THE ASTROPHYSICAL JOURNAL, **186**: 149–163, 1973 November 15

OPTICAL INTERSTELLAR LINES IN DARK CLOUDS

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Received 1973 April 12; revised 1973 June 18

ABSTRACT

Observations of the equivalent widths and radial velocities of the interstellar lines of Ca II, Na I, CH, and CH^+ are presented for 30 stars. A special effort was made to observe stars behind or within dense clouds with up to 3 mag of absorption. The interstellar lines in the cloud stars are compared with those in a group of highly reddened supergiants whose reddening arises from a large distance, i.e., a long path length through relatively thin material. The atomic interstellar lines of the cloud stars are weak compared to those of supergiants with the same color excess; the molecular lines are of comparable strength in the two groups, except that the ratio n_{CH}/n_{CH^+} is larger in the cloud stars. The ionization equilibrium is discussed, and it is concluded that the deficiency of atomic Ca and Na relative to hydrogen in the clouds is about a factor of 100 larger than in the supergiants.

Subject headings: abundances, nebular — interstellar matter — molecules, interstellar — nebulae

I. INTRODUCTION

The interstellar medium is currently a subject of great interest. Since the discovery of complex interstellar molecules, there has been a deluge of observations by radio astronomers concerning their distribution and the physical properties of the clouds within which they are formed. Intense theoretical activity has begun on understanding the formation of these molecules, the thermal balance of the clouds and other related problems. The suggestion by Field, Goldsmith, and Habing (1969) and by Mészáros (1972) that the grains in the clouds may grow at the expense of the heavy elements in the gas provides additional motivation for the present study. We attempt to provide observations of the optical interstellar lines for stars embedded in or behind dark clouds. Adams's (1949) pioneering survey concentrated on distant supergiants, as galactic structure was a major concern of the time. We concentrate on observing nearby stars which are highly reddened and located within dense clouds of absorbing material that can be seen on the *Palomar Sky Survey*. Tantalizing suggestions of peculiar optical interstellar lines in such clouds exist in the literature (Greenstein and Struve 1939, for example).

In order to avoid a multitude of problems, including a lack of detailed knowledge of the ionization equilibrium, we compare the behavior of the optical interstellar lines in a group of nearby stars with large color excesses located in or behind dark clouds (subsequently called the cloud stars) to the interstellar lines seen in distant, highly reddened supergiants, whose reddening arises from a long path length through an average of the interstellar medium (which we call the thin interstellar medium). The mean density of the thin interstellar medium must be quite small compared to that of the dense clouds, and the latter are sufficiently rare that the line of sight to a supergiant probably does not pass through such a dense cloud. We know that equal

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color excesses in a cloud star and a supergiant imply roughly equal column densities of dust between the stars and the observer; we will later assume that this also implies equal column densities of gas in front of the two stars.

II. SELECTION OF STARS

In order to find stars behind dense clouds, we used the catalog of dark clouds by Lynds (1962), considering only clouds of opacity 5 and 6 (i.e., the clouds with the greatest obscuration) with declinations between $-30°$ and $+50°$ (corresponding to the limits of the coudé of the 100-inch telescope). The *Smithsonian Astrophysical*

TABLE 1

PROGRAM STARS

Star	Spectral Type	E_{B-V}	m_V	Number of Spectra: blue 4.5 Å/mm	blue 9 Å/mm	red 09802	red Varo
Original List							
HD 147889	B2V	1.08	7.9		2		1[5]
BD +31°643	B3V[1]	.93	8.5		2		1[5]
HD 147701	B5V	.72	8.4		2		1[5]
HD 203938	B0.5IV	.71	7.1		2	1	
HD 172028	B3II	.76	7.8		1		1
HD 21483	B3III	.58	7.0		2		
HD 147888	B3V	.53	6.7		1		2
HD 185418	B0.5V	.47	7.5		1	1	
HD 46883	B2V[3]	.52	7.9		2		1
HD 167771	O8	.40	6.5		2		1[5]
HD 183143	B7Ia	1.30	6.9		2		1
HD 169754	B0.5Ia	1.31	8.4		1		1
HD 193426	B9I[3,6]	1.2[2]	8.0		2	1	
HD 192660	B0Ia	.88	7.5		2		1[5]
HD 190967	B1I[6]-II[7]	.65	8.4		2		1[5]
Other Cloud Stars							
ρ Oph AB	B2V+B2V	.47	4.6		1	1	1
σ Sco	B1III	.37	2.9		1	1	
ω' Sco	B1V	.22	4.0		2	1	
β' Sco	B0.5V	.17	2.6		1	1	
δ Sco	B0V	.11	2.3		1	1	
X Per	Ope	.62[4]	6.0	1			1
o Per	B1III	.32	3.8	1UV			1
ζ Per	B1Ib	.38	2.9	2UV			1
ξ Per	O7	.33	4.0	2UV			1
HD 23060	B2Vp	.34	7.5	1	1		1[5]
HD 22951	B0.5V	.29	5.0	1			1
HD 24131	B1V	.25	5.7	2			1
HD 21856	B1V	.23	5.8	2			
from Hiltner							
HD 24432	B3II	.76	6.8	1			
HD 41690	B1V	.45	7.7	1	1		1

References and Notes:

1. Strom - private communication
2. Crossley scans
3. High dispersion spectra
4. Harris (1956)
5. 120" exposure
6. Petrie and Pearce (1961)
7. Spectroscopic binary

Observatory Star Catalog (1966) was searched for O and B stars brighter than $m_v = 9.0$ whose positions were close to those of the centers of the clouds. A list of 90 candidates was thus obtained. Many of these stars had *UBV* colors (Blanco *et al.* 1970) typical of unreddened stars, which indicated that they were located in front of the cloud, rather than behind it. Those stars without broad-band photometry were observed with the Crossley 36-inch (91-cm) telescope of Lick Observatory, using a dual-channel photoelectric scanner with a 40 Å bandpass.

Seventeen stars remained after eliminating all stars with $E_{B-V} < 0.5$ mag. Of those, two subsequently were found to be of spectral type B9, but observations of one are of some interest. Two others, which were of spectral type B8 and quite faint, were never observed. It is gratifying that the most heavily reddened stars in the well-known clouds such as the ρ Oph complex, the II Per association, and the Taurus cloud turned up on the list of candidates. HD 147701, which is in the ρ Oph complex, was added to the original list after it was discovered that the magnitude of 9.4 given in the *Smithsonian Astrophysical Observatory Star Catalog* (1966) is a misprint, and its visual magnitude is actually 8.4. Additional, less heavily reddened stars in the ρ Oph cloud and the II Per region were observed. Two moderately reddened stars from Hiltner's (1956) survey of O and B stars were also observed as they are bright and conveniently located in the sky. The 30 stars for which observations were made are listed in table 1. The *UBV* colors and spectral types are from Blanco *et al.* (1970) unless otherwise noted; color excesses were then derived using the calibration of $B - V$ versus spectral type of Schild, Peterson, and Oke (1971). The stars are listed in order of color excess, except that the supergiants in the original list are ordered separately.

III. SPECTROSCOPIC OBSERVATIONS

Many of the program stars listed in table 1 are quite faint, and a compromise must be made between the amount of telescope time available and the resolution desired. Because most of these stars are in clouds with at least 1 mag of absorption, we expected that their interstellar lines would have at most one major component, and perhaps other components weak compared to that resulting from the cloud. We therefore observed these stars at dispersions insufficient to resolve the component structure. The blue spectra (all baked IIaO) had dispersions of 9 and 4.5 Å mm^{-1} for the brightest stars. All the blue spectra were taken at the coudé of the 100-inch (254-cm) telescope at Mount Wilson, with the exception of the stars brighter than $m_v = 5.0$, which were observed with the coudé auxiliary telescope (CAT) feed to the coudé of the 120-inch (305-cm) telescope at Lick Observatory. The red plates fall into several categories. A small number of 09802 emulsion plates (dispersion 18 Å mm^{-1}) were taken at the 100-inch telescope. Most of the red plates were taken with the CAT using a Varo image-intensifier system (built by Dr. G. H. Herbig) and 103aD emulsion plates with dispersions of 9 and 16 Å mm^{-1}. A small number of spectra were taken with the Varo image-intensifier system using the 120-inch telescope, through the kindness of Dr. R. Kraft. 09802 spectra for the Scorpius stars were taken at the coudé of the 60-inch (155-cm) telescope of Cerro Tololo Inter-American Observatory in November of 1972. In addition, for the brightest stars in the II Per cluster, ultraviolet exposures (4.5 Å mm^{-1} dispersion) down to 3200 Å were obtained using a UG5 filter at the coudé of the 100-inch telescope. All these spectra were secured in various observing sessions from February 1972 to February 1973. Also two IN exposures of ζ Per taken by Dr. L. Houziaux on 1960 November 29, and 1961 January 6, were located in the vaults of the Hale Observatories. We indicate in the final columns of table 1 the available spectroscopic material for each star.

All the blue spectra were measured with an oscilloscope Grant machine for radial velocities of the interstellar features (V_{int}). The dispersion is so high that the stellar

TABLE 2

VELOCITIES AND EQUIVALENT WIDTHS OF INTERSTELLAR LINES

		W_λ (mÅ)						
Star	V_{int} (km/sec)	CaII 3933	CaII 3968	NaI 5889	NaI 5895	CH$^+$ 4232	CH$^+$ 3957	CH 4300
Original List								
HD 147889	-15	< 60[4]		290	210	20:		60
BD +31°643	+12	105	≤ 60	240	210	50:	30:	50
HD 147701	-12	130:	≤100	175	165	≤25		35
HD 203938	-12	160	130	380	345	25:		
HD 172028	-11	150	110:	310	285	25:		15:
HD 21483	+ 7	145	90:					20:
HD 147888	- 8	75	45:	210	135			
HD 185418	-10	165	100:	280:	205:			
HD 46883	+18	165	110	260	180			30:
HD 167771	- 6	255	140	375	295			
HD 183143	- 4	770	500:	680	605	60:[1]	25:	30:
HD 169754	+16:	660:	700:	800	765:	35:		15:
HD 193426	-14	2	2	850:[3]	680:[3]	>65[2]		≤65[2]
HD 192660	- 6	630	400:	650	560	30:		20:
HD 190967	-13	390	235	845	695	15:		
Other Cloud Stars								
ρ Oph AB	- 3:	55		200	155	15:		27
σ Sco	-15:	60		230	195	12:		
ω' Sco	- 8:	35		175:	165:	15		29:
β' Sco	-10:	35		235	180			
δ Sco	-29:	40		300:	210:			
χ Per	+15	150	110	180	130	12:		20
o Per	+12	65		275	205	na		na
ζ Per	+11	55	27	130:	100:	3[6]		na
ξ Per	+10	85	57	250[5]	200[5]	25[6]	9:	na
HD 23060	+ 8	85	50	280	205			
HD 22951	+14	115	60	195	145			
HD 24131	+13	70	30	245	155			10:
HD 21856	+ 6	115	70			10:		10:
from Hiltner								
HD 24432	- 9	455	295			45:	20	25
HD 41690	+ 2	310	215	310:	240:			

Notes:
1. partially resolved from λ4233 Å of FeII
2. cannot resolve from stellar lines
3. may contain slight contribution from stellar lines
4. Greenstein and Struve (1939)
5. Routley and Spitzer (1952)
6. Hobbs (1973)

na. no plate material for this region

features are too broad to permit an accurate measurement of the stellar radial velocity. We estimate the accuracy of our measurement of V_{int} from the H and K lines of Ca II to be ± 3 km s^{-1}. In those cases where Adams (1949) has measured V_{int}, the agreement with our measurements is quite good. In all cases where the interstellar molecular lines of CH and CH$^+$ are definitely present, the radial velocity determined from these features is the same as that determined from the atomic interstellar lines to within the above quoted uncertainty. Our measurements of V_{int}, corrected for the Earth's orbital motion, are listed in the second column of table 2. The stellar radial velocities, as determined from our own poor measurements or from the Bibliography of Stellar Radial Velocities (Abt and Biggs 1972), are sufficiently different in nearly all cases that there can be no doubt that the lines of Ca II and Na I are interstellar.

The spectra were traced using the computer-assisted microphotometer of the Lick Observatory designed by Dr. Lloyd Robinson. Equivalent widths were measured for all interstellar features on the spectra. It is difficult to assess the accuracy of these measurements, as some of the plates are slightly underexposed. Results for cases where more than one plate of a star is available and comparison of our measurements for H and K of Ca II with those of Spitzer, Epstein, and Li Hen (1950) (based on Adams's [1949] spectra) suggest that except for the weaker features ($W_\lambda < 40$ mÅ) our values of W_λ are accurate to within ± 15 percent. Equivalent widths of the weaker features are probably correct to ± 10 mÅ. Errors in equivalent widths of the D lines from the image-tube plates, especially those at 16 Å mm^{-1}, may be slightly larger. The measurements of W_λ for the interstellar lines H and K of Ca II, D_1 and D_2 of Na I, λ4300 of CH, λλ4232 and 3958 of CH$^+$ are given in table 2. If no entry is given for the molecular lines, the line was not detected. Upper limits for detection are 15 mÅ for the 4.5 Å mm^{-1} spectra and 25 mÅ for the 9 Å mm^{-1} spectra. If no entry is given for H, the line is lost in Hϵ; no entry for the D lines implies that no spectra were available in that region. In table 3 we give additional data for the doublet of Na I at 3302 Å and the Ti II line at 3383 Å, which were observed in three stars, and for K I λ7699. Those measurements which are particularly unreliable (such as cases where the Ca II line is badly blended with Hϵ) are indicated by a semicolon.

None of the spectra were sufficiently well-exposed at 3875 Å to search for the CN lines, with the exception of those taken for the ultraviolet Na doublet. In those three cases, the upper limit to the strength of λ3875 of CN is 10 mÅ. The resonance lines of Ca I λ4226 was searched for in all spectra. There were only three possible detections (HD 167771, BD+31°643, and X Per) where the line may be present with equivalent width of about 10 mÅ. Dr. F. H. Chaffee communicates upper limits of 1 mÅ in ζ Per, o Per, and ξ Per.

The molecular lines were so weak in general that no information on their profiles could be obtained. The weaker lines of Ca II had full widths at half-maximum (FWHM) of 0.1 Å, which is not greater than the resolution of the spectra. The stronger lines had larger FWHMs of up to 0.8 Å. In some cases stellar H and K lines were present, but they were so broad that they could be separated from the interstellar components. In no case did we notice a second interstellar component of Ca II. This implies that no component with $\Delta v > 1.5$ FWHM ($= 11$ km s^{-1} for weak lines) was present with central intensity of more than a third that of the main component.

We plot in figures 1 and 2 the equivalent widths observed for λ3933 of Ca II and λ5895 of Na I as a function of color excess. Separate symbols are used for the supergiants, the cloud stars, and the two stars added from Hiltner's (1956) list. With the

TABLE 3

Equivalent Widths of Additional Interstellar Lines

Star	W_λ(mÅ)			
	Na I		Ti II	K I
	3302.4	3303.0	3383.8	7699.0
o Per	50	30	10:	*
ζ Per	30	20	6:	100:
ξ Per	30	15	< 10	*

* No spectra available for this region.

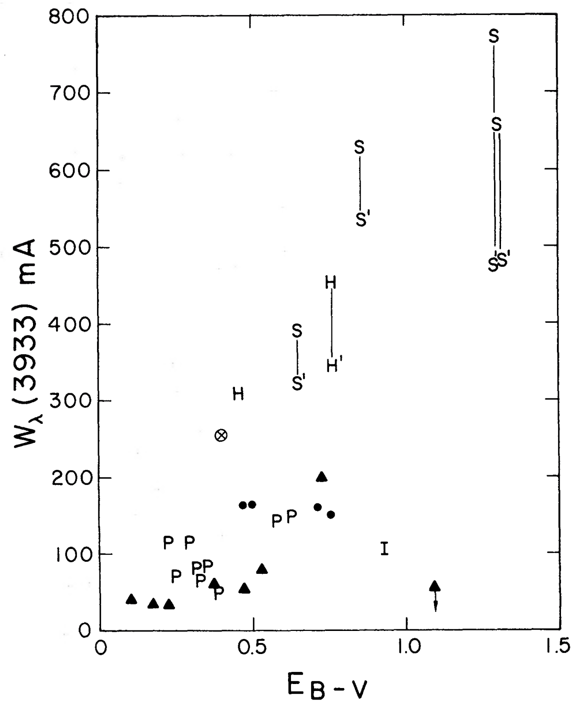

FIG. 1.—The equivalent width of the interstellar K line of Ca II as a function of color excess. The symbols are S (supergiant), H (additional stars from Hiltner), P (Perseus II association), *filled triangles* (ρ Oph cloud), *cross* (HD 167771), I (BD+31°643 in IC 348), and *dots* (other cloud stars). The primed symbols have been corrected for galactic rotation to $l^{\mathrm{II}} = 0$.

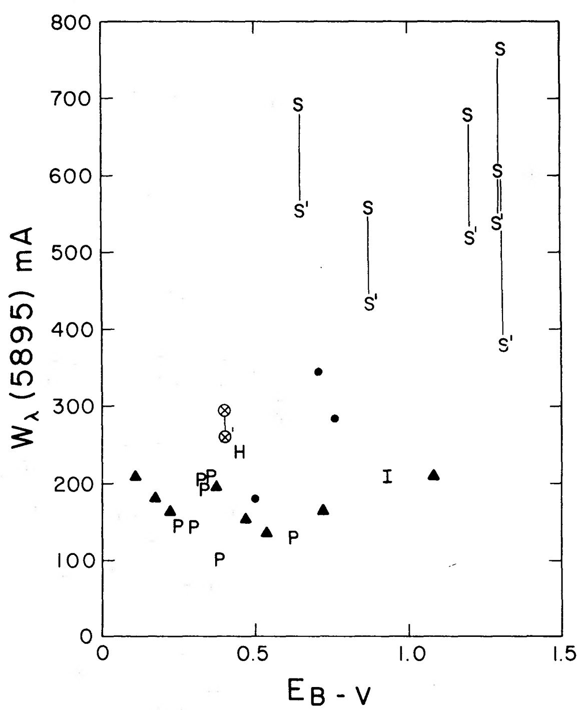

FIG. 2.—Equivalent width of the interstellar line of Na I at 5895 Å as a function of color excess. Symbols are the same as in fig. 1.

exception of the O star HD 167771, (denoted by $\otimes$), the dominant trend is that all of the cloud stars have much weaker interstellar lines at a given color excess than do the supergiants. The relationship is shown more clearly in figure 1, as the measurements of K are more accurate than those of D_1. Note also that the two stars from Hiltner behave like supergiants rather than cloud stars. This is not surprising, as it is difficult to find stars behind clouds, and therefore a random highly reddened star in the plane is more likely to be distant than to be behind a dense cloud. In the subsequent sections we explore the question of whether this weakness of the atomic interstellar lines in clouds represent a true deficit of heavy elements relative to hydrogen in the clouds, or can be otherwise explained.

IV. COLUMN DENSITIES

From the data in tables 2 and 3, we derive the doublet ratios (DR) for K and H of Ca II, D_1 and D_2 of Na I, and the ultraviolet doublet of Na I. For doublet ratios greater than 1.1, we use the theoretical curves of growth for a Gaussian velocity distribution within a single cloud (Strömgren 1948) to derive column densities of Na I and Ca II. We can derive column densities of Na I from the standard curves for the D lines, and from the ultraviolet doublet ratio, by recalling that for weak lines

$$N = 1.13 \times 10^{20} W_{Å} \lambda_{Å}^{-2} f^{-1} .$$

We use the f value for λ3302 of Wiese, Smith, and Miles (1969). This gives a second value of the Na I column density, denoted by $N(\text{Na I})_{\text{UV}}$. These two column densities for Na I are given in table 4.

We have obtained the same phenomenon as Herbig (1968) did with regard to the ultraviolet Na I lines; the deduced column densities are much larger than those obtained from the D lines alone. This is either a result of saturation or an incorrect transition probability for the ultraviolet doublet. It would be highly desirable to remeasure the transition probability of the ultraviolet Na doublet.

In table 5 we list column densities for Ca II, for Na I (from the D lines), and for CH and CH^+. Blank entries denote cases where DR < 1.1. The procedure for CH is identical to that of Herbig (1968). There is no way of directly determining b for the molecular lines from the available observational data, and we adopt the value of 2 km s^{-1}, slightly less than b as determined from the atomic lines. The column densities for CH^+ are calculated from λ4232 (the stronger line) only using $f_{el} = 2.2 \times 10^{-2}$ (Solomon and Klemperer 1972), $b = 2$ km s^{-1}, the Franck-Condon factors given by Green, Hornstein, and Bender (1973), and Strömgren's (1948) curve of growth. If we decrease the value of b to 1 km s^{-1}, then the molecular column densities for the stronger lines increase by up to a factor of 5.

We must also worry about the effect of galactic rotation on the interstellar lines seen in the supergiants. (The cloud stars are mostly too close to be affected.) Such effects are undoubtedly present, as the values of b derived are very large. A method of

TABLE 4

COMPARISON OF Na I COLUMN DENSITIES

Star	log $N(\text{Na I})_{\text{D}}$	log $N(\text{Na I})_{\text{UV}}$
o Per	12.5	13.9
ζ Per	12.2	13.5*
ξ Per	12.6	13.5*

* We assume DR = 2.

TABLE 5

COLUMN DENSITIES

Star	log N(CaII)	b	log $N(NaI)_D$	b	$N(CaII)/N(NaI)_D$	log N_{CH}	log N_{CH^+}	N_{CH}/N_{CH^+}
Original List								
HD 147889	a,c 11.7:		12.45	5	-0.7:	13.9	12.9:	+1.0
BD +31°643	a 12.1:	5:	12.8	4	-0.6	13.7	13.3:	+0.4
	b 12.2	4						
HD 147701	b 12.4	4				13.6	13.0:	+0.6
	c 12.1							
HD 203938	12.8	4	13.4	5	-0.6		13.0	
HD 172028	12.6	4	13.2	3	-0.6	13.2:	13.0	+0.2
HD 21483	12.4	6				13.3:		
HD 147888	12.0	4	12.2	6	-0.2			
HD 185418	12.4	7	12.5		-0.1			
HD 46883	12.4	3	12.4	5	0.0	13.5		
HD 167771	12.5	22	12.8	7	-0.3			
Supergiants								
HD 183143	13.1	34	13.5	7	-0.4	13.5:	13.5	0.0
HD 169754						13.2:	13.2	0.0
HD 193426			13.3:	11:				
HD 192660	13.0	24	13.3	10	-0.3	13.3:	13.1:	+0.2
HD 190967	12.8	15	13.2	12	-0.4		12.8:	
Other Cloud Stars								
ρ Oph	c 11.7		12.4:	3	-0.7	13.5	12.8:	+0.7
σ Sco	c 11.7		12.7:	3	-1.0:		12.7	
ω' Sco	c 11.5					13.5:	12.8:	+0.7
β' Sco	c 11.5		12.5:	4	-1.0:			
δ Sco	c 11.6		12.8:	5	-1.2:			
X Per	12.5	5	12.3	3	+0.2	13.3	12.7	+0.6
o Per	11.8		12.5	5	-0.7	13.3	12.6:	+0.7
ζ Per	11.7		12.2	2	-0.5	13.4	12.1	+1.3
ξ Per	12.2	3	12.6	4	-0.4	13.0	13.0	0.0
HD 23060	12.1	3	12.5	5	-0.4			
HD 22951	12.1		12.4	4	-0.3			
HD 24131	11.7		12.3	6	-0.6	13.0:		
HD 21856	12.2					13.0:	12.6:	+0.4
from Hiltner								
HD 24432	12.9	20				13.4	13.3	+0.1
HD 41690	12.8	9	12.6:	6	+0.2:			

Notes: a. assumes W_λ is upper limit
b. assumes b = 4 km/sec
c. assumes DR = 2

correcting the observed W_λ for galactic rotation is discussed by Spitzer (1948). We have assumed that the external velocity distribution of the clouds has a velocity dispersion ($b_{e,0}$) of 10 km s^{-1}. We approximate Spitzer's formula by

$$C = \frac{W_\lambda(l = 0)}{W_\lambda(l)} = \frac{b_{e,0}[1 - \exp(-\alpha E_{B-V}/b_{e,0})]}{b_e[1 - \exp(-\alpha E_{B-V}/b_e)]}$$

and

$$b_e = b_{e,0} + Ar\frac{\lambda}{c}\sin(2l^{\mathrm{II}}),$$

where $\alpha = 1.2$ A per mag for D_1 and D_2, and $\alpha = 0.6$ A per mag for H and K. Spitzer (1948) and Münch (1968) find that these formulae are in good agreement with the observational data.

Although this correction was derived for $\overline{W} = \frac{1}{2}[W_\lambda(D_1) + W_\lambda(D_2)]$, we have used it for each component separately. The corrections have been calculated for each of the supergiants, HD 167771, and the two stars from Hiltner. The minimum value of C is 0.63 for HD 183143, which has the maximum range in permitted radial velocity of gas along the line of sight, 0 to $Ar \sin(2l^{\mathrm{II}})$ km s^{-1} (= 15 km s^{-1} for this star). The corrected W_λ are plotted in figures 1 and 2. Because the distribution of random velocities of clouds appears to be better represented by an exponential velocity distribution than by a Gaussian, we may then derive the column density from the corrected W_λ, the doublet ratio, and the curve of growth for an exponential velocity distribution given by Münch (1968).

Another approach to this problem is to assume that the line of sight intersects sufficiently many clouds randomly distributed in velocity within the range permitted by galactic rotation that we may use the curve of growth for a single cloud with a Gaussian velocity distribution whose velocity dispersion is $(b_{e,0}^2 + b^2_{\mathrm{gal\ rot}})^{0.5}$ or an exponential velocity distribution with $b_{\mathrm{eff}} = b_{e,0} + b_{\mathrm{gal\ rot}}$. Since there are eight clouds kpc^{-1} (Münch 1968), this will not be a bad approximation for supergiants about 1 kpc away along the local arm.

Each of these three methods of deriving the column densities for the supergiants gives results averaged over this group of stars consistent to ± 0.1 dex in log N(Ca II) and ± 0.3 dex in log N(Na I). Of course, the values of the velocity dispersion obtained differ greatly among these methods. We therefore list in table 5 the parameters for the supergiants derived from the single-cloud curve of growth with a Gaussian velocity distribution. A similar correction procedure was tried for the molecular lines. As they have low central optical depths, the saturation is sufficiently small that any correction to the column density is not more than 0.1 dex.

The difference between the supergiant and the cloud atomic interstellar lines for large values of E_{B-V} could be understood purely as a curve-of-growth effect if peculiar conditions prevail. One such case would be if the interstellar lines of the cloud stars are actually a superposition of those of a large number of small clouds whose random velocity dispersion is about 3 km s^{-1} and whose internal turbulent or thermal velocity dispersion is much less than the random motions of the cloud. Another requires a Gaussian velocity distribution which is truncated more than 2 half-widths from the average velocity. However, the conditions required are not those generally thought to prevail in such clouds. Furthermore, the atomic cloud lines (i.e., the part of the line arising in the cloud itself) are even weaker (hence less subject to such corrections) than the numbers in table 2 indicate, as no correction has been made for the material between us and the dense cloud.

Thus the effects of galactic rotation and differing velocity dispersions probably do not eliminate the contrast between the weak atomic lines of the cloud stars and the stronger atomic lines of the supergiants. However, the column densities derived for the supergiants are less accurate because of the assumptions involved in the correction for galactic rotation.

We note that the interstellar molecular lines of stars in clouds continue to be as strong as those in supergiants at large values of E_{B-V} except that the ratio CH/CH^+ changes. An average of the value of the ratio log (CH/CH^+) for the cloud stars is +0.6, while for the supergiants and the stars from Hiltner (1956) it is +0.1. This systematic difference is larger than any possible error.

The upper limits to the column density of Ca I as derived from $\lambda 4226$ are $N(\mathrm{Ca\,I}) \leq 0.4 \times 10^{10}$ cm^{-2} for ξ Per, o Per, and ζ Per. For the stars with spectra at 4.5 Å mm^{-1}, N(Ca I) $\leq 5 \times 10^{10}$ cm^{-2}. For the other stars, N(Ca I) $\leq 10^{11}$ cm^{-2}. The marginal detections listed in § III correspond to $N(\text{Ca I}) = 4 \times 10^{10}\ \text{cm}^{-2}$. These numbers do not depend on b, the velocity parameter, as the line must be very weak.

V. IONIZATION EQUILIBRIUM

We must now consider whether the decrease in strength of atomic interstellar lines between the stars embedded in clouds and the supergiants can be explained by changes in the ionization equilibrium. Also, we must show that the dominant contribution to the interstellar lines seen in the cloud stars arises from the cloud and not from the intervening medium.

We assume that the ionization equilibrium is determined by photoionizations and recombinations only. Then the concentration of an atom (n_0) and its ion (n_i) are given by

$$n_i n_e / n_0 = \Gamma/\alpha\ ,$$

where α is the number of recombinations per cm^3 per second of ions and electrons and Γ is the probability of photoionization of an atom in the ground state per second. To calculate Γ at a given point, we require the radiation density at that point. Consider a star embedded in a cloud. At any point, the radiation density is the sum of that due to the general galactic field, that of the star, and that of the stars in the cloud. Let d be the distance along the line of sight as measured from the star; R is the radius of the cloud; ρ the density of the cloud; τ_c is the optical depth of the cloud in front of the star at 1000 Å. We assume that the effective optical depth varies as λ^{-1}, and that outside of the cloud an optical depth at 1000 Å of $13.4E_{B-V}$ is produced by interstellar reddening, with $E_{B-V} = 0.5$ mag kpc^{-1}. We approximate Habing's (1968) calculation of the general galactic field by $U_g{}^0 = 34 \times 10^{-18}$ ergs $\text{Å}^{-1}\ \text{cm}^{-3}$. Then, if $\lambda' = 1000/\lambda$, for λ in angstroms,

$$U_g(d, \lambda) = U_g{}^0 \exp[-\tau_c \lambda'(R - d)/R] \qquad \text{for } d < R\ ;$$
$$U_g(d, \lambda) = U_g{}^0 \qquad \text{for } d > R\ .$$

For a star of given radius r and effective temperature, we obtain F_ν from Carbon and Gingerich (1968). Then in the absence of any extinction, $U_*{}^0(d, \lambda) = F_\nu(4\pi/c) \times (c/\lambda^2)(r^2/4d^2)$. Therefore

$$U_*(d, \lambda) = U_*{}^0(d, \lambda) \exp(-\tau_c \lambda' d/R) \qquad \text{for } d < R\ .$$
$$U_*(d, \lambda) = U_*{}^0(d, \lambda) \exp[-(\tau_c + (d - R) \times 0.5 \times 13.4)\lambda'] \qquad \text{for } d > R\ (d, R \text{ in kpc})\ .$$

To compute the radiation field from the stars embedded in the cloud, we consider a cloud containing N_i stars of the ith spectral class which contribute to the ultraviolet flux (from O5 to A0), each suffering an average extinction of $\langle\tau\rangle$ magnitude (at 1000 Å) and with a mean separation of s. In the denser clouds studied by radio astronomers, N_i is 0 for all i, but for the great complexes in Perseus and Ophiuchus, N_i may be nonnegligible. For each spectral class we may derive $U_*{}^0(i, d, \lambda)$. Then

$$U_{\text{cloud}}(d, \lambda) = \Sigma_i N_i U_*{}^0(i, s, \lambda) e^{-\langle\tau\rangle\lambda'} \qquad \text{for } d < R\ ;$$

$$U_{\text{cloud}}(d, \lambda) = U_{\text{cloud}}(d < R, \lambda) \frac{R^2}{4(d - R)^2} e^{-(d-R) \times 0.5 \times 13.4\lambda'} \qquad \text{for } d > R\ (d, R \text{ in kpc}).$$

We have written a computer program which calculates the sum $U_{\text{cloud}} + U_g + U_*$ as a function of d and λ for any given effective temperature and luminosity class (hence radius) of the star, set of N_i, R, τ_c, $\langle\tau\rangle$, s, and ρ.

We must then integrate to obtain

$$\Gamma(d) = 10^{-8}h^{-1}\int_0^{\lambda_0} a_\lambda \lambda u_\lambda d\lambda, \ (\lambda \text{ in Å})$$

where a_λ is the photoionization cross-section (cm^2 atom^{-1}). This procedure has been done for Ca I, Ca II, and Na I. We use the same photoionization cross-sections as were used by Herbig (1968). We also use the same values of α (the recombination coefficient) corresponding to $T_e = 100°$ K for an H I region and $T_e = 10^{4}°$ K for an H II region. The integration is carried out from 504 Å to the threshold wavelength for d less than the radius of the Strömgren sphere produced by the star. This radius is calculated from the values given in Allen (1963) and the assumed density of the cloud ρ, as the Strömgren radius is proportional to $\rho^{-0.67}$. The integral is taken from the Lyman limit to the threshold wavelength outside of this region.

From the values of Γ/α for Na I, Ca I, and Ca II, we may calculate n(Na I)/n(Na), n(Ca I)/n(Ca II), and n(Ca II)/n(Ca III) given the electron density.

The accuracy of the computer program has been checked by reproducing (with $\langle\tau\rangle = N_i = \tau_c = s = 0$) the values of Γ tabulated by Herbig (1968) for ζ Oph to within a factor of 2.5 at all values of d. This agreement is very satisfactory, considering that we have used a slightly different stellar and galactic radiation field than did Herbig.

We now face the problem of determining the electron density, which depends mostly on the ionization of C and H. In the small Strömgren sphere around the star, we know that $n_e = n_{\mathrm{H}}$. Werner (1970) has predicted that within a large dense cloud the carbon will be predominantly neutral. However, he ignores the possibility of a significant ultraviolet radiation field from the stars embedded in the cloud. Solomon and Klemperer (1972) have calculated the ionization equilibrium problem for H, C, Na, and Ca. They too neglect a possible cloud radiation field, but include cosmic-ray ionization of H. They find n_e/n_{H} in the range of 10^{-3} to 10^{-4} for τ_c up to 6. Since the major cloud with which we are concerned has many embedded stars, we find that the additional radiation field from the cloud compensates for the extinction of the galactic field. The ratio n_e/n_{C} is proportional to $[\Gamma/(\alpha n_{\mathrm{C}})]^{0.5}$ for electrons from photoionization of carbon only; we therefore take as an approximation that $n_e/n_{\mathrm{H}} = 10^{-3}$ within the clouds, and that outside of the clouds, in the thin interstellar medium, $n_e/n_{\mathrm{H}} = 10^{-3}$.

We now construct a model for the most heavily reddened stars in the ρ Oph cloud. To obtain an estimate of the density, we assume that the gas-to-dust ratio is constant, independent of the density. Evidence is given by Savage and Jenkins (1972) that this is valid for E_{B-V} up to 0.4 mag. The most reddened star in this cloud (HD 147889) has $E_{B-V} = 1.1$, and the size of the cloud (1°.5 at 200 pc) is 5 parsecs. We know that $n_{\mathrm{H}} = 1$ cm^{-3} produces about 1 mag kpc^{-1} of extinction. Therefore we adopt $n_{\mathrm{H}} = 10^3$ cm^{-3} for this cloud. We assume $n_{\mathrm{H}} = 1$ cm^{-3} outside of the cloud. We obtain τ_c from the color excess of the most heavily reddened star. The values N_i are obtained by considering the stars from HD 147165 to HD 148605 with declination within 1° of HD 147889 in Garrison's (1967) study of the members of the upper Scorpius association. We adopt $\langle\tau\rangle = 7$ ($E_{B-V} \simeq 0.5$ mag) and $s = 2.5$ pc.

In table 6 we present the values of $\Gamma/(\alpha n_e)$ at a representative point in each region and the predicted column density through the region for Na I, Ca I, and Ca II. The column densities are calculated assuming that Ca and Na have solar abundances. As the star is a B2 V, the Strömgren sphere has a radius of only 0.13 pc.

There are several critical points to be seen from table 6. Because the electron density is high in the cloud, the calcium and sodium atoms tend to be less ionized than in the

TABLE 6

IONIZATION EQUILIBRIUM FOR HD 147889

d (pc)	Γ/α_{ne}			COLUMN DENSITY			REGION (pc)
	Na I	Ca I	Ca II	Na I	Ca I	Ca II	
Strömgren Sphere							
0.13	5.2(−1)	1.1(+1)	0.70(−2)	1.9(+14)	2.0(+13)	3.6(+14)	0–0.13
Cloud							
3	0.66(+1)	0.18(+3)	2.7(−2)	2.0(+15)	8.8(+13)	1.6(+16)	0.1–5
Outside Cloud							
7	1.2(+4)	0.4(+6)	7.5(+1)				
100	1.5(+3)	3.5(+5)	3.1(+1)	3.8(+11)	5.5(+7)	1.9(+13)	5–200

NOTE. $A(B) = A \times 10^B$.

normal interstellar medium. Within the cloud, almost all of the calcium is in the form of Ca II, and over 10 percent of the sodium is Na I. But we still have not reduced the level of ionization to the point where more than 1 percent of the calcium is in the form of Ca I. If we had not included the radiation field from the stars in the cloud, we would obtain a larger fraction of the Ca in the form of Ca I, as did Solomon and Klemperer (1972).

The conclusion that the general level of ionization is lower in the denser clouds implies that a larger fraction of the Ca and Na are in the observable forms (Ca II and Na I). This implies that the decrease in column density of Na I and Ca II in the clouds as compared with highly reddened supergiants is much larger than numbers in table 5 indicate. For equal total dust column density [hence by assumption, hydrogen (plus H_2) column density] the cloud has approximately a factor of 10 less Na I and Ca II than does the general interstellar medium. From table 6, we see that this may correspond to as much as a factor 10^{-3} less total Ca and Na in the cloud. In other words, *the depletion of calcium and sodium in the densest clouds that can be studied at optical wavelengths is large.*

This is also apparent in another way from table 6. The total column density of Ca II and Na I, assuming normal solar abundances, from the cloud region is much larger than the maximum permitted by the observations (table 5), even allowing for a factor of 10 error in the values of table 5 due to possible saturation effects. Thus it is possible that a large part of the interstellar atomic lines seen in stars embedded in dark clouds arises from the normal interstellar material between us and the cloud. This would not be the case for clouds closer than 1 kpc if there were no depletion.

The exceptional behavior of HD 167771 (designated by ⊗ in figs. 1 and 2) is now understood. The line of sight tc this O star passes through the periphery of an extensive cloud, but the star is so distant (d = 1.7 kpc) that most of the reddening (E_{B-V} = 0.4) is from the intervening medium rather than the cloud. Hence the atomic interstellar lines of this star fit very well onto the relationship displayed by the supergiants.

Another point to note is that because the density is high, the Strömgren spheres (SS) are very small. Unless the radius of the SS is greater than 1 pc, the contribution of that region to the total column density of Na I or Ca II will be small. To have an SS that large requires an O5 star embedded in a dense cloud, and there are no such stars in our program. (We ignore the possibility that the O star vaporizes the grains

TABLE 7

AVERAGE ABUNDANCES RELATIVE TO HYDROGEN

Cloud Stars	log Ca/H	log Na/H	log CH/H	log CH^+/H	No. of stars	Ca/Ca II	Na/Na I
$E_{B-V} > 0.9$............	−9.7	−8.3	−7.9	−8.7	2	1	7
$0.6 < E_{B-V} < 0.9$.......	−9.2	−7.7	−8.2	−8.5	5	1	7
$E_{B-V} < 0.6$ (ρ Oph).....	−9.2	−6.8	−7.8	−8.5	6	1	70
$E_{B-V} < 0.6$ (II Per)......	−9.2	−7.0	−8.1	−8.6	7	1	70
$E_{B-V} < 0.6$ (other)......	−9.0	−7.2	−7.9	...	2	1	70
Supergiants*............	−7.1	−5.1	−8.5	−8.5	8	30	1.5×10^3

* Includes two stars from Hiltner and HD 167771.

and hence increases the local density of Na and Ca; rather we feel it more likely that the gas and grains are pushed away from the star by radiation pressure.)

When considering the expected strength of interstellar Ca I, we see from table 5 that the SS region may be important. Our upper limits on λ4226 (see § IV) give the following ratios: Ca II/Ca I > 1.6×10^2 (o Per, ζ Per, ξ Per); Ca II/Ca I > 0.4×10^2 (other cloud stars); Ca II/Ca I > 3×10^2 (supergiants). These limits are satisfied by the entries of table 5. Recall that the three possible detections of λ4226 of Ca I (see § III) were in HD 167771 where the line could be coming from the SS region of this O star (which is itself probably not in a dense cloud), in X Per (again an O star with a large SS region), and in BD+31°643, which is in the central part of a very dark cloud, where the other stars in IC 348 are A stars, rather than of earlier spectral class. Although we are not willing to assert that Ca I definitely has been detected, at least the possible detections are in accord with our expectations from considerations of ionization equilibrium. If the radiation field from the cloud had not been included, so that Ca I/Ca II were much larger, then the Ca I line should have been seen. The fact that it has not been seen is evidence for the importance of the radiation field of the stars embedded in these clouds.

We now compute the average abundances relative to hydrogen, shown in table 7. Averages are made for the supergiants and for several intervals of color excess of the cloud stars. We obtain the hydrogen column density from the Lα data of Savage and Jenkins (1972) and Morton, Jenkins, and Macy (1972). In the majority of cases, where such data are not available, we use the relationship between color excess and N(H) given by Savage and Jenkins. We are thus forced to assume that $[N(H) + 2N(H_2)]$ is constant for all of the stars with $E_{B-V} > 0.5$ mag. For some of these regions, 21-cm profiles are available with a beam size of 0°.6 from Heiles (1973); however, for a star embedded in a cloud, we do not know how much of the 21-cm profile arises from H I gas behind the star. Furthermore, the 21-cm line is saturated. The optical depth can be obtained from 21-cm absorption features against extragalactic sources, and it is not greater than 3 (Heiles 1973). This implies that the total column density from 21-cm emission, corrected for saturation, is less than the expected column density of hydrogen derived from Savage and Jenkins's relation by about a factor of 2. The missing hydrogen may be in the form of H_2. Since about 10 percent of the hydrogen is H_2 in the outer parts of these clouds, as determined by rocket-ultraviolet measurements of H_2 absorption against the less reddened stars in Oph and Per (Smith 1973; Carruthers 1970), we may use the calculations of Hollenbach, Werner, and Salpeter (1971) to predict that $2H_2/(H + 2H_2)$ is unity in the central regions of these clouds. The postulated increase in radius of the grains due to depletion of the heavy elements from the gas may also change the optical depth produced by a given column density of grains. Thus we may expect the slope of the relationship N_H/E_{B-V} to change for large E_{B-V}

if the grain radius changes significantly. Which of these two effects is the more important is not yet clear.

To obtain the entries in the left part of table 7, the Ca II and Na I column densities of table 5 are corrected for ionization equilibrium by the factors (taken from table 6) given in the last two columns of table 7. For $E_{B-V} < 0.6$ mag, we assume $n = 10^2$ cm^{-3} rather than 10^3 cm^{-3}. The logarithms of the corrected column densities are averaged to give the final values shown in table 7.

The numbers in this table are not to be taken as more accurate than a factor of 10, at least. We do not know the ionization conditions exactly. Our knowledge of the velocity distributions for the clouds and the supergiants is poor, so that our derivation of column densities from observed W_λ is not very accurate. We do not know what fraction of the line of sight to the supergiants passes through relatively thin clouds, which will effectively decrease the column density of Ca and Na relative to H.

The important conclusions are the large depletion of Na and Ca in the clouds, and the deficiency of Ca in the supergiants. It is impossible to determine which of Ca and Na is more depleted in the clouds as compared to the supergiants, due to the inaccuracies and assumptions involved in these entries; however, it appears that $n_{\mathrm{Ca}}/n_{\mathrm{Na}}$ does not change by a factor of more than 50 between the clouds and supergiants. The relative change in the CH/CH$^+$ ratio and the approximately constant ratio $N_{\mathrm{CH}^+}/N_{\mathrm{H}}$ are of great importance, as the first supports our calculations that the ionization (i.e., n_1/n_0 is lower in the clouds. Although the data on the supergiants are poor, as all of the plates were at 9 Å mm^{-1}, the reader may peruse table 3 of Adams (1949) for further evidence that the lines of interstellar CH$^+$ are much stronger than interstellar CH in the spectra of supergiants.

It is unfortunate that we could not observe CN. Solomon and Klemperer predict a rapid increase in CN/H as $n_{\mathrm{CH}}/n_{\mathrm{H}}$ (or the density) increases. Observations of CN, together with CH/CH$^+$, would help to determine separately the increase in density in the cloud and the total ultraviolet radiation field in the cloud (including extinction of the galactic field by the cloud and also the presence of a radiation field from the stars embedded in the cloud).

VI. CONCLUSIONS AND DISCUSSION

The observations reported here are the first indication of depletion where the ionization equilibrium is to some extent observed, through the ratio CH/CH$^+$. Furthermore, by comparing the behavior of interstellar lines in cloud stars and supergiants, some problems are avoided, although others are added. In such dense clouds, it is impossible to hide Ca and Na in the unobservable forms (Ca III and Na II). It is also unlikely that Ca and Na are present as gaseous molecules in amounts larger than the atomic form. Therefore, we are forced to conclude that Ca and Na are missing from the gas to a greater extent in the clouds than the supergiants; if the ionization-equilibrium calculations of § V are at all correct, they are almost completely absent from the gas in the centers of dark clouds (Ca always being more depleted than Na). This fits in well with Carrasco, Strom, and Strom's (1973) inference from polarization data that the grains are larger in clouds—so much so that most of the heavy elements must be on the grains. If we can eventually determine more accurately the ratios Ca/Na in the clouds as compared with the thin interstellar medium, we may derive the ratio Ca/Na in the seed grains which presumably grow in the dense clouds. This will yield data useful in understanding the origin of the seed grains and the process of grain growth.

We have observed the molecules CH and CH$^+$ in the gas in approximately the expected proportions calculated by Solomon and Klemperer (1972) and by Watson and Salpeter (1972). The molecular species are not missing from the gas, contrary to the behavior of atomic Ca and Na. The increase in the ratio of CH/CH^+ in the clouds is predicted by Solomon and Klemperer.

It is unfortunate that we are forced (from § III onward) to assume a constant ratio of $H + 2H_2$ to color excess (i.e., to dust), although Watson and Salpeter (1972) believe that H and H_2 cannot significantly adhere to the grains. Rocket-ultraviolet measurements of the H_2 band and of Lα for the central stars of dark clouds will be very useful.

I am very grateful to the Hale Observatories for generous allotments of telescope time and to Drs. G. Grasdalen, C. Heiles, S. Strom, Mr. L. Carrasco, and an anonymous referee for helpful comments. Dr. F. Chaffee has discussed his unpublished observational material. The Miller Institute for Basic Research has provided financial support.

REFERENCES

Abt, H. A., and Biggs, E. S. 1972, *Bibliography of Stellar Radial Velocities* (Tucson: Kitt Peak National Observatory).
Adams, W. S. 1949, *Ap. J.*, **109**, 354.
Allen, C. W. 1963, *Astrophysical Quantities* (London: Athlone Press).
Blanco, V., Demers, S., Douglass, G. G., and Fitzgerald, M. P. 1970, *Pub. U.S. Naval Obs.*, Ser. 2, Vol. **21**.
Carbon, D. F., and Gingerich, O. 1969, in *Theory and Observation of Normal Stellar Atmospheres*, ed. Owen Gingerich (Cambridge: MIT Press).
Carrasco, L., Strom, S. E., and Strom, K. M. 1973, *Ap. J.*, **182**, 95.
Carruthers, G. R. 1970, *Ap. J.* (*Letters*), **161**, L81.
Field, G. B., Goldsmith, D. W., and Habing, H. J. 1969, *Ap. J.* (*Letters*), **155**, L149.
Garrison, R. F. 1967, *Ap. J.*, **147**, 1003.
Green, S., Hornstein, S., and Bender, C. F. 1973, *Ap. J.*, **179**, 671.
Greenstein, J. L., and Struve, O. 1939, *Ap. J.*, **90**, 625.
Habing, H. J. 1968, *B.A.N.*, **19**, 421.
Harris, D. L., III. 1956, *Ap. J.*, **123**, 371.
Heiles, C. 1973, private communication.
Herbig, G. H. 1968, *Zs. f. Ap.* **68**, 243.
Hiltner, W. A. 1956, *Ap. J. Suppl.*, **2**, 389.
Hobbs, L. M. 1973, *Ap. J.*, **181**, 79.
Hollenbach, D. J., Werner, M. W., and Salpeter, E. E. 1971, *Ap. J.*, **163**, 151.
Lynds, B. T. 1962, *Ap. J. Suppl.*, **7**, 1.
Mészáros, P. 1972, *Ap. J.*, **177**, 79.
Morton, D. C., Jenkins, E. B., and Macy, W. W. 1972, *Ap. J.*, **177**, 235.
Münch, G. 1968, in *Nebulae and Interstellar Matter*, ed. B. Middlehurst and L. H. Aller (Chicago University of Chicago Press).
Petrie, R. M., and Pearce, J. A. 1961, *Pub. Dom. Ap. Obs.* **12**, 1.
Routley, P. M., and Spitzer, L., Jr. 1952, *Ap. J.*, **115**, 227.
Savage, B. D., and Jenkins, E. B. 1972, *Ap. J.*, **172**, 491.
Schild, R., Peterson, D. M., and Oke, J. B. 1971, *Ap. J.*, **166**, 95.
Smith, A. M. 1973, *Ap. J.* (*Letters*), **179**, L11.
Smithsonian Astrophysical Observatory Star Catalog. 1966.
Solomon, P. M., and Klemperer, W. 1972, *Ap. J.*, **178**, 389.
Spitzer, L. 1948, *Ap. J.*, **108**, 276.
Spitzer, L., Epstein, I., Jr., and Li Hen. 1950, *Ann d'Ap.*, **13**, 147.
Strömgren, B. 1948, *Ap. J.*, **108**, 242.
Watson, W. D., and Salpeter, E. E. 1972, *Ap. J.*, **175**, 659.
Werner, M. W. 1970, *Ap. Letters*, **6**, 81.
Wiese, W. L., Smith M. W., and Miles, B. M. 1969, *NBS Standard Ref. Data. Ser.*, Vol. **22**.