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A COMPARISON OF OPTICAL AND RADIO WAVELENGTH OBSERVATIONS OF CH IN THE DIFFUSE INTERSTELLAR MEDIUM

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ABSTRACT

We report radio wavelength measurements and upper limits for CH emission from diffuse interstellar clouds in the direction of nearby bright stars whose optical wavelength spectra exhibit the absorption lines of CH. The $F = 1\text{–}1$ Λ-doublet transition at 3335.481 MHz was detected in the direction of 10 stars, and the $F = 1\text{–}0$ and $F = 0\text{–}1$ transitions at 3263.794 and 3349.193 MHz were detected in the direction of four stars. No departures from equilibrium line intensity ratios were observed. The velocities of the CH lines observed at optical and radio wavelengths are compatible with the assumption that in most cases the radio and optical transitions originate in the same diffuse interstellar cloud. The ratio of the column densities of CH inferred from the 10 measurements in the two spectral regions is $N_{\rm RAD}/N_{\rm OPT} = 1.68 \pm 0.34$, where the error bar denotes one standard deviation. These measurements ensure the compatibility of the reduction procedures in the two regions, and indicate that the oscillator strengths and excitation temperatures used in the reductions cannot be in error by more than a factor of 2. The CH molecules must be well distributed within the diffuse interstellar clouds, and if clumping exists it is not substantial. The central velocities and the velocity dispersions of the CH and CH$^+$ profiles in the direction of ζ Oph agree, suggesting that the two molecular species coexist throughout the diffuse interstellar cloud, and that neither molecule originates in separate compact or circumstellar regions. The column density, $N_{\rm CH}$, of the CH in the diffuse interstellar medium is strongly correlated with the extinction of starlight $m = 3.0\, E_{B-V}$, and the total hydrogen column density, $(N_{\rm H+2N_{H_2}})$, with $N_{\rm CH} = 6.3 \times 10^{13}\, E_{B-V} = 10^{-8}(N_{\rm H} + 2N_{\rm H_2})\ {\rm cm}^{-2}$ for $E_{B-V} \lesssim 0.6$ mag and for extinctions smaller than 2 mag. The relative abundance $N_{\rm CH}/N_{\rm H}$ is an order of magnitude higher than that predicted by the grain-formation theory of CH. When the linear relation found for extinctions less than 2 mag is extrapolated to the higher extinctions characteristic of dark clouds, column densities are predicted which are an order of magnitude higher than those observed. This difference may be due to uncertainties in the extinction estimates of dark clouds. Estimates of the relative column densities of CH and carbon monoxide, CO, obtained from radio wavelength measurements of the diffuse interstellar clouds agree with those obtained from observations at optical and ultraviolet wavelengths with $N_{\rm CH}/N_{\rm CO} \sim 0.3$. The relative abundance of CH and OH in the diffuse interstellar medium is comparable to that in dark clouds with $N_{\rm CH}/N_{\rm OH} \sim 0.3$, but the dark clouds appear to have a relative overabundance of CO or a relative underabundance of CH and OH with $N_{\rm CH}/N_{\rm CO} \sim 10^{-4}$ in dark clouds.

Subject headings: interstellar: abundances — interstellar: molecules — radio sources: lines

I. INTRODUCTION

The study of the physical state of the interstellar medium was initiated when Hartmann (1904) discovered the interstellar lines of ionized calcium (Ca II) and sodium (Na I) in the optically visible spectra of bright stars, and when Dunham (1937) and Dunham and Adams (1941) subsequently discovered the interstellar lines of the diatomic molecules CH, CH$^+$, and CN which also appear in the optical wavelength spectra of bright stars. At this time the structure and possible differential rotation of our Galaxy were a predominant concern, and observers were mainly occupied in measuring the velocities and intensities of the interstellar lines seen in the spectra of distant, bright O and B stars (Plaskett and Pearce 1933; Adams 1949). It has only been during the past decade that the major emphasis has shifted to studies of the composition and physical state of individual interstellar clouds. In order to avoid the confusing effects of both differential galactic rotation and the presence of several intervening clouds, strong, single interstellar features have been searched for in the optical wavelength spectra of nearby stars with large color excesses. Cohen (1973) and Hobbs (1973, 1974) have discussed the optical wavelength spectra of Ca II, Na I, CH$^+$, and CH in the direction of almost 30 stars which appear to be located behind or within single diffuse clouds of the interstellar medium. Three of these stars (ζ Ophiuchi, ο Persei, and ζ Persei) have been the subject of extensive studies at optical wavelengths (Herbig 1968; Chaffee 1974) and at ultraviolet wavelengths, using the

Copernicus satellite (Morton 1975; Snow 1977). The latter work has led to a description of the interstellar lines of a wide variety of ionized atoms and diatomic molecules, and these descriptions provide important constraints on the different mechanisms for molecular formation. Nevertheless, the molecular lines are normally so weak that there is considerable uncertainty in the abundances and formation sites inferred from observations of the lines.

In the meantime, radio astronomers have detected a plethora of molecules in the dense, dark interstellar clouds which hide bright stars from view at optical wavelengths. Much of interstellar matter is, however, concentrated in the more diffuse interstellar regions through which the nearby bright stars are viewed, and in this paper we report the observation of radio wavelength emission of CH in these regions. In § II we present the radio wavelength observations, in § III we compare these observations with optical wavelength observations of CH and CH^+, and in § IV we discuss molecule-dust and molecular correlations in both the diffuse interstellar clouds and the dark dust clouds.

II. RADIO WAVELENGTH OBSERVATIONS OF CH EMISSION FROM DIFFUSE INTERSTELLAR CLOUDS

We have observed the radio wavelength transitions of the $^2\Pi_{1/2}$, $J = \frac{1}{2}$ ground-state Λ-doublet of CH in the direction of nearby bright stars whose optical wavelength spectra exhibit the absorption lines of CH. The stars come from Cohen's (1973) list of highly reddened stars which are located behind or within dense clouds of absorbing material. Because the color excesses of the stars ($0.25 \leq E_{B-V} \leq 1.31$) imply a starlight extinction of between 1 and 3 mag, these observations refer to the diffuse interstellar clouds rather than to the more obvious dark clouds whose extinctions usually range between 3 and 6 mag. Observations of a total of 16 stars were made in 1977 September with the 43 m telescope of NRAO. The main beam efficiency is ~0.6, the half-power beamwidth is ~9′, and the point-source sensitivity is 1 K ~ 20 Jy at our observing frequency of ~3355 MHz. The overall system noise during the observations was ~45 K. Two 192-channel autocorrelation spectrometers were used with 1.25 MHz bandwidths and individual channel resolutions of 0.58 km s^{-1}. Frequency switching at ±126 kHz was employed with one bandwidth centered at the rest frequency of the chosen transition and the other centered 312 kHz away. The respective rest frequencies of the $F = 0$–1, 1–1, and 1–0 Λ-doublet transitions were taken to be 3263.794, 3335.481, and 3349.193 MHz (Rydbeck *et al.* 1974). The $F = 1$–1 transition was detected in the direction of 10 of the stars, and the $F = 1$–0 and/or the $F = 0$–1 transition was subsequently detected in the direction of four of them. The difference spectrum for each detection was inverted and the two frequency-switched profiles were added to give the single profiles which are illustrated in Figures 1 and 2.

Each observed profile was fitted with a Gaussian profile, and the peak antenna temperature, T_A, the full width to half-maximum, ΔV, and the radial velocity with respect to the local standard of rest, V, were determined by the method of least squares. The results for the 10 detected stars are given in Table 1, whereas the peak-to-peak fluctuations of ~0.05 K provide an upper limit to the CH column density in the direction of the six undetected stars (see Table 2). As illustrated in Table 1, the ratios of the line intensities of the $F = 0$–1, 1–1, and 1–0 transitions are, within the observational uncertainties, consistent with the 1:2:1 ratio characteristic of local thermodynamic equilibrium and small optical depths.

III. COMPARISONS OF OPTICAL AND RADIO WAVELENGTH OBSERVATIONS OF INTERSTELLAR CH

The column densities, N_{OPT}, of the ionized atoms or molecules giving rise to a given transition observed at optical wavelengths are often inferred from the optical depth, τ_0, in the line center through the equation (Strömgren 1948; Herbig 1968)

$$\log \tau_0 = \log N_{\text{OPT}} \frac{\pi^{1/2} e^2}{mc^2} \frac{f\lambda^2}{b}, \tag{1}$$

where λ and f respectively denote the wavelength and oscillator strength of the transition, and the Doppler constant $b = (\lambda/c)(2kT/M)^{1/2}$ for the thermal motion of an atom or molecule of mass, M, at temperature T. Usually a theoretical curve of growth is calculated which relates τ_0 to the line equivalent width, W, in units of b. For a given value of W and b, the τ_0 is read from the curve of growth and N_{OPT} is calculated from equation (1). The CH and other molecular lines which are visible at optical wavelengths are, however, usually so weak that no detailed information on their profiles is available. In this case, a value for b is inferred from measurements of the stronger lines of ionized calcium or sodium. Alternatively, the lines are assumed to be unsaturated ($\tau_0 \to 0$), and the equation

$$N_{\text{OPT}} = \frac{mc^2}{\pi^{1/2} e^2} \frac{W}{\lambda^2 f} \approx 1.13 \times 10^{20} \frac{W}{\lambda^2 f} \quad \text{cm}^{-2} \tag{2}$$

is used. In the numerical approximation the equivalent width, W, and the wavelength, λ, of the observed transition are given in angstroms. If either the curve of growth or equation (2) is used, the dominant uncertainty in the column density, N_{OPT}, comes from the uncertainty in the measurements of the equivalent widths of the weak molecular lines. In Table 2, for example, we present the column densities, N_{OPT}, given by Cohen (1973) by using optical wavelength transitions of CH whose widths of 10 to 30 Å have uncertainties of ±10 Å. Also given in Table 2 are the radial velocities of the optical transitions, V_{OPT}, where the heliocentric velocities given by Cohen (1973), Hobbs (1973, 1974) and Chaffee (1974) have been corrected for the standard solar motion by using the formula given by Lang (1974). As a result, the radial velocities determined at optical and radio wavelengths both refer to the local standard of rest.

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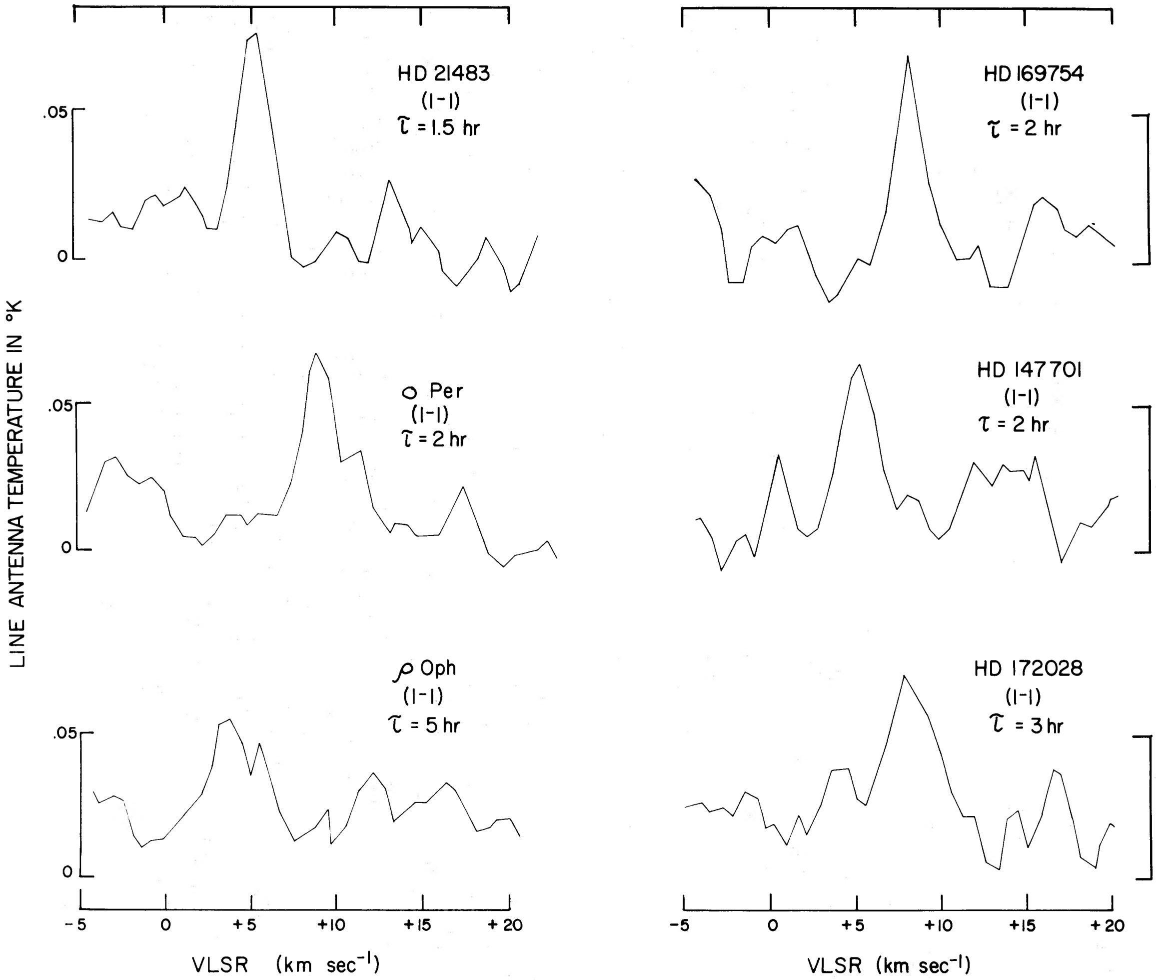

FIG. 1.—Representative profiles of the $F = 1\text{–}1$ radio wavelength transition of CH in the direction of nearby bright stars. The total observation time is τ and the spectra have been Hanning smoothed to give a velocity resolution of 0.93 km s^{-1}.

TABLE 1

$F = 1\text{–}1$, $F = 1\text{–}0$, AND $F = 0\text{–}1$ RADIO WAVELENGTH TRANSITIONS OF CH IN DIFFUSE INTERSTELLAR CLOUDS*

Star	α(1950.0)	δ(1950.0)	F	T_A (K)	ΔV (km s^{-1})	V (km s^{-1})
HD 21483.......	$03^h25^m42^s$	+30°12′12″	1–1	0.076 ± 0.006	1.5 ± 0.3	+5.4 ± 0.1
			1–0	0.030 ± 0.005	2.2 ± 0.5	+5.7 ± 0.2
			0–1	0.050 ± 0.010	1.2 ± 0.4	+5.4 ± 0.2
o Per............	03 41 11	+32 07 54	1–1	0.070 ± 0.007	2.3 ± 0.3	+8.2 ± 0.1
			1–0	0.038 ± 0.005	2.7 ± 0.5	+7.7 ± 0.2
			0–1	0.040 ± 0.007	2.0 ± 0.8	+7.4 ± 0.1
χ Per............	03 52 13	+30 54 02	1–1	0.030 ± 0.005	2.7 ± 0.5	+7.3 ± 0.2
HD 147701......	16 21 19	−24 55 10	1–1	0.050 ± 0.009	1.6 ± 0.4	+4.4 ± 0.2
HD 147889......	16 22 25	−24 21 05	1–1	0.140 ± 0.020	1.8 ± 0.3	+3.4 ± 0.1
			1–0	0.078 ± 0.007	1.8 ± 0.2	+3.1 ± 0.9
ρ Oph...........	16 22 54	−23 20 70	1–1	0.026 ± 0.004	3.2 ± 0.6	+3.3 ± 0.3
ζ Oph...........	16 34 24	−10 28 00	1–1	0.027 ± 0.005	1.5 ± 0.3	−0.8 ± 0.2
HD 169754......	18 24 53	−11 23 23	1–1	0.054 ± 0.008	1.2 ± 0.3	+7.2 ± 0.1
HD 172028......	18 35 21	−00 26 37	1–1	0.050 ± 0.008	3.5 ± 0.6	+7.1 ± 0.3
			1–0	0.045 ± 0.008	1.8 ± 0.3	+6.7 ± 0.3
HD 207538......	21 46 08	+59 28 06	1–1	0.020 ± 0.004	3.9 ± 0.9	−3.0 ± 0.3

* In all cases the uncertainties are the formal errors in a Gaussian fit at the 1 σ level.

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TABLE 2

OPTICAL AND RADIO WAVELENGTH MEASUREMENTS OF CH IN DIFFUSE INTERSTELLAR CLOUDS

Star	E_{B-V} (mag)	$N_{\rm OPT} \times 10^{13}$ (cm^{-2})	$N_{\rm RAD} \times 10^{13}$ (cm^{-2})	$V_{\rm OPT}$* (km s^{-1})	$V_{\rm RAD}$* (km s^{-1})
HD 169754	1.31	1.6	2.6	+32?	+7.2
HD 183143	1.30	3.2	$\lesssim$3.2	+14	...
HD 147889	1.08	7.9	10.2	−5	+3.4
BD +31°643	0.93	5.0	...	...	...
HD 192660	0.88	2.0	$\lesssim$3.2	+11	...
HD 172028	0.76	1.6	7.1	+6	+6.7
HD 24432	0.76	2.5	$\lesssim$6.4	−11	...
HD 147701	0.72	4.0	3.2	−2	+4.4
HD 207538	0.64	...	3.1	+7	−3.0†
χ Per	0.62	2.0	3.3	+7	+7.3†
HD 21483	0.58	2.0	4.6	+1	+5.4†
ρ Oph	0.47	3.2	3.4	+7	+3.3
ζ Per	0.38	3.1‡	3.2§	+4, +7	+2.0
ξ Per	0.33	1.4	$\lesssim$3.2	+4	...
o Per	0.32	3.1‡	6.5	+5, +8	+8.2†
ζ Oph	0.32	3.4	1.6	0	−0.8†
HD 24131	0.25	1.0	$\lesssim$3.2	+7	...
HD 21856	0.23	1.0	$\lesssim$3.2	+1	...

NOTE.—Stars are listed in order of increasing color excess E_{B-V}.

* Velocities inferred from measurements at optical wavelengths usually have large errors of ±3 km s^{-1}. The uncertainties for the radio wavelength velocity measurements are given in Table 1.

† These radial velocities agree, within the measurement uncertainties, with the velocities of radio wavelength CO emission observed in the same direction (Knapp and Jura 1976).

‡ Revised to 2.3 by Chaffee and Lutz 1977, using a different f-value.

§ From Hjalmarson *et al.* 1977.

At radio wavelengths the column densities of CH can be inferred from the antenna temperatures, T_A, and the half-widths, ΔV, of the $F = 1$–1 transition through the equation (Lang 1974)

$$N_{\rm RAD} = \frac{8\pi k\nu}{hc^2A}\frac{T_x\Delta T_A\Delta\nu_L}{\eta_A[(T_x\Omega_c/\Omega_A) - T_B]}$$

$$\approx 2.9 \times 10^{14}\frac{T_x\Delta T_A\Delta V}{\eta_A[(T_x\Omega_c/\Omega_A) - T_B]}\ {\rm cm}^{-2}, \quad (3)$$

where we have assumed that the diffuse interstellar cloud is optically thin and that it subtends a solid angle $\Omega_c \lesssim \Omega_A$, where Ω_A denotes the solid angle of the main antenna beam and $\eta_A \sim 0.6$ denotes its efficiency. It is also assumed that the cloud has constant properties over the region observed, and that the contribution to the antenna temperature from continuum sources within the antenna beam is negligible. The temperature of the universal background, T_B, has been taken to be $T_B = 2.8$ K, and in our calculations we have taken the excitation temperature to be $T_x = -15$ K [from the measurement (error ~ ±5 K) of Rydbeck *et al.* (1976)]. In the numerical approximation we have adopted a line frequency of $\nu = 3335.481$ MHz and the Einstein A coefficient of Burdyuzha and Varshalovich (1973); and the full width at half-maximum, $\Delta\nu_L$, of the line is assumed to be in velocity units, ΔV, of km s^{-1}. The values of T_A and ΔV given in Table 1 were then used with equation (3) together with the assumption that the interstellar clouds fill the main beam $\Omega_c \sim \Omega_A$ to give the column densities listed in Table 2. When no radio wavelength transition was detected, upper limits were given to $N_{\rm RAD}$ by assuming that $\Delta V = 2$ km s^{-1} and that T_A is equal to the peak-to-peak noise fluctuations in the antenna temperature.

Because the radial velocities measured at optical wavelengths usually have uncertainties of ±3 km s^{-1} (except for certain interferometric measurements [Hobbs 1973]), little can be inferred from a comparison with the radio wavelength velocity estimates except that in a few cases the radio observations might refer to clouds which lie behind the stars. In most cases the velocity data are compatible with the assumption that the radio and optical transitions originate in the same diffuse interstellar cloud. The data given in Table 2 show that the ratio of the column densities inferred from measurements at radio and optical wavelengths is $N_{\rm RAD}/N_{\rm OPT} = 1.68 \pm 0.34$, where the error bar denotes one standard deviation. In spite of the large measurement uncertainties and the radically different assumptions employed in the two spectral regions, the column densities agree within two standard deviations. This agreement means that the oscillator strengths used for the optical wavelength transitions and the excitation temperature of −15 K used for the radio wavelength transitions cannot be in error by more than a factor of 2, and that the CH molecules must be well distributed throughout the molecular clouds and the radio wavelength antenna beam. The CH does not exhibit any detectable clumping within the interstellar cloud, and the CH cloud has an angular extent which is equal to or larger than the antenna beam of 9′. If the CH were clumped or if it subtended an angular size less than 9′, then the factor Ω_c/Ω_A in equation (3) would be smaller and N_{RAD} would, on the average, be even larger than N_{OPT}.

Of special interest is a comparison of the profiles of the CH and CH^+ lines. Because the chemical models which describe the formation of CH and other interstellar molecules cannot reproduce the observed high abundance of CH^+, theoreticians have argued that CH and CH^+ cannot coexist in the interstellar clouds. Black and Dalgarno (1973, 1977), for example, have reasoned that the CH^+ may belong to a circumstellar region, or that the CH molecules are formed in a dense molecular core. When compared with optical wavelength results, our observations suggest that the CH is well distributed and that it is not found in a dense central core. If the CH^+ is circumstellar, we might expect substantially different velocities and velocity dispersions for CH and CH^+. The CH lines visible at optical wavelengths are generally so weak, however, that no detailed information on their profiles is obtainable. In Figure 3 we compare our profile of CH in the direction of the ζ Oph cloud with Hobbs's (1973) profile of CH^+ in the same direction. (Here we have corrected the heliocentric velocity to the local standard of rest so that the CH^+ peak near the heliocentric velocity of $-12.6\ \mathrm{km\ s^{-1}}$ corresponds to a velocity of $0.0\ \mathrm{km\ s^{-1}}$ in the local standard of rest.) Both the velocity dispersion and the central velocities of the CH and CH^+ profiles agree, and this agreement supports the idea that the two molecular species do coexist throughout the ζ Oph cloud. A comparison of CH^+ profiles with the profiles given in Figures 1 and 2 may help distinguish between circumstellar and interstellar formation sites in other directions.

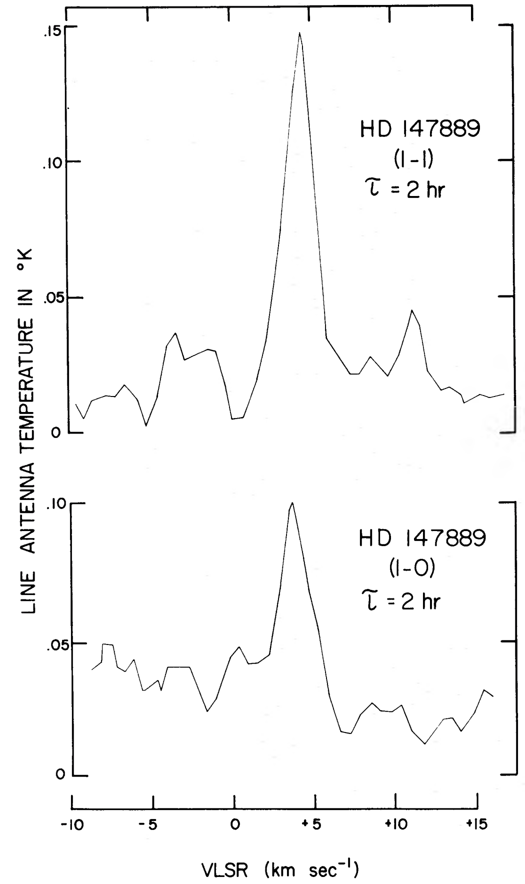

FIG. 2.—Profiles of the $F = 1$–0 and 1–1 radio wavelength transitions of CH toward the star HD 147889. The observations are, within the measurement uncertainties, compatible with the equilibrium line intensity ratios of 1:2.

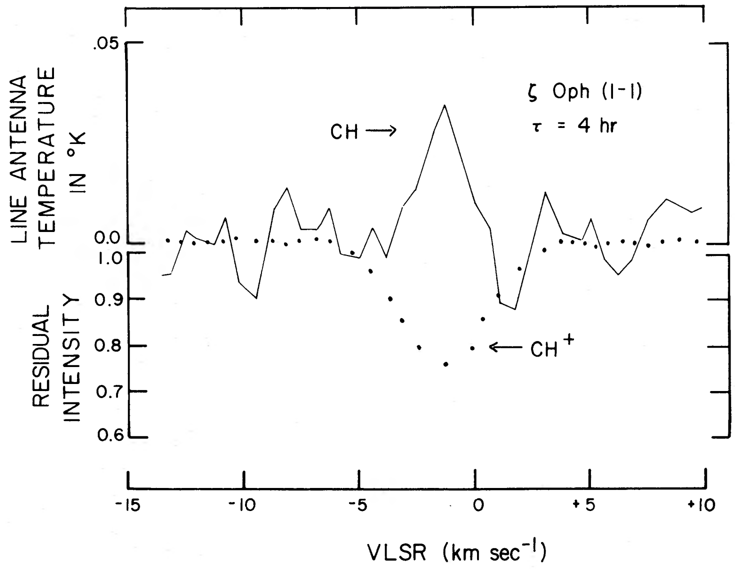

FIG. 3.—A comparison of the radio wavelength CH profile (this paper) and the optical wavelength CH^+ profile (Hobbs 1973) in the direction of ζ Oph.

IV. MOLECULE-DUST AND MOLECULAR ABUNDANCE CORRELATIONS

The dust grains which are responsible for the reddening and extinction of starlight play a crucial role in molecular formation processes by absorbing lethal ultraviolet light and by providing a formation site for some molecules. An observational basis for a connection between dust grains and molecules was first provided by spacecraft observations of the column densities of the atomic hydrogen, N_H, and the molecular hydrogen, N_{H_2}, along the line of sight to nearby bright stars. Savage and Jenkins (1972) and Jenkins and Savage (1974) showed that N_H is strongly correlated with the star's color excess E_{B-V}, with

$$N_H = 6.2 \times 10^{21} E_{B-V} \text{ cm}^{-2} , \qquad (4)$$

for $E_{B-V} \lesssim 0.05$ mag. For more distant stars, a large fraction of the hydrogen is in molecular form, and the observations suggest that the total hydrogen column density increases with the column density of dust grains according to the relations (Jenkins and Savage 1974)

$$N_H + 2N_{H_2} = 7.5 \times 10^{21} E_{B-V} \text{ cm}^{-2} , \qquad (5)$$

for $E_{B-V} \lesssim 0.5$ mag, and (Lang 1974)

$$m = 3.0 \, E_{B-V} , \qquad (6)$$

where m is the extinction of visual starlight in magnitudes.

The observed amounts of atomic and molecular hydrogen are in good agreement with the theory of Hollenbach, Werner, and Salpeter (1971) in which molecular hydrogen is formed on grain surfaces at a rate which is limited by the frequency of collisions between hydrogen atoms and grain surfaces. Watson and Salpeter (1972) have extended this theory by reasoning that CH and other molecules are formed on grain surfaces with $N_{CH} \sim 10^{-9} N_H$ for diffuse interstellar clouds with $m \lesssim 0.5$. Alternatively, gas-phase chemical reactions which employ radiative association with H (Solomon and Klemperer 1972) or with H_2 (Black and Dalgarno 1973, 1977) may account for the production of CH with $N_{CH} \lesssim 2 \times 10^{-7} N_H$. Whatever the correct formation process, we would expect N_{CH} to be either directly or indirectly related to the extinction, m, through the direct formation of CH on grains or through the dependence of N_H or N_{H_2} on extinction as expressed in equations (4) and (5).

The data given in Table 2 and illustrated in Figure 4 were fitted to the linear relation $N_{CH} = a_1 m + a_0$ by the method of least squares. The values of m were taken to be 3.0 E_{B-V} (Johnson 1963), and radio wavelength values of N_{CH} were used except when they provided upper limits. In this case the optical wavelength values of N_{CH} were used. For the special case of o Per the optical wavelength value was used because the radio measurements refer to a dust cloud which lies mainly behind the star (Snow 1975). As illustrated by the solid line in Figure 4, we obtain an intercept near zero ($a_0 = -0.015$) and a slope of $a_1 = 2.1$ for the least-squares fit to all of the data with $m \leq 2.0$. The linear correlation coefficient for the points considered was 0.77. When our results are combined with those of Jenkins and Savage (1974) (eq. [5]), we obtain

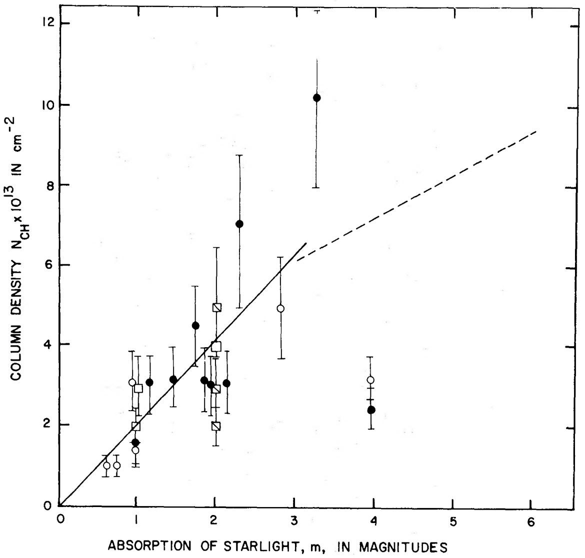

FIG. 4.—The column density, N_{CH}, of CH plotted as a function of optical extinction $m = 3.0 \, E_{B-V}$. *Filled circles*, radio wavelength observations given in this paper; *open circles*, optical wavelength measurements used when only upper limits are available at radio wavelengths; *squares*, radio wavelength observations given by Hjalmarson *et al.* 1977 for $m < 3$. *Solid line*, the linear least-squares fit to the data represented by circles for $m \leq 2.0$; *dashed line*, a similar fit to 79 points for dark clouds with $3 \leq m \leq 6$ (taken from Hjalmarson *et al.* 1977 and Lynds 1972). The change in slope at large extinctions may be due to uncertainties in the extinction measurement or to clumping in the dark clouds.

$$N_{CH} = 2.1 \times 10^{13} m = 6.3 \times 10^{13} E_{B-V}$$
$$\approx 10^{-8}(N_H + 2N_{H_2}) \text{ cm}^{-2} \qquad (7)$$

for $m \lesssim 2.0$ and $E_{B-V} \lesssim 0.6$ mag. The relative abundance of CH and H seems to be an order of magnitude higher than that predicted by the grain-formation theory $N_{CH} \sim 10^{-9} N_H$ according to Watson and Salpeter (1972). Our equation (7) for N_{CH} and N_H in the diffuse interstellar medium compares favorably with Rydbeck *et al.*'s (1976) observations of neutral hydrogen regions in the direction of Cas A. Under the assumption that the CH clouds in these regions have constant properties and fill the main antenna beam (beamwidth = 15′, beam efficiency = 0.6, and an excitation temperature of −15 K), they obtain $N_{CH} = 10^{13}$ cm^{-2} = $4 \times 10^{-8} N_H$ and $N_{CH} = 4 \times 10^{13}$ cm^{-2} = $10^{-8} N_H$, respectively, for the Orion (local 1 km s^{-1} feature) and the Perseus (−47 km s^{-1} feature) arms in the direction of Cas A. They also obtain similar values of $N_{CH} = 0.6$ to $20 \times 10^{-8} N_H$ for the less diffuse, dark dust clouds under the same assumptions.

Our radio wavelength data for diffuse interstellar clouds with low extinction may be compared with similar radio wavelength measurements of dark interstellar clouds whose several magnitudes of visual extinction make them obvious features in the sky. The dashed line in Figure 4 denotes the linear least-squares fit to 79 values of $N_{\rm CH}$ given by Hjalmarson *et al.* (1977) for dark clouds with $3 \le m \le 6$, where the values of m are taken from Lynds's (1962) eye estimates of extinction. When the linear relation found for extinctions smaller than 2 mag is extrapolated to higher extinctions characteristic of dark clouds, column densities are predicted which are an order of magnitude higher than those observed. This difference may well be unreal, however, for the dark cloud data exhibit a large scatter (the linear correlation coefficient for the 79 points is only 0.14), and the extinction data are based on relatively inaccurate eye estimates. Moreover, a systematic underestimate of $N_{\rm CH}$ would result if the dense dark clouds are on the average smaller or more clumped than the diffuse interstellar clouds. Nevertheless, there does seem to be a very real deficiency of CH in very compact, dense molecular clouds where $N_{\rm CH} \sim 10^{13}$ to 10^{14} cm^{-2} when m reaches values between 10 and 100 (Zuckerman and Turner 1975; Rydbeck *et al.* 1976).

Of special interest is a comparison of the column densities of CH with those of carbon monoxide, CO, and the hydroxyl radical, OH. Measurements of ζ Per, o Per, and ζ Oph taken at optical and ultraviolet wavelengths indicate that $N_{\rm CH}/N_{\rm OH} \sim 0.3 \sim N_{\rm CH}/N_{\rm CO}$ for the diffuse interstellar clouds (Morton 1975; Crutcher and Watson 1976; Chaffee and Lutz 1977; Snow 1977). Radio wavelength measurements indicate that $N_{\rm CH}/N_{\rm OH}$ has a similar value of between 0.2 and 0.4 for both the dark dust clouds (Rydbeck *et al.* 1976; Hjalmarson *et al.* 1977) and the more diffuse interstellar medium including the Orion and Perseus arms in the direction of Cas A (Rydbeck *et al.* 1976). Moreover, when our radio wavelength measurements of $N_{\rm CH}$ are compared with Knapp and Jura's (1976) radio wavelength measurements of $N_{\rm CO}$, an average value of $N_{\rm CH}/N_{\rm CO} = 0.3$ is also obtained for the diffuse interstellar medium (from o Per, ρ Oph, ζ Oph, and HD 207538). Although the relative abundance of CH and OH is approximately the same for the diffuse interstellar medium and the dark dust clouds, there is a relative overabundance of CO in dark clouds (or equivalently a relative underabundance of both CH and OH in dark clouds). We obtain an average value of $N_{\rm CH}/N_{\rm CO} = 10^{-4}$ for 22 dark dust clouds under the assumption that the optically thick C^{12}O lines are related to the optically thin C^{13}O lines by the terrestrial isotope ratio of 89 (here we have used the data of Dickman 1975; Milman *et al.* 1975; and Hjalmarson *et al.* 1977). A similar value of $N_{\rm CH}/N_{\rm CO} = 10^{-4}$ was obtained by Rydbeck *et al.* (1976) for their dark cloud data. Theoretical models of molecular formation and destruction must take into account the relative overabundance of CO in dark clouds (or equivalently a relative underabundance of both CH and OH in dark clouds) when compared with the diffuse interstellar medium. Moreover, the models must take into account the strong correlation of CH with dust in the diffuse interstellar medium together with Knapp and Jura's (1976) observation that the CO in diffuse interstellar clouds does not correlate well with other interstellar species and correlates only moderately well with dust.

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