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ELECTRON AND LOCAL GAS DENSITIES IN DIFFUSE INTERSTELLAR CLOUDS FROM MEASUREMENTS OF Ca I ABSORPTION

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ABSTRACT

Electron and local gas densities in 12 diffuse interstellar clouds have been determined from absorption measurements of Ca I λ4226 and Ca II λ3934 and an assumed fractional ionization $x_e = 3 \times 10^{-4}$. Individual velocity components have been analyzed separately. The values for the electron density range from 0.055 to 0.57 cm^{-3}, while the local gas densities are between 180 and 1900 cm^{-3}. The large values for the electron and local gas densities toward ι, ζ, and perhaps 23 Ori, where few hydrogen molecules occur, may arise from recently compressed gas behind a shock.

Subject headings: interstellar: abundances — interstellar: matter

I. INTRODUCTION

The electron density is an important physical quantity, although one which is difficult to determine directly for many analyses of diffuse interstellar clouds. One method for deducing the electron density n_e is to compare the column densities obtained from the absorption lines of two consecutive ionization stages of a given element. Ultraviolet data for C I and C II form one such set. Because the permitted lines of C II are strongly saturated and, hence, the column density of C II is quite uncertain, the value derived for n_e from the carbon data would span a large range. A better choice for this kind of analysis involves the significantly weaker lines of Ca I and Ca II (Hobbs 1971; White 1973). The absorption line of Ca I at 4226 Å is particularly weak ($W_\lambda \approx 1$ mÅ); thus, the number of directions that have been analyzed with calcium data is rather limited. Another, novel, more approximate method for determining n_e was applied by Stokes (1978). He compared measurements of Ca II lines with Ti II lines for ~ 40 directions.

We derive n_e for 12 lines of sight from Ca I λ4226 observations. For most of our directions, previously published data for Ca II (e.g., Marschall and Hobbs 1972) are used, but the present analysis is restricted to specific velocity components. From knowledge of the expected ionization fraction in neutral diffuse clouds, we then estimate the local gas density n and discuss the plausibility of these estimates. Finally, our results are compared with those of Stokes (1978) as a check on his more indirect method of analysis.

II. DATA

The neutral calcium data come from two sources. For most of the directions studied, the Ca I line at 4226 Å was observed with the Reticon silicon photodiode array on the coudé spectrograph of the 2.7 m telescope at McDonald Observatory (Vogt, Tull, and Kelton 1978). The exposures were made as part of the observations of CH^+ at 4232 Å by Federman (1982). Thus, the discussion by Federman regarding the analysis of the CH^+ lines applies to the Ca I lines also. In brief, the spectra were exposed for a sufficient time to ensure detection of lines with central absorption depths of 1%–2%, the lines were measured with a spectral resolution of 4.4 km s^{-1}, and the profiles were fitted by a Gaussian in order to extract the velocity at line center. The spectra are shown in Figure 1; only directions with positive detections were analyzed. The Ca I data for the lines of sight toward 55 Cyg, λ Cep, and 1 Cas are from Hobbs (1971). The results for Ca I are displayed in Table 1. The errors for the equivalent widths W_λ are based on the root mean square fluctuations in the continuum in the vicinity of the line. Since the lines are weak, the ratio of the error to W_λ applies to all quantities derived from W_λ. For the two directions in common with the work of White (1973), the present and the earlier measurements for λ4226 agree. The spectra for δ Sco, ν Sco, and 15 Sgr in Figure 1 are somewhat noisy. The identification of Ca I absorption toward δ and ν Sco is confirmed by the agreement in the measured equivalent widths between the present work and that of White (1973). For the

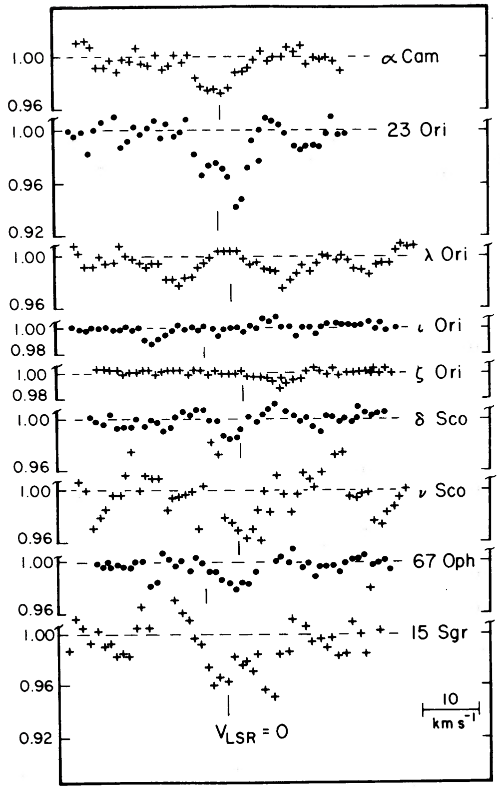

FIG. 1.—Spectra showing new detections of Ca I absorption. Spectra are displayed alternately by plusses and filled circles for easier viewing. The vertical tick mark below each spectrum indicates zero velocity in the frame of the local standard of rest.

absorption toward 15 Sgr, the identification is reasonable because of the similarity in the velocities of Ca I and CH^+ (see Federman 1982). The column density N(Ca I) was calculated assuming that λ4226 is weak and has an oscillator strength of 1.55.

The number of directions with detectable Ca I absorption at a limit of 1–2 mÅ represents ~25% of all measurements by Federman (1982) with this limit. Since the very weak Ca I absorption probably arises only from the densest diffuse gas, of which it therefore is a sensitive observational diagnostic, a comparison of directions with a substantial amount of H_2 [$N(H_2) \gtrsim 10^{19}$ cm^{-2}] appears more appropriate. (There are only three directions in the present work where Ca I was detected and where there is little H_2; these directions are discussed below.) The percentage of directions with W_λ (Ca I) ≈ 1–2 mÅ is ~33% of those showing $N(H_2) \gtrsim 10^{19}$ cm^{-2}. Because of his better quality data, White (1973) measured Ca I absorption for two directions (ζ Per and β^1 Sco) where we could not. Thus, in ~50% of the observed lines of sight with substantial H_2 content, the Ca I line at 4226 Å is seen at $W_\lambda > 1$ mÅ.

In order to obtain a value for n_e, the column density of Ca II for specific velocity components must be known. The velocity intervals for calculating N(Ca II) were determined from K I, Na I, or Ti II data when individual velocity components were not discernible in the Ca II data (e.g., Hobbs 1978). The value for N(Ca II) used in the present analysis, as well as the fraction of the total Ca II represented by each component, also is shown in the table. The notes to the table indicate the references for the Ca II data not obtained by Marschall and Hobbs (1972).

III. RESULTS AND DISCUSSION

Knowledge of N(Ca I) and N(Ca II) for a specific velocity component leads to the determination of n_e for that component: $n_e = \beta N(\text{Ca I})/N(\text{Ca II})$, where $\beta = \Gamma/\alpha$; Γ is the photoionization rate for Ca I, and α is the electron recombination rate constant for Ca II. With the assumption that Ca I resides in the interior of a diffuse cloud, a value $\beta = 25$ cm^{-3}, one-half the value stated in Hobbs (1971), is used in the present analysis. Such a value is applicable to ionizing flux which is attenuated by a factor of 2 as it penetrates to the interior of the cloud. Species such as Ca I and many diatomic molecules that require high densities both for their formation and for shielding from the galactic ultraviolet radiation field probably coexist in the denser interior regions of clouds (e.g., Federman 1981). Confirmation of this fact for the present data comes from the good agreement between the velocity at line center for Ca I and available molecular data (e.g., Federman 1982). The value for β is based on the analysis by Herbig (1968) of the available atomic data. The uncertainty in the value for β is difficult to assess, but it probably exceeds the factor of 2 used above to account for attenuation. The derived electron densities are listed in the table; the values range from 0.055 to 0.57 cm^{-3}. It should be emphasized again that those values probably are selectively appropriate to only the denser regions along the various light paths.

Once electron densities are known, estimates for the local gas density n are possible. Jenkins and Shaya (1979) and Hobbs, York, and Oegerle (1982) found a carbon abundance of $1–2 \times 10^{-4}$ for many diffuse clouds, indicating little depletion of gaseous carbon in these clouds. Since most of the electrons in neutral diffuse clouds comes from the ionization of carbon, with ionization of H, Fe, Mg, and Si also contributing, an ionization fraction $x_e = 3 \times 10^{-4}$ will be adopted. With this value for x_e, the range for n in Table 1 inferred from the present values of n_e is from 180 to 1900 cm^{-3}. This range for n is consistent with chemical models for diffuse clouds (e.g., Black and Dalgarno 1977).

Also displayed in Table 1 are the column densities of H_2 measured by Savage *et al.* (1977). It is likely the Ca I and H_2 coexist for the reason stated above regarding

TABLE 1

DATA FOR DETERMINING n_e

Star	V_{LSR} (km s^{-1})	W_λ(Ca I) (mÅ)	N(Ca I) $\times 10^9$ (cm^{-2})	N(Ca II) $\times 10^{11}$ (cm^{-2})	$\frac{N(\text{Ca II})}{N_T(\text{Ca II})}$	$\frac{N(\text{Ca I})}{N(\text{Ca II})} \times 10^3$	$n_e \times 10^2$ (cm^{-3})	n (cm^{-3})	$N(H_2)$ (cm^{-2})	$n_e \times 10^2$ [a] (cm^{-3})
α Cam ...	−0.8	2.4±0.4	9.8	≳ 45.	~ 0.62	2.2	5.5	180.	2.2(20)[b]	5.9
23 Ori	+3.2	5.6±0.4	23.	10.[c]	...	23.	57.	1900.	1.0(18)	...
λ Ori......	−8.6	1.9±0.2	7.7	11.	0.34	7.0	17.	550.	1.3(19)	undefined
	+9.0	1.9±0.2	7.7	14.	0.44	5.5	14.	460.		8.3
ι Ori	−9.1	0.7±0.1	2.8	1.6	0.22	17.	42.	1400.	4.9(14)	9.0
ζ Ori......	+7.8	1.0±0.1	4.1	2.9	0.34	14.	35.	1100.	5.4(15)	6.1
δ Sco......	−1.7	0.9±0.1	3.7	2.7	1.0	14.	35.	1100.	2.6(19)	30.
ν Sco......	+0.5	2.4±0.4	9.8	9.	1.0	11.	27.	900.	7.8(19)	11.
67 Oph ...	+5.4	1.6±0.2	6.5	12.	1.0	5.4	13.	430.	1.8(20)	...
15 Sgr	−1.3, +6.7	5 7±0.8	23.	≳ 26.[d]	...	≲ 8.8	22.	750.	1.9(20)	...
55 Cyg ...	0.0, +5.0	8.3[e]	34.	13., 12.	0.62	14.	35.	1100.	...	...
λ Cep	+1.5	9.2[e]	37.	> 54.	~ 0.90	< 6.8	< 17.	< 550.	6.0(20)	> 6.6
1 Cas	−6.5	1.8[e]	7.3	17.	< 0.41	4.3	11.	360.	1.4(20)	15.

NOTE.— N_T(Ca II) from Hobbs 1974, 1978.
[a] n_e from Stokes 1978, or his analysis used.
[b] Numbers in parentheses are powers of 10.
[c] Ca II from Beintema, unpublished.
[d] Unpublished.
[e] Ca I from Hobbs 1971.

UV shielding. Toward 23, ι, and ζ Ori, the H_2 column density is low (the H_2 lines are optically thin), yet the derived value for n is substantial. For densities ~ 1000 cm^{-3}, the lines of H_2 become optically thick in a short distance, and because of self-shielding, a large amount of H_2 is expected (Federman, Glassgold, and Kwan 1979).

The principal result of the present work is the apparent discrepancy between these two rather well determined quantities, $n \gtrsim 1000$ cm^{-3} and $N(H_2) \lesssim 1 \times 10^{18}$ cm[illegible] n a component by component analysis of H_2 for stars in Orion, including ζ Ori, Spitzer and Morton (1976) also derived high gas densities. They ascribed the high densities to the recent passage of a shock that has a velocity of 10–15 km s^{-1}. An expanding H II region or supernova remnant is the probable cause of the shock. Among the three lines of sight with little H_2 (23, ι, and ζ Ori), that toward 23 Ori shows both the largest column density of H_2 by a factor of ~ 200 and a strong CH^+ line, which suggests the presence of a shock (Federman 1982). These results thus indicate that toward ι and ζ Ori, the shock has not progressed into the neutral cloud as far as the shock toward 23 Ori, thereby explaining the smaller molecular column densities toward ι and ζ Ori.

A partial test of our results for n_e lies in comparing them with those of Stokes (1978); most of the lines of sight were analyzed by both techniques. Stokes calculated n_e from N(Ca II) and N(Ti II). The last column of the table displays his estimates for n_e and their corresponding limits. The two results for δ and ν Sco are not independent, since Stokes used those Ca I measurements to calibrate his method. Both techniques give similar n_e for the directions in common, except again for ι and ζ Ori, two of the three anomalous cases noted above. For these two directions, Stokes found values for n_e lower by a factor of ~ 5 than our values. Thus, the estimates for n would be correspondingly lowered, but still high for purely atomic gas.

Several conclusions can now be summarized from our analysis. First, for nine lines of sight, plausible values for n_e and n are found from the ratio N(Ca I)/N(Ca II). Second, toward ι, ζ, and perhaps 23 Ori, where few hydrogen molecules exist, the large values for n_e and n may be due to gas compressed by the recent passage of a shock. Third, the indirect method of Stokes (1978) for deducing n_e appears generally to be applicable.

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