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OPTICAL INTERSTELLAR LINES IN SOUTHERN SUPERGIANTS

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ABSTRACT

Photoelectric photometry of 35 southern supergiants reveals a good correlation of the central residual intensity of the diffuse interstellar line at 4430 Å with color excess. From spectra of the brighter southern supergiants, I have derived column densities of Na I and Ca II, and, in a few cases, of CH and CH^+. These results are averaged and compared with previous studies of the interstellar medium at high galactic latitudes and in the denser regions of the plane. The basic peculiarities of the interstellar lines in these two regions, as discussed in Papers I and II, are more sharply delineated by this comparison. Models for the gas in the halo are derived, and I obtained the mass of gas in the halo (from 1×10^7 to 6×10^7 $M_\odot$) and a maximum value of the metal depletion of the halo gas relative to the disk gas (from 300 to 90, depending on whether grains exist in the halo). This maximum value implies that the gas in the halo has been significantly contaminated by material which has undergone nuclear processing.

Subject headings: abundances, nebular — galactic structure — interstellar matter

I. INTRODUCTION

The southern skies are rich in bright, heavily reddened B supergiants. These stars are convenient probes for the less dense regions of the interstellar medium, as they are very distant and do not lie behind nearby dense clouds. We therefore observed their optical interstellar lines, including the diffuse interstellar features at 4430 and 4780 Å (§ II). The results of these measurements are given in § III, and compared with those of Cohen (1973; henceforth called Paper I) for the high-density regions of the interstellar medium (IM) and with those of Cohen (1974*b*; Paper II) for the material far above the galactic plane. Models of the IM, especially for the region far above the plane of the Galaxy, are discussed in § IV.

II. OBSERVATIONS

A list of bright ($M_v < 8.0$) southern supergiants with moderate to heavy reddening, as judged from the *UBV* colors, was compiled from Blanco *et al.* (1970). Thirty-six of them were observed with the Harvard scanner at the 91-cm telescope of Cerro Tololo Inter-American Observatory (CTIO) in 1973 May. A 4 Å exit slit was chosen, and the region from 4450 to 4410 Å was scanned with points 4 Å apart, while 10 Å further on the high and low wavelength sides were scanned with points 5 Å apart. At least 10,000 counts per point (in many cases several times that number) were accumulated. This gives photoelectric profiles of the 4430 Å diffuse interstellar feature.

Twelve of the brighter supergiants were observed with the coudé spectrograph of the 1.5-m telescope of CTIO. Spectra were obtained at a dispersion of 9 Å mm^{-1} on baked IIa-O and IIIa-J plates. Also, using the 098-02 emulsion, I obtained spectra for the region of the interstellar Na I lines at 5900 Å with a dispersion of 18 Å mm^{-1}. A few additional spectra of some of the objects were obtained at the coudé focus of the 100-inch (2.5 m) telescope of the Mount Wilson Observatory. A list of the stars observed at coudé dispersions, their color excess (calculated from the calibration of Schild, Peterson, and Oke 1971), and distances (using absolute magnitudes from Allen 1963), is given in table 1. The spectral classification of the brighter stars is from Hiltner, Garrison, and Schild (1969). Radial velocities were measured for the interstellar features on the blue spectrograms, principally the Ca II lines, and they are given in table 1 reduced to the local standard of rest. Furthermore, I indicate the expected radial velocity for interstellar gas at half the distance to the star, derived from standard galactic dynamics using $A = 15$ km s^{-1} kpc^{-1},

$$V_r = \tfrac{1}{2}[Ar_* \sin(2l^{II}) \cos^2(b^{II})] . \qquad (1)$$

In several cases, the Ca II lines appeared to be double, and the measured radial velocities for both components are given.

The spectra were traced with the PDS digital microphotometer of Kitt Peak National Observatory (KPNO) and reduced to intensity units with the aid of calibration exposures secured simultaneously with the spectrograms. The equivalent widths (W_λ) of all the sharp interstellar features present on the spectra, plus the diffuse features at 5780 and 5797 Å, were measured. These measurements are given in tables 2 and 3. Only in the case of HD 169454, where the velocity separation of the components is very large, could I resolve the two components on the tracings. In the other cases, one could see that the line profile was either asymmetric or broader than usual, but the values of W_λ of tables 2 and 3 include the entire feature. However, I

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† Guest observer.

TABLE 1

Basic Data for Program Stars

Star	Spectral Type	E_{B-V}	V^{pred}_{LSR} ($\frac{1}{2}r_*$) (km sec^{-1})	V^{obs}_{LSR} (km sec^{-1})	r_* (pc)
HD 75149	B4 Ia	0.41	+ 2	+ 9	1600
HD 79186	B5 Ia	0.34	+ 1	+ 3	1600
HD 91619	B5 Ia	0.51	- 9	-8,-20:	2200
HD 99953	B2 Ia	0.55	-11	-14	1900
HD 115842	B0.5 Ia	0.55	-12	-13	1800
HD 148379	B1.5 Iap	0.67	- 6	-6,-11	1200
HD 152236	B1.5 Iap	0.74	- 3	- 6	800
HD 157038A	B4 Ia	0.87	- 3	-3,-18	1200
HD 169454	B1 Ia	1.18	+ 4	+9,+92	900
BD -14° 5037	B1.5 Ia	1.63	+ 4		1000
HD 171012	B0.5 Ia	0.70	+ 8	+ 8	1900
HD 158408	B2 IV	0.01	0	- 1:	130
HD 170235	B2 IVp	0.38	+ 1	+ 2	450
HD 170580A	B2 V	0.34	+ 2	- 2	300

indicate next to V_r the relative strength of the two components as judged from visual inspection of the spectra. There are three stars in common with the survey of Adams (1949), and the values of W_λ for these stars are in reasonable agreement ($\pm$15 percent) with those measured by Spitzer, Epstein, and Li Hen (1950), except for λ3933 in HD 169454, which was assigned a D accuracy by them.

From these measured values of W_λ, the column densities of Na I, Ca II, CH, and CH^+ were derived using the curve of growth given by Münch (1968) for a single cloud with a Gaussian velocity distribution. These values are given in tables 3 and 4. In the cases where 3968 Å of Ca II was not measured because it was too blended with Hε, the Ca II line was sufficiently weak that the doublet ratio is assumed to be 2. Unfortunately, the doublet ratios of the Na I lines were often precariously close to 1, and the cautionary remarks in Nachman and Hobbs (1973) and Cohen (1974*a*) apply. Because these stars are in the galactic plane, the column density of hydrogen along the line of sight to the star cannot be obtained from radio 21-cm observations, and unfortunately there are no measurements of strength of the interstellar Lα feature for these stars. Therefore, we are forced to adopt the standard ratio of hydrogen column density

TABLE 2

Equivalent Widths

Star	V_{LSR}	Relative Strengths	Ca II 3933 (mÅ)	Ca II 3968 (mÅ)	Na I 5889 (mÅ)	Na I 5845 (mÅ)	5780 (mÅ)	5797 (mÅ)	4430 %
Supergiants									
HD 75149	+ 9		560	250:	535	400			5.5
HD 79186	+ 3		390	250:	385	260	200		4.0
HD 91619	- 8 -20	6 1	600	360	680	600			4.0
HD 99953	-14		435	275:	640	475	400		5.0
HD 115842	-13		295	185	555	485	120		5.0
HD 148379	-11 - 6	5 4	470	280	720	620	480	140	8.0
HD 152236	- 6		370	230	820	730	320	160	5.0
HD 157038A	- 3 -18	5 4	620	450	830	705	440	130	9.0
HD 169454	+ 9 +92	7 1	690 80	360:	710 150	660 <100	360	130	9.0
BD -14° 5037					815:	745:	580	130	13.5
HD 171012	+ 8		410	255	555	470	500	110	5.0
Other Stars									
HD 158408	- 1:		45		≤ 60		<100		< 1.0
HD 170235	+ 2		275	170	390	320	270		
HD 170580A	- 2		240	120:	460	355	220	70	

TABLE 3

W_λ for Molecular Lines

Star	W_λ (mÅ) CH+ 4232	W_λ (mÅ) CH 4300	V^1_{LSR}	log (N_{CH^+})	log (N_{CH})	log (N_{CH}/N_{HI})
HD 79186	20	13	+ 1	12.9	13.1	-8.2
HD 115842	10	25	-14	12.6	13.4	-8.0
HD 152236	15	10	- 1	12.8	13.0	-8.5
HD 157038A	46	10:	- 6	13.5	13.0	-8.6
HD 169454		10:	+ 9		13.0	-8.8

Note
1. Weighted average of value observed for each molecular line (weights are W_λ of line).

to total absorption given by Jenkins and Savage (1974), $N_H/E_{B-V} = 6 \times 10^{21}$ atoms cm^{-2} mag^{-1}. With this relation, we derive the ratios of the interstellar constituents to neutral hydrogen that are given in tables 3 and 4.

The photoelectric observations of the residual intensity (RI) at the center of the diffuse interstellar feature at 4430 Å for those stars which were not observed at coudé dispersion are given in table 5, together with the color excesses which were obtained using the same sources as those of the stars in table 1. It is estimated that these values have an error of ± 1.0 percent, mostly due to difficulty in locating the continuum.

III. DISCUSSION

The supergiants are a very homogeneous group with respect to the part of the interstellar medium which gives rise to their interstellar lines. This is because they are closely confined to the galactic plane and are sufficiently distant that they see an average of the less dense regions of the interstellar medium. None of them are behind obvious, large, dense interstellar clouds, and the average density of the gas along the line of sight, N_{HI}/r_*, is about 1 atom cm^{-3}, so that a significant contribution to the interstellar lines from dense regions ($n \geq 50$ cm^{-3}) will not occur. Because this group is relatively homogeneous, it is interesting to plot the RI at the center of the 4430 Å feature as a function of color excess as shown in figure 1. The correlation appears to be linear, with a scatter which can be largely, if not completely, explained by the observational uncertainties.

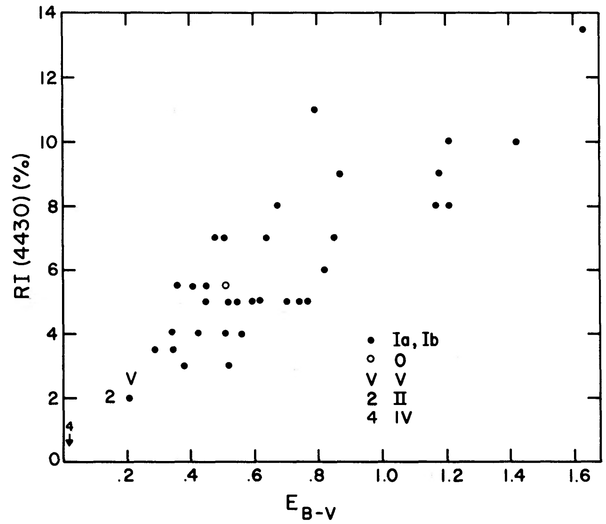

FIG. 1.—The correlation between photoelectrically measured residual intensities at the center of the 4430 Å diffuse interstellar line and the color excess for southern B supergiants plus a few other O and B stars.

We cannot directly compare this plot with the results of Snow and Cohen (1974) on the behavior of 4430 Å in dense regions because of the lack of a conversion between photoelectric (4 Å slit) and photographic results. However, we note that there does not

TABLE 4

Column Densities

Star	V_{LSR}	log ($N_{Ca\ II}$)	log ($N_{Na\ I}$)	log ($N_{Ca\ II}/N_{Na\ I}$)	log ($N_{Ca\ II}$/H I)
Supergiants					
HD 75149		12.8:	12.8	0.0	-8.5
HD 79186		12.8:	12.6	+0.2	-8.4
HD 91619		13.0	13.5	-0.5	-8.4
HD 99953		12.8	12.9	-0.1	-8.6
HD 115842		12.7	13.2	-0.5	-8.7
HD 148379		12.9	13.3	-0.4	-8.6
HD 152236		12.8	13.5:	-0.7	-8.7
HD 157038A		13.1	13.3	-0.2	-8.5
HD 169454	+ 9	12.9	13.5:	-0.6	-8.9
	+92	11.9	11.9:	0.0	
BD -14° 5037			13.6:		
HD 171012		12.8	13.2	-0.4	-8.7
Other Stars					
HD 158408		11.6	≤12.1		-8.4:
HD 170235		12.6	12.9	-0.3	-8.7
HD 170580A		12.4	12.8	-0.4	-8.8

TABLE 5

4430 Å Observations of Additional Southern Supergiants

Star	E_{B-V}	RI (4430 Å) %
Luminosity Class Ia, Ib, Iab		
HD 80558	0.64	7.0
HD 92964	0.48	7.0
HD 96248	0.42	4.0
HD 91619	0.29	3.5
HD 97707	0.75	5.0
HD 102997	0.45	5.0
HD 106343	0.35	3.5
HD 111282	0.36	5.5
HD 111973	0.45	5.5
HD 114213	1.17	8.0
HD 142468	0.85	7.0
HD 144969	1.21	8.0:
HD 148688	0.60	5.0
HD 149038	0.38	3.0
HD 149076	0.59	5.0
HD 150898	0.21	2.0
HD 152235	0.82	6.0
HD 152667	0.56	4.0
HD 154090	0.52	3.0
HD 155985	0.51	7.0
HD 166628	0.79	11.0
CD -51°9193	1.21	10.0:
CD -33°11242	1.42	10.0:
Luminosity Class II		
HD 83183	0.15	2.0
Luminosity Class V		
HD 98695	0.21	2.5
O Star		
HD 124214	0.51	5.5

appear to be a group of points which is abnormally low in RI(4430) compared with the lower envelope of the expected scatter. Since the profile of 4430 Å and its correlation with the color excess has been discussed amply by Herbig (1975) and others, I remark only that the 4430 Å line, as a function of E_{B-V}, appears to behave in a manner expected for supergiants which sample only the less dense regions of the interstellar medium. The results are similar for the less accurate measurements of the other diffuse lines at 5780 and 5797 Å.

Let us now consider the implications of the spectroscopic results as displayed in table 4. The average value of log [N(Ca II)/N(H I)] is -8.7, with a very small dispersion about the mean. The average log [N(Na I)/N(H I)] is -8.4, with a larger dispersion around the mean, while the average log [N(Ca II)/N(Na I)] is -0.3. The molecular lines lead to a value of log (N_{CH}/N_{CH^+}) of $+0.2$, in good agreement with the value for the supergiants included in Paper I. The uncertainty in each individual abundance may be somewhat large, due primarily to difficulties with the saturation correction, but these averages should be correct to ± 0.15. In table 6, we compare the results from the southern supergiants with those from stars with $|b^{II}| > 30°$ and, more particularly, stars which are more than 500 pc above the plane (Paper II) and with those from stars behind or within dense, dark clouds (i.e., stars with large values of E_{B-V}/distance of star), choosing the five most extreme cases from Paper I. The numbers from Papers I and II are normalized to $N(\mathrm{H})/E_{B-V} = 6 \times 10^{21}$ atoms cm^{-2} mag^{-1}. Since all these results were obtained in an identical manner from observations, measurements, and reductions by the present author, the discrepancies between the entries larger than 0.2 are probably real. The general agreement of the results for the southern supergiants with those of Jenkins and Savage (1974), which refer largely to the less dense regions of the plane, is quite encouraging. The intercomparison of the first three lines of table 6 indicates that, relative to the less dense interstellar medium, the denser parts show larger depletions of Ca II and Na I with respect to hydrogen, which differences become further enhanced when ionization equilibrium for Ca and Na is considered, as discussed in Paper I. Furthermore, the material far above the plane is qualitatively different from the normal, low-density interstellar medium.

We indicate in table 6 the agreement between the predicted local standard of rest radial velocity,

TABLE 6

Average Properties of the Interstellar Medium

Region of Interstellar Medium	ΔV_{LSR} (km sec^{-1})	Notes	Log N(CaII/NaI)	Log N(CaII/HI)	Log N(NaI/HI)	No. Stars
Less dense in plane	3.1	1,3	-0.3	-8.7	-8.4	12
Most dense near plane (Paper I)	7.8	2	-0.6	-9.6	-9.0	5[4]
Far above plane (Paper II)	6.6	3	+0.2	-8.3	-8.6	23
Jenkins and Savage (1974)			-0.4	-9.0	-8.6	

1. for gas at half the distance to the star.
2. for gas at the distance of the star (stars embedded in dark dense cloud)
3. for principal component only.
4. HD 147889, HD 147701, BD+31°643, HD 21483, HD 147888

(V_{LSR}) (eq. 1) for the interstellar lines and the observed values. The quantity

$$\left[\sum_1^n (V_{LSR}^{pred} - V_{LSR}^{obs})^2 n^{-1}\right]^{0.5}$$

for the principal component only in a star is given for each of the groups under consideration. For the supergiants, as can be seen in table 1, the agreement is quite good for interstellar lines formed at half the distance of the star. For the other two regions of the interstellar medium, the agreement is poor; often the predicted V_{LSR} has a different sign from the observed radial velocity, or the distance derived from equation (1) and the observed V_{LSR} for interstellar lines in a given star is much larger than the distance to the star. Furthermore, especially in the high-galactic-latitude stars, there are often weaker components at velocities quite different from V_{LSR}^{pred}. It thus appears that only in the less dense regions of the plane does the radial velocity of the interstellar medium accurately correspond to that predicted from a large-scale theory of galactic rotation. In the denser regions and far above the plane, local disturbances distort this uniform rotation. No matter where along the line of sight to the star the matter lies which produces the interstellar lines observed at high galactic latitudes, the material is in most cases not corotating with the gas in the plane.

IV. IMPLICATIONS OF THE OBSERVATIONAL RESULTS

Let us now try to develop the implications of our results as displayed in table 6 for the ionization mechanism of the interstellar medium. As we recall from Paper I, we may derive the ratio Ca/Na from the observed Ca II/Na I ratio with the photoionization corrections using only the mean interstellar radiation field and a guess at n_e. For the low-density regions of the interstellar medium, n_e from pulsar dispersion measurements is given by Dalgarno and McCray (1972) as $n_e/n_H = 0.08$. Thus, we have the Ca and Na photoionized by light from the stars, and the electrons coming not from the metals, but from some ionization of H, presumably by soft X-rays or cosmic rays. If we assume $n_H = 1\ \mathrm{cm}^{-3}$, from table 7 of Paper I and table 6, we obtain Ca/Na = 1/30 in the low-density interstellar medium in the plane. This is much smaller than the Ca/Na ratio in the Sun and other stars, where Ca/Na is about unity. Habing (1969) has indicated that variations of n_e, T_e, or the radiation field cannot eliminate this discrepancy, and it probably is caused by Ca adhering preferentially to the grains (Mészáros 1972).

Let us now consider the gas above the plane. Again the Ca and Na are photoionized, while the electrons are from ionization of hydrogen rather than the metals. Because the Ca II/Na I ratios are peculiar as compared with the plane, it is assumed that most of this material is actually located far above the plane. Arguments such as those of Hobbs (1974) will not affect this statement, for although in his models N(Ca II)/N(H I) may be a function of N(H I), N(Ca II)/N(Na I) is independent of N(H I).

The neutral hydrogen may, however, not be at $z > 100$ pc. If we take the mean value of n_{HI} derived from N_{HI}/r_* for the high galactic latitude stars, we obtain $n_{HI} = 0.1\ \mathrm{cm}^{-3}$. However, the half-width of the plane in neutral hydrogen is about 70 pc (Kerr and Westerhout 1965), and N(H I) arising in that layer is 2×10^{20} atoms cm^{-2}. We therefore subtract 2×10^{20} csc b^{II} atoms cm^{-2} from the observed column density as a correction for the contribution from the hydrogen in the plane, and then divide by the distance to the star for all the stars of Paper II with $z > 1$ kpc. We then obtain a corrected n_{HI} of $0.04\ \mathrm{cm}^{-3}$. This implies that the coincidences in velocity peaks of interstellar Ca II and Na I with 21-cm H I measurements are largely fortuitous for high-galactic-latitude stars, especially close to $V_{LSR} = 0$, where most of the gas in the plane is expected to be. Furthermore, if the column density through the plane is as large as 3×10^{20} atoms cm^{-2}, then n_{HI} above the plane may be reduced to zero.

Let us therefore proceed with the assumption that there is essentially no neutral hydrogen above the plane. Because of the peculiar N(Ca II)/N(Na I), I believe that most of the Na I and Ca II are above the plane. However, we observe $N(\mathrm{Na\ I})/N(\mathrm{H\ I}) = 10^{-8.6}$. To avoid exceeding the ratio Na/H = $10^{-5.8}$, which prevails in the Sun, we must have $n_e \geq 1.7 \times 10^{-3}\ Z_\odot/Z\ \mathrm{cm}^{-3}$, where Z is the metal abundance in the halo and $Z_\odot$ is that in the Sun, so that $Z_\odot/Z > 1$ if the halo is assumed to have some metal depletion (i.e., Population II abundances). If some of the Na is on grains, or if collisional ionization is occurring (Routly and Spitzer 1952; Silk 1971), the lower limit for n_e becomes larger. However, if most of the Na I is actually in the plane, the lower limit on n_e is too large. The value of n_e must be less than $1\ \mathrm{cm}^{-3}$; otherwise we would see strong Hα emission, which, if it is seen, is certainly not strong. Note that we now have a maximum value for $Z_\odot/Z$ of 600.

The principal uncertainty for a model of the IM at high galactic latitudes is the question of the existence of grains. The author assumes that the grains, if formed, are not disrupted, as there is no evidence that grains are disrupted in H II regions in the plane. Furthermore, the E_{B-V}/21-cm H I ratio indicated an excess of grains or a deficit of H I (see Paper II), but the first alternative is highly implausible. Since there appeared to be a reasonable amount of reddening, one would assume that grains have formed in the halo gas as in the plane. Thus I believe that the IM above the plane has grains, and hence does not have a solar Ca/Na ratio in the gas. Therefore we must emerge with Ca/Na $\sim$ 1/30 and Ca (total)/$n_e \equiv$ Ca II + Ca on grains/n_e = $(\mathrm{Ca/H})_\odot \times (Z/Z_\odot)$. We would then explain the weakness of Na I by collisional ionization with $T \sim 10{,}000$ K. Using the recombination and photoionization rates of Paper I, at $n_e \geq 10^{-2}\ \mathrm{cm}^{-3}$,

$$N(\mathrm{Ca})/N(\mathrm{Na}) = N(\mathrm{Ca\ II})/N(\mathrm{Na\ I})_{\mathrm{obs}}(n_e/1.5)$$
$$= 2n_e/(1.5\ \delta)\,,$$

where δ is a correction for collisional ionization of Na I. From table 6, we see that $\delta \leq 3$, as the ratio of Ca II/Na I is a factor of 3 less above the plane than in the plane. For $n_e \geq 0.15\ \text{cm}^{-3}$, $N(\text{Na})/N(\text{Ca}) \leq 15$, and we have lost a lot of Na I, which certainly is not hiding in the grains. So if we wish to preserve the ratio $N(\text{Ca})/N(\text{Na}) \approx 1/30$, then $n_e \leq 0.15\ \text{cm}^{-3}$. If we wish to assume that grains never formed, then we require $N(\text{Ca})/N(\text{Na}) \approx 1$, or $n_e \approx 1\ \text{cm}^{-3}$. This is pushing our upper limit on n_e from the lack of emission. For $n_e \geq 10^{-2}\ \text{cm}^{-3}$, most of the Ca is in the form of Ca II, and we then require $N(\text{Ca II})/n_e \approx N(\text{Ca II})/n_e = 10^{-5.8}\ (Z_\odot/Z)$. This requires $n_e \geq 3.3\ 10^{-3}\ (Z_\odot/Z)\ \text{cm}^{-3}$, so $Z_\odot/Z$ must be less than 300 to avoid running into the upper limit on n_e. Note that because the Ca II is more likely actually to be far above the plane than the Na I, due to the more peculiar ratio of the former to H I, these limits are more reliable than those obtained previously from Na I by a similar argument.

It is unfortunate that the widths of the 21-cm lines cannot be used to set an upper limit on T of the IM above the plane. The full width at half-maximum of the lines is 8–10 km s^{-1} (Heiles and Habing 1974) or $T \leq 10{,}000$ K, but probably most of the 21-cm line is coming from close to the plane. The Doppler widths of Na and Ca are too small even at 10,000 K to be detected.

The final result of this discussion is that, assuming the Ca II and Na I interstellar lines arise largely above the plane while the 21-cm radio line arises in or close to the plane, then if grains form above the plane similarly to those in the plane, $n_{\text{H I}}$ above the plane $\leq 0.04\ \text{cm}^{-3}$, $1/600 \leq 1/600 \times Z_\odot/Z \leq n_e$ above the plane $\leq 0.15\ \text{cm}^{-3}$, and $Z_\odot/Z \leq 90$, for $z \leq 1$ kpc. In this case, the weakness of the interstellar Na I relative to Ca II lines is explained by collisional ionization.

If there are no grains above the plane, which seems unlikely from the E_{B-V}/(21-cm H I) ratios, then $n_{\text{H I}}$ above the plane $\leq 0.04\ \text{cm}^{-3}$, $1/300 \leq 1/300\ (Z_\odot/Z) \leq n_e$ above the plane $\leq 1\ \text{cm}^{-3}$, and $Z_\odot/Z \leq 300$, for $z = 1$ kpc. Therefore, a first approximation of the mass of gas in the halo out to 1 kpc under these assumptions is $10^7\ M_\odot$ for a model with grains, and $6 \times 10^7\ M_\odot$ for a model with no grains. Unless the halo goes out far beyond 10 kpc and its density increases beyond 1 kpc above the plane, it seems difficult to make the mass of the halo gas comparable to that of the Galaxy. Furthermore, the maximum $Z_\odot/Z$ observed in Population II stars is at least 600 (Cayrel de Strobel 1966), so that some enrichment of the halo gas must have occurred. In the case of the model with grains, a considerable amount of enrichment, to at least $Z_\odot/Z = 90$, is required.

This discussion of the IM above the plane is very crude, and can be refined by considering the contribution of the plane to the Ca II and, more importantly, the Na I interstellar lines. Further refinements require more observational data than presently available. The measurement of linear polarization as a function of λ for high galactic latitude stars to determine the size of the grains would be very useful, although the expected polarization is very small.

A summary of the important results that we have established is:

1. The IM above the plane shows a pattern of Ca and Na interstellar lines different from the less dense regions of the plane as established by a group of supergiants.
2. The denser regions of the plane also show a different ratio of Ca II/H I and Na I/H I from that derived from the supergiants.
3. Only in the supergiants do the radial velocities of the interstellar lines agree with those expected from galactic rotation.
4. From the observations of halo stars, we can derive a model of the IM above the plane. It is ionized, the total mass of the halo gas is much less than that of the galaxy, and the material is enriched in metals compared with the most extreme Population II stars.

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