Mon. Not. R. astr. Soc. (1992) **254,** 264–272

Observations of interstellar Na I and Ca II towards five southern stars and some comments on the location of the denser diffuse clouds in the southern Milky Way

I. A. Crawford

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

Accepted 1991 August 23. Received 1991 August 19; in original form 1991 July 16

SUMMARY

High-resolution observations (3.6 km s^{-1} FWHM) of interstellar Na I and Ca II lines towards five southern early-type stars are presented. All five stars have strong absorption lines with low LSR radial velocities ($|v_{\rm lsr}| \lesssim 5$ km s^{-1}) which are interpreted as arising in material associated with the ridge of local molecular clouds identified by Dame *et al.* It is argued that the strong, low-velocity, atomic and molecular lines observed towards other southern stars close to the galactic plane also arise in this material, and special reference is made to the foreground interstellar spectrum of the Sco OB1 association. Four of the observed stars also have absorption components consistent with an origin in the Sagittarius–Carina spiral arm, and two (HD 111904 and 164402) have highly negative velocity components ($v_{\rm lsr} \lesssim -40$ km s^{-1}) which are interpreted as arising in expanding shells centred on the Cen OB1 and Sgr OB1 associations, respectively.

1 INTRODUCTION

This paper presents high-resolution observations of interstellar Na I D_2 (5889.950 Å) and Ca II K (3933.663 Å) absorption lines towards five southern early-type stars. All five stars were selected for observation because they lie beyond the Scorpio–Centaurus interstellar bubble, which has been discussed in a previous paper (Crawford 1991a). By observing stars which lie beyond both the near and far sides of the bubble it was hoped that both would be clearly detected in the absorption spectra. In the event, the presence of strong absorption lines at low LSR velocities towards four of the stars made an unambiguous identification of these (relatively weak) components impossible, and Sco–Cen shell components were found not to be present towards the remaining star (HD 129557). Nevertheless, the interstellar spectra of these stars are still of interest, especially for the information they yield on the distribution of interstellar material, both in the vicinity of the Sun and within the Sagittarius spiral arm. Details of the observed stars are given in Table 1.

2 OBSERVATIONS AND REDUCTIONS

The observations reported here were obtained with the coudé echelle spectrograph of the Mt Stromlo 74-inch telescope during 1989 June and July. The spectrograph was used with the 130-inch focal-length camera, giving a dispersion of 0.53 Å mm^{-1} at the sodium D lines and 0.35 Å mm^{-1} at the calcium K line. The adopted slit width was 300 μm, giving a velocity resolution (FWHM) of 3.6 km s^{-1} (R=83 000). The exposure times were all in the range 2400 to 5300 s; for example, the exposures made of HD 111904 were 3000 s (Na I) and 3600 s (Ca II).

The spectra were recorded with the Mt Stromlo Photon Counting Array (Rodgers *et al.* 1988) and were reduced using FIGARO (Shortridge 1988) on the UCL STARLINK node; full details of the reduction procedure have been given previously (e.g. Crawford, Barlow & Blades 1989; Crawford 1991a). Following wavelength calibration the observed wavelengths were converted to the LSR velocity frame, assuming a solar motion of 20 km s^{-1} towards l=57°, b= +22° (Allen 1973). The atmospheric water lines that occur in the region of the Na D_2 line were removed by dividing each spectrum by that of the unreddened star γ Lup, as described by Crawford (1991a). The observed spectra are shown in Fig. 1.

It is necessary to guard against contamination of the interstellar features by stellar photospheric lines; this is a particular problem in the case of the stellar Ca II K line, which can attain a non-negligible equivalent width even in the earliest B stars (Hobbs 1973). Three of the five stars (HD 135240, 135591 and 164402) are of sufficiently early spectral type, and have sufficiently high rotational velocities, that stellar contamination is expected to be negligible (Table 1). However, a stellar K line is certainly present in the spectrum of

HD 111904 (B9Ia), and there is also evidence for one in the spectrum of HD 129557 (B2III). In both cases the equivalent widths (650 ± 90 and 57 ± 16 mÅ, respectively) are in agreement with those expected for stars of these spectral types (*cf.* the theoretical results presented by Crawford 1990a), and the profiles are consistent with the projected stellar rotational velocities (Table 1). These lines were removed by fitting a Gaussian to those parts of the Ca II profile that lie outside the velocity range occupied by the (clearly interstellar) Na D_2 components, and dividing the observed data by the fitted curve. The Gaussian fits are shown as insets in Fig. 1.

3 LINE PROFILE ANALYSIS AND COLUMN DENSITIES

Column densities and velocity dispersions were obtained by means of a line profile analysis similar to that described in previous work (e.g. Crawford *et al.* 1989). Theoretical line profiles were calculated using the DIPSO program (Howarth & Murray 1988). The adopted oscillator strengths were 0.655 for Na D_2 and 0.688 for Ca K (Morton & Smith 1973), and the unresolved hyperfine splitting of the D_2 line (separation 0.97 km s^{-1}) was allowed for in the analysis.

The results of the line profile analysis are given in Table 2, which lists the LSR radial velocity, $v_{\rm lsr}$, column density, N, and velocity dispersion, b, determined for each component. The theoretical line profiles generated with these parameters are shown (after convolution with the instrumental profile) superimposed on the observed spectra in Fig. 1. Table 2 also lists the ranges of column density and velocity dispersion, ΔN and Δb, which were found to be consistent with the observed profiles.

Several components were found to be essentially unresolved, and for these an upper limit to b is given in Table 2. As the line saturates at a lower column density for smaller b, it is necessary to estimate a lower limit to b in order to obtain an upper limit for N. Here a lower limit of $b = 0.3$ km s^{-1} has been adopted, which is less than the lowest b value found by Blades, Wynne-Jones & Wayte (1980) from their very high-resolution ($R = 6 \times 10^5$) study of interstellar Na I lines. The very high column density upper limits (typically a few $\times 10^{14}$ cm^{-2}) listed in Table 2 for those components with an upper limit indicated under Δb are the result of adopting this lower limit for b.

4 DISCUSSION

Before turning to a discussion of the individual spectra, we will first discuss the distribution of interstellar matter within a kiloparsec of the Sun for the galactic longitude range of interest here. This will enable us to place the present observactions in perspective. We will also use this perspective to briefly discuss the origin of the foreground (i.e. low-velocity) material that exists towards the Scorpius OB1 association (Crawford *et al.* 1989).

4.1 The distribution of nearby interstellar matter in the longitude range $10° \geq l \geq 300°$

The positions of the five stars observed here are plotted in galactic coordinates in Fig. 2. This figure also shows the following interstellar features.

(i) The boundaries of the molecular clouds identified by Dame *et al.* (1987); the names of these clouds are indicated.

(ii) The locations of dark clouds identified in the extensive survey of southern dark clouds by Feitzinger & Stüwe (1984); only clouds with surface areas greater than one square degree are included, and these are indicated by open circles of the appropriate surface area.

Table 1. Basic data for the stars observed. References are given in the footnotes.

Star (HD)	l	b	V	Sp. type	Ref.	$v \sin i$ (km s^{-1})	$E(B-V)$	Ref.	Dist. (pc.)	Ref.
111904	303.2	+2.5	5.8	B9 Ia	1	81	0.34	1	2500	1
129557	318.6	+3.8	6.1	B2 III	2	34	0.19	2	660	2
135240	319.7	−2.9	5.1	O7.5 III	3	189	0.26	1	950	3
135591	320.1	−2.6	5.5	O7.5 III	3	121	0.22	1	1200	3
164402	7.2	0.0	5.8	B0 Ib	2	100	0.26	2	1600	1

References for spectral types: (1) *Bright Star Catalogue* (BSC; Hoffleit & Jaschek 1982); (2) Garrison, Hiltner & Schild (1977); (3) Walborn (1972).

References to colour excesses: (1) observed colours from BSC, intrinsic colours from Deutschman, Davis & Schild (1976); (2) observed colours from Schild, Garrison & Hiltner (1983), intrinsic colours from Deutschman *et al.*

References to distances: (1) OB association distance (Humphreys 1978); (2) calculated using absolute magnitude of Deutschman *et al.* (1976); (3) calculated using O-star absolute magnitudes of Walborn (1972).

All $v \sin i$ values are from the BSC, except that for HD 129557 which is from Buscombe & Stoeckley (1975).

(iii) The extent of the H I self-absorption region identified by Riegel & Crutcher (1972; marked by a dotted line) and which, as noted by Crutcher & Lien (1984), appears to be spatially correlated with the local dust clouds. Detailed contour maps of this cloud can be found in figs 3 and 4 of Riegel & Crutcher (1972).

(iv) The position of the Sco OB1 association (marked by a ⊗ symbol), the interstellar spectrum of which has been

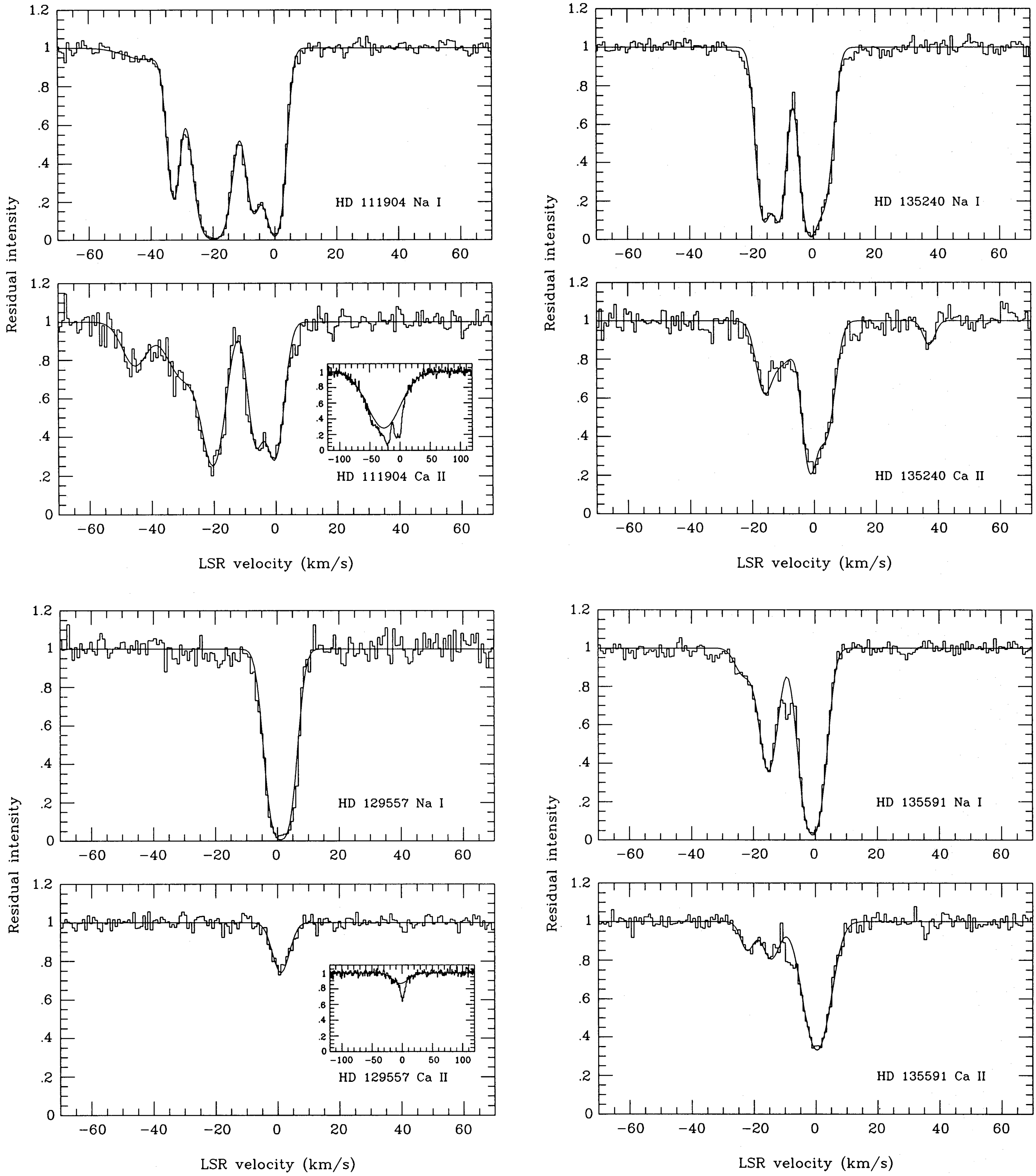

Figure 1. The observed interstellar Na I and Ca II absorption lines. The observed intensities are plotted as histograms; the smooth curves are theoretical line profiles with the parameters given in Table 2. Where appropriate, the fits made to the stellar Ca II *K* lines are shown as insets.

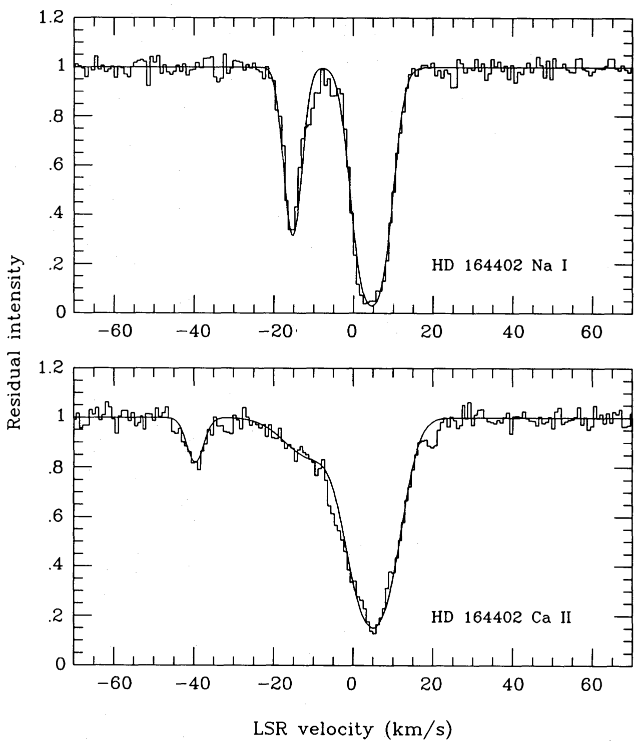

Figure 1 – *continued*

extensively studied in previous work (Crawford *et al.* 1989; Crawford 1989, 1990b).

Dame *et al.* (1987) quote distances of about 170 pc for all of the molecular clouds indicated in Fig. 2. These estimates were obtained from a number of authors, and we will briefly discuss some of them here; we will also refer to other distance estimates where appropriate. Rodgers (1960) obtained a distance of 174 ± 18 pc for the Coalsack, while Franco (1989) found a maximum distance of 180 ± 26 pc but noted that some absorption may occur as close as 120 pc. Dame *et al.* (1987) estimated the distance of G317 − 4 to be 170 pc based on the extinction survey of Neckel & Klare (1980); from their $A_V(r)$ diagram of the appropriate region, I estimate the uncertainty on this distance to be at least ± 50 pc. Murphy, Cohen & May (1986) obtained a *maximum* distance of 170 pc for the Lupus clouds, but note that they may be as close as 130 pc; the absence of Na I and Ca II absorption lines towards ρ Sco, and the presence of only very weak lines towards μ^1 Sco, and HD 143699, all of which are seen projected against the Lupus complex, indicate that the clouds are not closer than about 140 pc (Crawford 1991a). Chini (1981) obtained a distance of 165 ± 20 pc for the ρ Oph clouds; however, de Geus, de Zeeuw & Lub (1989) obtained 125 ± 25 pc for the cloud centre, and distances to the near and far edges of 80 and 170 pc respectively. All these distance estimates are consistent with the value of 170 pc adopted by Dame *et al.* (1987), but suggests that some of this molecular material may actually be somewhat closer.

It is of interest to estimate the distances to the larger dark clouds identified in this region by Feitzinger & Stüwe (1984; open circles in Fig. 2). Feitzinger & Stüwe (1986) estimate that most of the clouds in their catalogue are closer than 400 pc. For those regions approximately coincident with the larger clouds marked in Fig. 2, the data of Neckel & Klare (1980) indicate an abrupt increase in absorption (typically by 0.5–1 mag) at a distance of $\lesssim 200$ pc. Most of these regions also show a second jump in A_V (typically by another 1–2 mag) at distances greater than about 700 pc. This is clearly illustrated in fig. 9(a) of Neckel & Klare (1980).

Finally, we note that Crutcher & Lien (1984) obtained a distance of 125 ± 25 pc for the large H I cloud identified by Riegel & Crutcher (1972; dotted box in Fig. 2) which, as discussed by Crutcher & Lien, appears to be spatially correlated with the local dust clouds. Thus the available evidence indicates that the nearest dust clouds, together with Riegel & Crutcher's H I cloud, all belong to the ridge defined by the nearby molecular cloud complexes (Dame *et al.* 1987; *cf.* their fig. 7). Dame *et al.* (their section V) note that the major cloud complexes in this ridge may be connected by lower density material, and they speculate that this ridge marks the inner edge of the local spiral arm.

For an assumed distance of 170 pc, all lines of sight through this ridge will pass within $\lesssim 15$ pc of a dark and/or molecular cloud (*cf.* Fig. 2). It is very likely, therefore, that the spectra of stars in this direction will exhibit absorption lines that arise either in the outskirts of the individual clouds, or in diffuse gas permeating the entire ridge. In this context it is of interest to recall the conclusion of Federman & Willson (1982) that 'for most lines of sight, diffuse clouds are the outer, relatively transparent portions of dark clouds.'

All of these foreground clouds have low LSR radial velocities; Dame *et al.* (1987) give *average* velocities of −4, −6, +5 and +3 km s^{-1} for the Coalsack, G317 − 4, Lupus and ρ Oph clouds, respectively. Of course, these clouds actually exhibit a range of velocities, but this is fairly restricted; for example, Nyman, Bronfman & Thaddeus (1989) found the Coalsack to occupy the velocity range −6 to 0 km s^{-1}, and Murphy *et al.* (1986) found the Lupus clouds to have velocities in the range 0 to +12 km s^{-1}.

4.2 HD 111904

HD 111904 is a member of the Centaurus OB1 association, which lies in the Sagittarius–Carina spiral arm at a distance of 2.5 kpc (Humphreys 1978). The distribution of OB associations given by Humphreys (and plotted on the galactic plane by Lynds 1980) shows that the Cen OB1 association lies towards the far side of the Sagittarius arm. Thus, the line of sight to HD 111904 would be expected to sample interstellar material within the Sagittarius arm as well as that associated with the inner edge of the local arm. Moreover, as many OB associations have been found to be surrounded by expanding shells, swept up by the cumulative action of the winds from the member stars, highly blueshifted components might also be expected. The optical absorption lines towards HD 111904 have a complicated velocity structure which is qualitatively consistent with these considerations.

As the line of sight passes through the band of local dark clouds it passes very close to the Southern Coalsack. Indeed, as indicated in Fig. 2, it actually passes within the area of sky assigned to the Coalsack by Dame *et al.* (1987), although it misses the outer (2 K km s^{-1}) CO contour of Nyman *et al.* (1989) by about half a degree, or 1.5 pc at a distance of 170 pc. The molecular gas in the Coalsack mostly occupies the velocity range −6 to 0 km s^{-1} (Nyman *et al.* 1989; their fig.

Table 2. Equivalent widths, w_λ (mÅ, 2σ errors); LSR velocities, $v_{\rm lsr}$ (km s^{-1}, 1σ errors); velocity dispersions, b (km s^{-1}); and column densities, N (cm^{-2}), for the interstellar Na I D_2 and Ca II K lines towards the observed stars. The equivalent widths are summed over all identified velocity components and the errors are based on the continuum scatter and an assumed 2 per cent zero-level error. Δb and ΔN are the ranges of b and N that give acceptable fits to the observed profiles; for unresolved lines an upper limit is given under Δb, and the upper limit to N calculated for an assumed lower limit to b of 0.3 km s^{-1}. For components identified in only one species, the column density upper limit for the other has been estimated from the equivalent width upper limit at that velocity, assuming a linear curve of growth.

			Na I Components					**Ca II Components**				
Star	w_λ(*Na I*)	w_λ(*Ca II*)	v_{lsr}	b	N	Δb	ΔN	v_{lsr}	b	N	Δb	ΔN
HD 111904	635 ± 26	285 ± 14	−41.7 ± 12.2	9.0	1.0 (11)	5.0 – 11.0	0.6 – 1.3 (11)	−45.4 ± 2.1	5.0	3.5 (11)	3.0 – 7.0	2.0 – 5.0 (11)
			−33.0 ± 0.3	1.5	1.0 (12)	≤ 2.0	0.8 – 100 (12)	−29.4 ± 5.1	7.0	6.5 (11)	4.0 – 10.0	4.0 – 9.0 (11)
			−20.0 ± 0.4	4.8	5.5 (12)	3.0 – 5.5	3.5 – 50 (12)	−20.1 ± 0.9	4.0	1.5 (12)	3.5 – 4.5	1.3 – 1.8 (12)
			−6.8 ± 0.8	2.2	1.2 (12)	≤ 3.5	1.0 – 200 (12)	−6.6 ± 0.9	2.2	8.0 (11)	1.5 – 3.5	6.0 – 12 (11)
			+0.1 ± 0.7	2.2	4.5 (12)	1.0 – 3.0	3.5 – 100 (12)	−1.0 ± 1.3	3.0	1.2 (12)	2.0 – 4.0	0.9 – 1.4 (12)
HD 129557	234 ± 13	23 ± 3	+1.0 ± 0.3	3.5	5.0 (12)	2.0 – 5.0	3.0 – 50 (12)	+0.9 ± 0.4	3.0	2.8 (11)	2.5 – 4.0	2.0 – 3.5 (11)
HD 135240	416 ± 18	162 ± 9	−16.3 ± 0.3	1.5	2.0 (12)	≤ 2.5	1.2 – 300 (12)	−16.4 ± 1.0	2.5	3.0 (11)	1.5 – 4.0	2.0 – 4.5 (11)
			−10.9 ± 0.3	1.5	2.0 (12)	≤ 2.2	1.2 – 300 (12)	−9.9 ± 2.2	6.0	4.0 (11)	4.0 – 9.0	3.0 – 6.0 (11)
			−1.8 ± 0.3	1.5	1.5 (13)	≤ 2.0	1.0 – 900 (12)	−1.4 ± 0.8	2.0	1.2 (12)	1.5 – 2.5	0.8 – 1.4 (12)
			+4.1 ± 0.3	2.2	9.0 (11)	1.2 – 3.5	7.0 – 20 (11)	+4.2 ± 0.9	3.0	8.5 (11)	2.5 – 4.0	6.0 – 10 (11)
			...	...	≤ 1.5 (10)	...	...	+37.2 ± 1.2	1.5	9.0 (10)	≤ 2.0	7.0 – 15 (10)
HD 135591	308 ± 14	124 ± 6	−24.2 ± 2.6	3.0	1.0 (11)	2.0 – 4.0	0.6 – 1.4 (11)	−22.1 ± 1.6	2.0	1.2 (11)	≤ 3.0	1.0 – 1.5 (11)
			−15.2 ± 0.4	3.0	7.0 (11)	2.0 – 3.5	6.0 – 8.0 (11)	−14.4 ± 3.3	3.0	2.0 (11)	2.0 – 4.0	1.0 – 2.5 (11)
			−1.0 ± 0.2	3.5	3.0 (12)	3.0 – 4.0	2.5 – 4.0 (12)	+0.3 ± 0.6	5.0	1.5 (12)	4.0 – 5.5	1.2 – 1.7 (12)
HD 164402	294 ± 14	225 ± 11	...	...	≤ 3.2 (10)	...	...	−39.7 ± 0.8	2.0	1.5 (11)	≤ 3.5	1.2 – 3.0 (11)
			−15.3 ± 0.3	1.8	7.0 (11)	≤ 2.5	5.0 – 200 (11)	−12.5 ± 3.4	9.0	4.0 (11)	7.0 – 11.0	3.0 – 5.0 (11)
			+4.5 ± 0.2	4.0	3.0 (12)	2.5 – 4.5	2.5 – 10 (12)	+4.7 ± 0.4	6.5	3.2 (12)	6.0 – 7.5	3.0 – 4.0 (12)

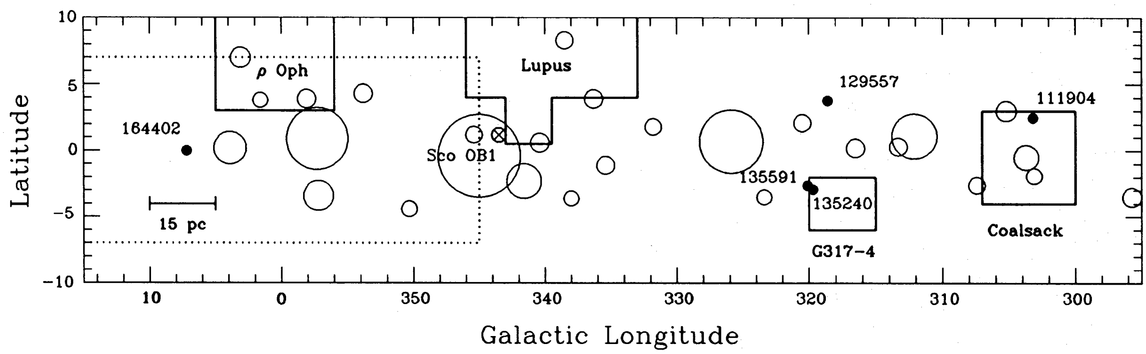

Figure 2. The locations of the observed stars plotted in galactic coordinates (solid circles labelled with HD numbers). The positions of the nearby molecular (Dame *et al.* 1987) and dark (Feitzinger & Stüwe 1984) clouds are plotted as rectangles and circles, respectively. The molecular clouds are named according to the scheme of Dame *et al.* 1987 (their fig. 7). The region occupied by the H I cloud identified by Riegel & Crutcher (1972) is marked by a dotted rectangle. The position of the Sco OB1 association is indicated by a ⊗ symbol. The scale bar assumes a distance of 170 pc, the estimated (maximum) distance of the molecular clouds; all five stars, and the Sco OB1 association, lie well beyond these clouds.

4), so the two least negative velocity components observed towards this star have velocities that suggest an origin in outlying atomic gas associated with the Coalsack. A very similar velocity structure was found for the interstellar CH lines towards HD 110432 which is another star lying beyond the Coalsack (Crawford 1991b).

The map of OB associations presented by Lynds (1980) shows that the line of sight to Cen OB1 passes through about 1 kpc of the Sagittarius arm; i.e. from the association itself at a distance of 2.5 kpc (Humphreys 1978) to the near edge of the Sagittarius arm at a distance of about 1.5 kpc. The galactic rotation model of Fich, Blitz & Stark (1989) indicates that material corotating with the Galaxy within this distance interval would be expected to occupy the velocity range $-25 \lesssim v_{\rm lsr} \lesssim -15$ km s^{-1}. This is consistent with the radial velocity of Cen OB1 itself being -23.8 km s^{-1} (Humphreys 1972), and with the velocities found for the Sagittarius–Carina molecular clouds by Cohen *et al.* (1985). Thus, we see that the strong absorption line observed at -20 km s^{-1} in both Na I and Ca II occurs at exactly the velocity expected for material within the Sagittarius arm; the breadth of this line almost certainly indicates that it is composed of several unresolved components, all of which would have velocities consistent with diffuse clouds in the Sagittarius arm.

In addition to the components which may be identified as arising in the local and Sagittarius spiral arms, two other components were observed towards HD 111904. These have velocities of about -30 and -45 km s^{-1} and, relative to the galactic rotation velocity at Cen OB1, are blueshifted by about 5 and 20 km s^{-1} respectively. A peculiar velocity of 5 km s^{-1} lies within the range of velocities typically found for individual diffuse clouds, and is not inconsistent with an origin within the Sagittarius arm. However, the -45 km s^{-1} component cannot plausibly be explained in the same way.

As noted above, OB associations are often found to lie within expanding interstellar bubbles (e.g. Munch 1957; Walborn & Hesser 1975; Cowie, Songaila & York 1979; Crawford *et al.* 1989), and it seems reasonable to attribute the -45 km s^{-1} component to an origin in a similar shell surrounding Cen OB1. This interpretation is considerably strengthened by a consideration of the Na I/Ca II ratio of this component. Unlike the other four components observed towards HD 111904, this alone has Ca II stronger than Na I; the column densities given in Table 2 imply $0.12 \le N(\mathrm{Na\,I})/N(\mathrm{Ca\,II}) \le 0.65$. In previous work on the Sco OB1 association (Crawford *et al.* 1989) it was found that, in contrast to the foreground diffuse clouds, the high-velocity shell components had $0.2 \le N(\mathrm{Na\,I})/N(\mathrm{Ca\,II}) \le 2$, an observation which was attributed to the removal of adsorbed Ca atoms from grain surfaces by intermediate velocity shocks. The low Na I/Ca II ratio of the most negative velocity component towards HD 111904 is fully consistent with a similar interpretation.

4.3 HD 129557

HD 129557 is the closest of the five stars discussed in this paper and has much the simplest interstellar spectrum, with only one component positively identified in both Na I and Ca II. This component is very strong in Na I, but relatively weak in Ca II; the Na I/Ca II ratio was found to be in the range $8.6 \le N(\mathrm{Na\,I})/N(\mathrm{Ca\,II}) \le 250$ (where the very large upper limit allows for the fact that the Na I line may be fully saturated). Large Na I/Ca II ratios of this kind are characteristic of relatively cold and dense diffuse clouds in which gas-phase Ca atoms have become adsorbed onto grain surfaces (*cf.* discussion in section V of Crawford *et al.* 1989, and references therein). The velocity of this component ($v_{\mathrm{lsr}} = +1$ km s^{-1}) is consistent with that found for the local dark clouds (Section 4.1), and it is suggested that this component arises in a relatively dense diffuse cloud belonging to this complex.

As there is only one strong absorption component towards this star, we might also expect to have observed weaker components arising in the foreground Sco–Cen shell (Crawford 1991a); the expected velocities are about -9 and $+9$ km s^{-1} for the near and far sides of the shell. However, there is no evidence for components at these velocities towards HD 129557, although weak Ca II components may have been hidden by the stellar *K* line that was removed from this spectrum (*cf.* Section 2). On the other hand, it is known, from the non-observation of shell components towards some members of the Sco–Cen association (Crawford 1991a), that the diffuse clouds which make up this shell do not form a contiguous structure; some gaps do exist in the shell.

4.4 HD 135240

This star has strong absorption in both Na I and Ca II at low LSR velocity, the asymmetric profile of which indicates that at least two components are present. In addition there are two more negative velocity components (between -10 and -16 km s^{-1}) which are much stronger in Na I than in Ca II.

The low-velocity components occupy a very similar velocity range to the strong component towards the foreground star HD 129557, and are likewise attributed to an origin in the ridge of dark clouds discussed in Section 4.1. At the estimated distance of this material, the angular separation of the two stars (6°.8) corresponds to $\lesssim 20$ pc.

The estimated distance to HD 135240 (950 pc) places it at the near edge of the Sagittarius arm (according to the map of Lynds 1980), and the -10 km s^{-1} component is consistent with an origin in the near side of the Sagittarius arm (adopting the rotation model of Fich *et al.* 1989). Whatever the exact location of the absorbing cloud, the large Na I/Ca II ratio $(2 \le N(\mathrm{Na\,I})/N(\mathrm{Ca\,II}) \le 1000)$ suggests a fairly high density.

The most negative velocity component (at -16 km s^{-1}) has a velocity that is somewhat high to be explained by galactic rotation in the Sagittarius arm, although its peculiar velocity (i.e. its velocity relative to the systemic velocity at this distance) is within the range typically found for diffuse clouds and, as for the -10 km s^{-1} component, the high Na I/Ca II ratio also suggests an origin in a dense diffuse cloud.

There appears to be a Ca II component at the extreme positive velocity of $+37$ km s^{-1} towards this star. As is typical for high-velocity components, it has a very low Na I/Ca II ratio (≤ 0.2). However, although a good illustration of the Routly–Spitzer effect (Routly & Spitzer 1952), the origin of this large positive velocity is problematical; the receding side of the Sco–Cen bubble is expected to have a radial velocity of only $+9$ km s^{-1} in this direction, so is unable to account for this component.

4.5 HD 135591

HD 135591 lies within half a degree of HD 135240 on the sky and at a comparable distance; at the distance of the (nominally) closer of the two stars the lines of sight are separated by 8 pc, and at the distance of the foreground clouds by only 1.5 pc. Like HD 135240, HD 135591 exhibits strong absorption close to zero LSR velocity, and, although modelled here as a single component, the width of the Ca II line suggests that unresolved components are present in the low-velocity material towards this star, as was found to be the case for HD 135240.

The high (negative)-velocity components differ significantly between HD 135240 and 135591, being much stronger in the direction of the former. It is likely that the -15 km s^{-1} component towards HD 135591 arises in the same material as the -16 km s^{-1} component towards HD 135240; not only are the velocities very similar, but the Na I/Ca II ratios are also consistent. Moreover, the fact that the three-component fit to the Na I spectrum of HD 135591 fails to account for all the absorption observed at about -10 km s^{-1} may imply that the component observed at this velocity towards HD 135240 is also present towards this star, although much weaker.

The highest velocity component towards HD 135591 ($v_{\mathrm{lsr}} \sim -23$ km s^{-1}) may have a quite different origin; not only is its peculiar velocity rather high (~ 10 km s^{-1} relative to the systemic velocity), but it has a low Na I/Ca II ratio

[$0.4 \leq N$(Na I)/N(Ca II)≤ 1.4] which is characteristic of the removal of Ca atoms from grain surfaces. There are at least two possible explanations for the origin of this component, either: (i) it arises in a swept-up shell local to the star, or (ii) it arises in the very local interstellar medium, where Lallement, Vidal-Madjar & Ferlet (1986) have identified a number of (relatively weak) Ca II components with LSR velocities as negative as -25 km s^{-1}. In any case, the presence of a high-velocity, low Na I/Ca II ratio component towards HD 135591, which is absent towards HD 135240, implies inhomogeneities on a scale of $\lesssim 1.5$ pc (for the local interstellar medium) or $\lesssim 8$ pc (at the distance of HD 135240).

4.6 HD 164402

The Na I spectrum of HD 164402 is fairly simple, with just two components at LSR velocities -15.3 and $+4.5$ km s^{-1}. The $+4.5$ km s^{-1} component is typical of the low-velocity gas observed towards all five stars, and can also be assigned an origin in diffuse gas associated with the local band of dark clouds. This interpretation is supported by the fact that the line of sight passes within about 15 pc of the southerly limit of the ρ Oph dark cloud (Fig. 2) which has a radial velocity of $+3$ km s^{-1} (Dame *et al.* 1987). Moreover, the line of sight passes through the large region of H I self-absorption identified by Riegel & Crutcher (1972). Riegel & Crutcher identified H I velocity components at $+4$ and $+7$ km s^{-1}, both of which are consistent with the observed velocities and widths of the low-velocity Na I and Ca II lines towards HD 164402.

This component has also been observed by Bates & Catney (1991) towards stars in the globular cluster M22 ($l = 9^\circ\!.9$, $b = -7^\circ\!.6$), the line of sight to which passes within about 24 pc of that to HD 164402 at the estimated maximum distance of the absorbing material (170 pc). M22 lies approximately mid-way between the ρ Oph clouds to the north and the R CrA cloud to the south (with projected separations of about 40 and 30 pc, respectively), and the observations of Bates & Catney support the view that this low-velocity gas fills the regions between the molecular clouds along the ridge identified by Dame *et al.* (1987).

HD 164402 is a member of the Sgr OB1 association, which lies at a distance of 1.6 kpc in the Sagittarius arm (Humphreys 1978). Thus, in addition to the local absorption, we might expect to find evidence for absorption within the Sagittarius arm, as was the case for the line of sight to HD 111904. However, the low galactic longitude ($l = 7^\circ\!.2$) means that, even for a distance of 1.6 kpc, only a low (positive) LSR velocity is expected to result from galactic rotation; the rotation model of Fich *et al.* (1989) predicts a maximum velocity of $+6$ km s^{-1}, with a range of $+4$ to $+6$ km s^{-1} corresponding to that portion of the line of sight that lies within the Sagittarius arm. On the other hand, Mohr & Mayer (1957) found the Sgr OB1 radial velocity to be $+15.8$ km s^{-1}, and Dieter (1960) identified H I 21-cm emission at this velocity as being local to the association. If these radial velocities are reliable (that of Mohr & Mayer was based on only two stars) we might expect components with velocities more positive than those predicted by the model of Fich *et al.* Note, however, that positive velocities up to about $+10$ km s^{-1} would result in lines blended with those arising in the local clouds. The fact that the Na I line at this velocity is fairly narrow (i.e. no broader than that found towards the other stars) suggests that the line of sight through the Sagittarius arm to HD 164402 is fairly clear of dense (high Na I/Ca II ratio) clouds. On the other hand, the Ca II component at this velocity is much broader than the Na I line, an observation which suggests that it *is* composed of several unresolved low-density (low Na I/Ca II ratio) components, some of which may arise in the Sagittarius arm.

In the Na I spectrum there is a single blueshifted component, with a velocity of -15.3 km s^{-1}. As galactic rotation produces positive velocities in this quadrant, this negative velocity is most plausibly explained by the presence of a shell expanding away from the Sgr OB1 association. There is no comparably strong and narrow Ca II line at this velocity, although a very broad Ca II feature is present at about this velocity (-12.5 ± 3.4 km s^{-1}). The breadth of the Ca II feature again suggests that it is probably an unresolved blend of components, only one of which would correspond to the -15.3 km s^{-1} Na I component (which implies a rather large Na I/Ca II ratio). If the broad Ca II line at this velocity is a blend of several components, the others may arise in the local interstellar medium; the vectors A, O and I of Lallement *et al.* (1986) all predict local components with velocities in the range -9 to -16 km s^{-1} for this line of sight.

Finally, there is a Ca II component towards HD 164402 which has the very high velocity of -39.7 km s^{-1} and an equivalent width of 14 ± 2 mÅ. The observation of a component at this velocity confirms its original identification by Adams (1949), who found a weak Ca II component at -41.3 km s^{-1} on a photographic spectrum of this star. There is no sign of a corresponding Na I component, and the inferred limit to the column density ratio is N(Na I)/N(Ca II)≤ 0.3. The high velocity and very low Na I/Ca II ratio strongly suggest that this component arises in an outflow associated with the Sgr OB1 association.

4.7 The low-velocity gas towards the Sco OB1 association

The line of sight to the Sco OB1 association ($l = 343^\circ\!.5$, $b = +1^\circ\!.2$) has been the subject of earlier work. Here, we take the opportunity to interpret the low-velocity ($|v_{\rm lsr}| \lesssim 10$ km s^{-1}) components observed towards this OB association in terms of the distribution of foreground material sketched in Section 4.1. This velocity range is dominated by very strong Na I and Ca II lines (fully saturated in Na I; *cf.* fig. 2 of Crawford *et al.* 1989), and molecular lines due to interstellar CH, CH$^+$ and CN (Crawford 1989, 1990b).

From Fig. 2 we see that the line of sight passes very close to the boundary of the Lupus molecular cloud as mapped by Murphy *et al.* (1986), and also close to a number of the dark clouds identified by Feitzinger & Stüwe (1984). In fact, reference to the CO map of Murphy *et al.* (their fig. 2) shows that the line of sight passes within one degree of the outer (1.5 K km s^{-1}) CO contour, corresponding to 3 pc at a distance of 170 pc. This is therefore a likely location for the origin of the molecular lines found towards Sco OB1.

All nine of the Sco OB1 stars observed by Crawford (1989) were found to have at least one CH$^+$ component, and seven of them were found to have at least one CH component; CN was found to be present towards four of the latter seven stars (Crawford 1990b). For every star towards which molecular lines were found to be present, at least one component occurs in the velocity range occupied by the Lupus complex (0.0 to +11.6 km s^{-1} Murphy *et al.* 1986) and some stars have two CH and CH$^+$ components in this velocity range. It is argued here that these components arise in molecular gas associated with the Lupus clouds. If so, it implies that some of the line profile variation across the association, noted in the earlier work, is due to inhomogeneities on a smaller scale than previously suspected. For example, based on an assumed maximum cloud distance of 700 pc, Crawford (1990b) noted that variations in the CN lines across the central cluster (NGC 6231) implied spatial variations on scales of less than 0.8 pc; if the absorption actually occurs as close as 170 pc (Murphy *et al.* 1986) then the upper limit to this scale is lowered to 0.2 pc.

Two Sco OB1 stars (HD 152236 and 152424) were found to have molecular components with velocities more negative than the range occupied by the Lupus clouds. HD 152236 has a component identified in both CH and CN (and possibly also in CH$^+$) at an LSR velocity of about -5 km s^{-1}, and HD 152424 has CH components at -11.6 and -6.1 km s^{-1} (the latter also identified in CH$^+$). It is suggested that these components arise in diffuse molecular clouds lying beyond the Lupus complex. The extinction survey of Neckel & Klare (1980; their region 343/+1) reveals a sharp jump in extinction at a distance of about 700±120 pc, and it is probable that the negative-velocity molecular components arise in the clouds responsible for this increased absorption. The galactic rotation model of Fich *et al.* (1989) indicates that interstellar clouds corotating with the Galaxy would have radial velocities in the range -5 to -6 km s^{-1} for distances between 730 and 850 pc; this is consistent with the distance obtained by Neckel & Klare for a rise in the extinction, and supports the suggestion that the components with these velocities arise in these more distant clouds. On the other hand, the dynamical distance for the weak, -11.6 km s^{-1}, CH component towards HD 152424 is 1.5 kpc, a distance that would place it on the outskirts of the Sagittarius arm (*cf.* fig. 1 of Lynds 1980).

5 CONCLUSIONS

The conclusions of this work are summarized below.

(i) The lines of sight to the observed stars pass less than about 15 pc from the local molecular clouds mapped by Dame *et al.* (1987) and/or the larger of the dark clouds mapped by Feitzinger & Stüwe (1984). It is argued that the strong, low-velocity ($|v_{\rm lsr}| \lesssim 5$ km s^{-1}), absorption components observed towards all five stars arise in outlying gas associated with this ridge of denser material.

(ii) By implication, it appears probable that the strong, low-velocity lines of Na I and Ca II (e.g. Rickard 1974), and the molecular lines (when present at the same velocities), which occur towards other stars in the southern Milky Way, also arise in this material, which Dame *et al.* consider may represent the inner edge of the local spiral arm. As the interstellar gas is presumably contiguous along the ridge, with molecules being found in the most dense regions, it may be misleading to visualize these absorption lines as forming in *discrete* clouds. This supports the view of Federman & Willson (1982) that diffuse 'clouds' are often the outer regions of dark clouds.

(iii) The low-velocity components observed towards the Scorpius OB1 association are consistent with this interpretation. Specifically, it is argued that the molecular lines observed towards this association (Crawford 1989, 1990b) arise in an outlying region of the Lupus dark cloud complex.

(iv) In addition to the components which are interpreted as arising in the local spiral arm, four of the stars (HD 111904, 135240, 135591 and 164402) have components with velocities in the approximate range of -10 to -20 km s^{-1}, which are consistent with an origin in the Sagittarius–Carina spiral arm.

(v) HD 111904 (Cen OB1 association) and HD 164402 (Sgr OB1 association) were found to have very high-velocity (-45 and -40 km s^{-1}, respectively) components with low (≤ 0.65 and ≤ 0.3) Na I/Ca II ratios. Similar features are found towards other OB associations, and are interpreted as arising in shells swept up by the cumulative effect of mass loss from the association member stars.

ACKNOWLEDGMENTS

The observations on which this paper is based were obtained while the author held a Royal Society Overseas Fellowship at the Mt Stromlo Observatory. Bibliographic information was obtained from the SIMBAD data retrieval system of the Astronomical Data Centre, Strasbourg.

REFERENCES

Adams, W., 1949. *Astrophys. J.*, **109**, 354.
Allen, C. W., 1973. *Astrophysical Quantities*, 3rd edn, p. 252, Athlone Press, London.
Bates, B. & Catney, M. G., 1991. *Astrophys. J. Lett.*, **371**, L37.
Blades, J. C., Wynne-Jones, I. & Wayte, R. C., 1980. *Mon. Not. R. astr. Soc.*, **193**, 849.
Buscombe, W. & Stoeckley, T. R., 1975. *Astrophys. Space Sci.*, **37**, 197.
Chini, R., 1981. *Astr. Astrophys.*, **99**, 346.
Cohen, R. S., Grabelsky, D. A., May, J., Bronfman, L., Alvarez, H. & Thaddeus, P., 1985. *Astrophys. J. Lett.*, **290**, L15.
Cowie, L. L., Songaila, A. & York, D. G., 1979. *Astrophys. J.*, **230**, 469.
Crawford, I. A., 1989. *Mon. Not. R. astr. Soc.*, **241**, 575.
Crawford, I. A., 1990a. *Observatory*, **110**, 145.
Crawford, I. A., 1990b. *Mon. Not. R. astr. Soc.*, **244**, 646.
Crawford, I. A., 1991a. *Astr. Astrophys.*, **247**, 183.
Crawford, I. A., 1991b. *Astr. Astrophys.*, **246**, 210.
Crawford, I. A., Barlow, M. J. & Blades, J. C., 1989. *Astrophys. J.*, **336**, 212.
Crutcher, R. M. & Lien, D. J., 1984. *Local Interstellar Medium, IAU Colloq. No. 81*, p. 117, eds Kondo, Y., Bruhweiler, F. C. & Savage, B. D., NASA.
Dame, T. M., Ungerechts, H., Cohens, R. S., de Geus, E. J., Grenier, I. A., May, J., Murphy, D. C., Nyman, L.-Å. & Thaddeus, P., 1987. *Astrophys. J.*, **322**, 706.
de Geus, E. J., de Zeeuw, P. T. & Lub, J., 1989. *Astr. Astrophys.*, **216**, 44.
Deutschman, W. A., Davis, R. J. & Schild, R. E., 1976. *Astrophys. J. Suppl.*, **30**, 97.
Dieter, N. H., 1960. *Astrophys. J.*, **132**, 49.
Federman, S. R. & Willson, R. F., 1982. *Astrophys. J.*, **260**, 124.
Feitzinger, J. V. & Stüwe, J. A., 1984. *Astr. Astrophys. Suppl.*, **58**, 365.
Feitzinger, J. V. & Stüwe, J. A., 1986. *Astrophys. J.*, **305**, 534.
Fich, M., Blitz, L. & Stark, A. A., 1989. *Astrophys. J.*, **342**, 272.
Franco, G. A. P., 1989. *Astr. Astrophys.*, **215**, 119.
Garrison, R. F., Hiltner, W. A. & Schild, R. E., 1977. *Astrophys. J. Suppl.*, **35**, 111.

Hobbs, L. M., 1973. *Astrophys. J.*, **179**, 823.
Hoffleit, D. & Jaschek, C., 1982. *Bright Star Catalogue*, 4th edn, New Haven, Yale University Observatory.
Howarth, I. D. & Murray, J., 1988. *Starlink User Note*, No. 50, Rutherford Appleton Laboratory.
Humphreys, R. M., 1972. *Astr. Astrophys.*, **20**, 29.
Humphreys, R. M., 1978. *Astrophys. J. Suppl.*, **38**, 309.
Lallement, R., Vidal-Madjar, A. & Ferlet, R., 1986. *Astr. Astrophys.*, **168**, 225.
Lynds, B. T., 1980. *Astr. J.*, **85**, 1046.
Mohr, J. M. & Mayer, P., 1957. *Bull. astr. Insts Czech.*, **8**, 142.
Morton, D. C. & Smith, W. H., 1973. *Astrophys. J. Suppl.*, **26**, 333.
Munch, G., 1957. *Astrophys. J.*, **125**, 42.
Murphy, D. C., Cohen, R. & May, J., 1986. *Astr. Astrophys.*, **167**, 234.
Neckel, T. & Klare, G., 1980. *Astr. Astrophys. Suppl.*, **42**, 251.
Nyman, L.-Å., Bronfman, L. & Thaddeus, P., 1989. *Astr. Astrophys.*, **216**, 185.
Rickard, J. J., 1974. *Astr. Astrophys.*, **31**, 47.
Riegel, K. W. & Crutcher, R. M., 1972. *Astr. Astrophys.*, **18**, 55.
Rodgers, A. W., 1960. *Mon. Not. R. astr. Soc.*, **120**, 163.
Rodgers, A. W., Van Harmelen, J., King, D., Conroy, P. & Harding, P., 1988. *Publs astr. Soc. Pacif.*, **100**, 841.
Routly, P. M. & Spitzer, L., 1952. *Astrophys. J.*, **115**, 227.
Schild, R. E., Garrison, R. F. & Hiltner, W. A., 1983. *Astrophys. J. Suppl.*, **51**, 321.
Shortridge, K., 1988. *Starlink User Note*, No. 86, Rutherford Appleton Laboratory.
Walborn, N. R., 1972. *Astr. J.*, **77**, 312.
Walborn, N. R. & Hesser, J. E., 1975. *Astrophys. J.*, **199**, 535.