially the adoption of very low b values for the determination of column density upper limits).

The velocities obtained from the line profile analysis show that all three components identified previously in Na I are also present in Ca II, although the Na I lines are much the strongest, at least for the two main components. A search was also made for the CH $R_2(1)$ line at 4300.313 Å, but with negative results. At the velocities of each of the components observed in Na I and Ca II the CH equivalent width upper limit was found to be about 1 mÅ, corresponding to a column density limit of $N(\mathrm{CH}) \lesssim 1.2 \times 10^{12}$ cm^{-2}.

3 DISCUSSION

3.1 The Na I/Ca II ratios

Jura (1976) showed that, for conditions that generally occur in diffuse interstellar clouds, the Na I/Ca II ratio is proportional to the ratio of the depletion factors of Na and Ca. As the depletion of Na is known to be approximately constant in the diffuse interstellar medium (e.g. Phillips, Pettini & Gondhalekar 1984; Jura 1975), he argued that variations in the Na I/Ca II ratio are largely due to variations in the gas-phase abundance of Ca owing to density dependent depletion onto grain surfaces. For example, Hobbs (1976) quotes a typical Na I/Ca II ratio of ~ 2 for 'standard' diffuse interstellar clouds (i.e. those having $n_{\mathrm{H}} \sim 10$ cm^{-3} and $T \sim 80$ K), whereas he found Na I/Ca II ~ 0.1 for warm, low-density ('intercloud') material (characterized by $n_{\mathrm{H}} \sim 0.1$ cm^{-3}, $T \sim 2500$ K). Similar material towards the Sco OB1 association has been found to have a Na I/Ca II ratio $\lesssim 0.4$ (Crawford, Barlow & Blades 1989); a review of previously published results [Section IV(d) of Crawford *et al.*] found 'intercloud' Na I/Ca II ratios in the range 0.1 to 0.7, where the larger values presumably reflect denser and/or cooler material. For the most dense diffuse clouds (i.e. those having densities in the range 10^2 to 10^3 cm^{-3}, and which exhibit substantial molecular column densities) the Na I/Ca II ratio can be as high as 100 as more Ca becomes adsorbed onto the grains (e.g. it has a value of about 90 in the diffuse molecular cloud towards ζ Oph; Siluk & Silk 1974).

In order to obtain the Na I/Ca II ratios of the components observed here it is necessary to assume a value for the velocity dispersion, b. This is particularly important in the present case where most of the observed lines were not resolved. In the absence of turbulence, $b_{\mathrm{Na}}/b_{\mathrm{Ca}} = 1.3$, so if the velocity dispersion is assumed to be solely due to thermal broadening the Na I/Ca II ratio should be evaluated for b values in this ratio. On the other hand, if internal cloud turbulence dominates it is appropriate to assume that both species have the same value of b. For a canonical diffuse cloud temperature of 80 K, b values $\gtrsim 0.5$ km s^{-1} imply that turbulence is the dominant broadening mechanism. Thus, the Na I/Ca II ratio of each component was calculated for a range of b values as follows: for very narrow lines ($b_{\mathrm{Na}} \leqslant 0.5$ km s^{-1}) the b values were assumed to be in the ratio 1.3:1, while for broader lines the b values for each ion were assumed to be the same. The calculation was performed from a lower limit of $b_{\mathrm{Na}} = 0.3$ km s^{-1}, to the upper limit determined from the observed line profile (Table 1). For the three identified velocity components this analysis yielded the following range of Na I/Ca II ratios: 0.67–1.0 (-22 km s^{-1} component); 9.4–133 (-18 km s^{-1} component); and 3.9–6.7 (-4.3 km s^{-1} component). Note that the small range deduced for the latter component is a consequence of the fact that a *lower* limit to b_{Na} is available from the observed line profile.

In Paper 1 it was shown that the (estimated) Na I/H ratios of these components implies that they arise in standard diffuse clouds, and not in warm, low-density 'intercloud' type material. The high Na I/Ca II ratios of the strongest two components reinforce this conclusion, while the lower ratio found for the -22 km s^{-1} component suggests an origin in lower density gas.

3.2 The Sco–Cen shell

It was suggested in Paper 1 that these components may arise in a shell of neutral gas which forms the boundary of the Sco–Cen interstellar bubble. The evidence for neutral shells associated with the Sco–Cen association has recently been reviewed by de Geus (1991), who finds evidence for three separate shells. The largest of these, which is the only one to intercept the line-of-sight to HD 174632, is centred at a distance of 140 ± 20 pc in the direction $l = 320° \pm 3°$, $b = +10° \pm 3°$; this shell has a radius of about 110 ± 10 pc and is expanding at 10 ± 2 km s^{-1} (*cf.* table 1 of de Geus 1991). If we adopt these shell parameters we find that, for this line-of-sight, the near and far sides of the shell lie at distances of 70 and 108 pc. As the star lies at a distance of about 180 pc (Paper 1), it is tempting to try and identify absorption components that arise in both the approaching and receding parts of the shell. However, a shell expansion velocity of 10 km s^{-1} predicts near- and far-side heliocentric velocities of -11.1 ± 0.4 and -7.7 ± 0.4 km s^{-1}, respectively, which are not in agreement with any of the observed velocities.

It is possible to obtain a shell model which gives velocities within a few km s^{-1} of the values observed for the two strongest components, and which is described by parameters within the uncertainties listed by de Geus (1991). For example, a shell centred 136 pc from the sun at $l = 323°$, $b = +7°$, with a radius of 110 pc and expanding at 12 km s^{-1}, would result in heliocentric velocities of -14.6 km s^{-1} (near-side) and -4.2 km s^{-1} (far-side). We see that the latter is essentially identical to that of one of the main components towards HD 174632, and that the former is within about 3 km s^{-1} of the other. However, a shell with these parameters gives a poorer fit to the absorption components observed towards the 23 Sco–Cen stars studied by Crawford (1991) and, in any case, the Na I/Ca II ratios of the HD 174632 components are larger (in the case of the -18 km s^{-1} component, much larger) than those identified as belonging to the Sco–Cen shell. It therefore appears unlikely that either of these components arises in the Sco–Cen shell.

In Paper 1 it was stated that the interior of the Sco–Cen bubble is thought to be similar to the interior of the Local Bubble, and therefore devoid of dense interstellar clouds. However, reference to the distribution of nearby dark clouds presented by Dame *et al.* (1987, their fig. 7) shows that there is a string of dark (CO emitting) clouds within 200 pc of the sun in the longitude range $300° \lesssim l \lesssim 4°$, which are well within the confines of the Sco–Cen bubble as defined, for example, by Cox & Reynolds (1987) and de Geus (1991). Thus, contrary to the impression given in Paper 1, it is possible for lines-of-sight through the Sco–Cen bubble to pass through dense interstellar material other than that at the boundary with the Local bubble. Indeed, there is abundant evidence that the lines-of-sight to stars in the Upper-Scorpius subgroup of the Sco–Cen association ($341° \lesssim l \lesssim 2°$) pass through relatively dense 'diffuse' gas inside the Sco–Cen shell and which is probably associated with the dark clouds (Crawford 1991 and references therein). The Na I/Ca II ratios of the two strongest components observed towards HD 174632 are consistent with an origin in similar material.

We will now re-examine the evidence for the locations of each of the three interstellar clouds observed towards HD 174632, and in so doing will address one of the as yet unanswered points raised by the referee of Paper 1.

3.3 The -4.3 km s^{-1} component

The line-of-sight to HD 174632 passes close (i.e. within about 1.2°) to the boundary of the R CrA dark cloud, as given by Dame *et al.* (1987, *cf.* their table 2). Marraco & Rydgren (1981) obtained a distance of 129 pc for the R CrA cloud, which is consistent with the value of 150 ± 50 pc obtained by Gaposchkin & Greenstein (1936) on the basis of star counts. At a distance of 129 pc, 1.2° corresponds to a distance of only 2.7 pc. As the distance to the star is estimated to be 180 pc, we see that it is quite plausible that at least one of the absorption components arises in the vicinity of the dark cloud.

Dame *et al.* (1987) give the mean LSR radial velocity of the R CrA cloud as $+6$ km s^{-1}. In this direction heliocentric velocities are 9.4 km s^{-1} more negative than LSR values, so we see that the component observed at $v_{\mathrm{helio}} = -4.3$ km s^{-1} is within 1 km s^{-1} of the velocity of the dark cloud. Moreover, Cardelli & Wallerstein (1989) obtained a mean heliocentric velocity of -3.9 ± 1.0 km s^{-1} for atomic and molecular lines towards the star TY CrA, which is embedded within the R CrA dark cloud; this velocity is essentially identical to that found for this component. Although in this case the lines-of-sight are separated by 6.5° (corresponding to 15 pc), this is comparable to the diameter of the cloud mapped in CO by Dame *et al.* (1987) and is not inconsistent with the suggestion that the diffuse gas is associated with the molecular cloud. The Na I/Ca II ratio of this material is similar to that of the 'standard' diffuse clouds discussed by Hobbs (1976), and suggests a density of several tens of H atoms cm^{-3}. The non-detection of CH indicates that molecular gas does not extend to this distance from the R CrA dark cloud.

We note that the heliocentric velocity predicted to arise from galactic rotation at a distance of 129 pc in this direction (assuming the Oort constant, $A = 13$ km s^{-1} kpc^{-1}; Fich, Blitz & Stark 1989) is -9.1 km s^{-1}. Thus the R CrA dark cloud, and associated diffuse gas, have a peculiar velocity of about $+5$ km s^{-1}. As this cloud lies just beyond the far-side of the Sco–Cen shell it is possible that the expansion of the latter is at least partly responsible for this positive velocity, but note that 5 km s^{-1} is well within the range of residuals obtained by Fich *et al.* from their rotation model (*cf.* their fig. 5a).

Out to a distance of 180 pc (i.e. the estimated distance to the star) galactic rotation would be expected to result in heliocentric velocities in the narrow velocity range -9.4 to -9.0 km s^{-1}, so we see that the other two components have peculiar velocities of about -13 and -9 km s^{-1}. It is therefore necessary to try and explain the origin of these large negative velocities in the (relatively) local interstellar medium.

3.4 The -18 km s^{-1} component

The velocity of this component is very close (i.e. within about 1 km s^{-1}) to that predicted by two of the local interstellar wind vectors identified by Lallement, Vidal-Madjar &

Ferlet (1986; their vectors *A* and *O*). However, there are two arguments against attributing this component to the local flows identified by Lallement *et al.* First, components identified with these vectors generally have low Na I/Ca II ratios ($\lesssim 1.0$; Crawford 1991) characteristic of warm, low-density gas), whereas this component has a much larger ratio. Secondly, the fact that no strong Na I components exist towards the star σ Sgr (Hobbs 1978; $l=9.6°$, $b=-12.4°$, dist. $=65\pm20$ pc) suggests that this component, like that at -4.3 km s^{-1}, lies byeond the local bubble, and hence outside the region discussed by Lallement *et al.* (at the distance of σ Sgr, the lines-of-sight are separated by 5.1 ± 1.6 pc).

The large Na I/Ca II ratio suggests an origin in a relatively dense diffuse interstellar cloud, similar to that responsible for the -4.3 km s^{-1} component. However, the velocity of this component is significantly more negative than that of the R CrA dark cloud, and no component was found at this velocity towards TY CrA by Cardelli & Wallerstein (1989). If this component does arise in the vicinity of the dark cloud, it implies that part of the associated diffuse gas has been given a peculiar velocity of at least 14 km s^{-1} towards the sun. It is possible that star formation activity in the nearby dark cloud, which is known to contain a number of T Tauri stars (e.g. Knacke *et al.* 1973), H–H objects (Strom, Strom & Grasdalen 1974) and IR sources (Vrba, Strom & Strom 1976), could have resulted in the ejection of material. And, indeed, Levreault (1988) has detected at least one bipolar CO outflow, with a velocity of 18 km s^{-1}, within the R CrA dark cloud. However, it must be said that neither the narrow line width (Table 1) or the high Na I/Ca II ratio suggest that the material has been significantly disturbed.

On the other hand, it may be that this component arises in a diffuse cloud within the Sco–Cen bubble. As noted above, the survey of Dame *et al.* (1987) implies that clouds of dense gas do exist within this bubble. However, as only part of the negative velocity can, apparently, be accounted for by expansion of the bubble (Section 3.2), the problem of explaining the velocity remains.

3.5 The -22 km s^{-1} component

This component lies within 3 km s^{-1} of the velocity predicted by vectors *A* and *O* of Lallement *et al.* (1986). The relatively low Na I/Ca II ratio inferred for this component ($0.7\lesssim$ Na I/Ca II $\lesssim 1.0$) is also consistent with the range of values found for this material towards the Sco–Cen association by Crawford (1991).

Additional evidence that this component arises in the local interstellar medium (i.e. within the Local bubble) is provided by the observation of a weak Ca II line, at a very similar velocity (-24 km s^{-1}), towards σ Sgr (quoted by Hobbs 1978). As discussed in Paper 1, and reiterated above, σ Sgr lies within the Local bubble but close to the boundary with the Sco–Cen bubble (*cf.* fig. 2 of Paper 1). The upper limit to the Na I column density reported by Hobbs (1978) implies a Na I/Ca II ratio of <0.25, which is also consistent with an origin in the warm, low-density, local interstellar medium. Note, however, that the somewhat larger Na I/Ca II ratio found for the component towards HD 174632 does suggest that this material is not completely uniform on scales of a few parsecs.

4 CONCLUSIONS

The spectrum of interstellar Ca II obtained towards HD 174632, together with renewed consideration of the distribution of dark clouds within a few hundred parsecs of the sun (as mapped by Dame *et al.* 1987), has enabled us to extend the study of this sightline originally presented in Paper 1. The conclusions of the present work are as follows.

(1) The large Na I/Ca II ratios of the two strongest Na I components suggests that they arise in relatively dense diffuse clouds. This is in agreement with the results of Paper 1, where the same conclusion was reached on the basis of the estimated Na I/H ratios.

(2) Contrary to the conclusion of Paper 1, neither the velocities, or Na I/Ca II ratios, of the components suggests an origin in the Sco–Cen shell.

(3) The line-of-sight passes within a few parsecs of the R CrA dark cloud. The -4.3 km s^{-1} component has essentially the same velocity (i.e. within 1 km s^{-1}) as the R CrA cloud, and it is suggested that this component arises in diffuse gas that is local to the dark cloud.

(4) The Na I/Ca II ratio of the -18 km s^{-1} component strongly suggests that it also arises in a fairly dense ($n_{\rm H}>10$ cm^{-3}) diffuse cloud. However, it is difficult to account for the velocity of this component, which is significantly more negative than that of the R CrA dark cloud. Assuming that an origin in the Sco–Cen shell is ruled out for the reasons given in (2) above, it may be that the high velocity of this component reflects energetic activity within the R CrA cloud, possibly associated with star formation.

(5) Several lines of evidence suggest that the -22 km s^{-1} component arises within the Local bubble (specifically, within about 65 pc of the sun) and represents material similar to that identified by Lallement *et al.* (1986) within a few tens of parsecs of the sun. Both the velocity and Na I/Ca II ratio are consistent with this interpretation.

ACKNOWLEDGMENTS

The observations on which this paper is based were obtained while the author held a Royal Society Overseas Fellowship at Mt Stromlo. In addition to the Royal Society, I thank the Director and staff of the Mt Stromlo and Siding Spring Observatories for their hospitality, and the Central Research Fund of the University of London for provision of a travel grant. I thank the referee for thoughtful comments on the original manuscript.

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