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EVIDENCE FOR SHOCKED INTERSTELLAR GAS TOWARD THE PERSEUS OB2 ASSOCIATION

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ABSTRACT

Optical measurements of absorption lines of CH^+ and CH toward ζ, o, and ξ Persei reveal a shift in velocity between the two molecular species. The equivalent width of the CH^+ varies directly with both the amount of shift seen and the line width. The present observations confirm predictions of the chemical model formulated by Elitzur and Watson. The model requires shocks for producing sufficient amounts of CH^+; therefore, strong evidence for shocked interstellar gas is now available. Reexamination of the optical results for OH toward ζ and o Persei indicates that a substantial fraction of the OH also was formed in the high-temperature shocked gas.

Subject headings: interstellar: molecules — shock waves

I. INTRODUCTION

Optical absorption features for the interstellar molecular species CH^+ and CH have been observed in spectra of many early-type stars. Steady state chemical models using recently determined reaction rates are unable to reproduce the observed column densities of both CH^+ and CH (Langer 1976, 1978; Black and Dalgarno 1977; Federman 1979). Elitzur and Watson (1978, 1980 [hereafter EW]) have proposed a time-dependent model (i.e., one involving fluid motion in the form of shocks) to account for the measured column densities. In the model of EW, CH^+ is found in the hot postshock gas, while all the other molecules incorporating heavy atoms, including CH, are situated primarily in the cold postshock gas. Since CH^+ and CH are formed in different regions of the fluid flow, a shift in velocity is expected between the centers of the lines for these two species. For typical shock conditions in diffuse clouds, the predicted shift is approximately 3 km s^{-1}.

Searches have been made for these shifts. Chaffee (1975) and Frisch (1979) noted shifts in velocity between the absorption features of CH^+ and CH toward ζ Oph and χ Oph. Radio observations show other molecules toward ζ Oph (Crutcher 1979; Liszt 1979) to have emission lines at the velocity of CH, not at that of CH^+. Toward the Perseus stars (o, ζ, and ξ Per), Chaffee (1974) measured the absorption lines of CH^+ and CH; however, his velocity resolution was not sufficient to reveal shifts of $\sim$3 km s^{-1}. In this *Letter*, data obtained with higher-velocity resolution are presented for the same three stars. Toward o Per and ξ Per the absorption line of CH at 4300 Å is found to be redshifted with respect to the 4232 Å absorption line of CH^+.

II. OBSERVATIONS

Absorption lines at 4232.539 Å for CH^+ and at 4300.321 Å for CH were measured during 1979 December toward o, ζ, and ξ Per. The molecular spectra were obtained with the Reticon photodiode array on the coudé spectrograph of the 2.7 m telescope at McDonald Observatory (Vogt, Tull, and Kelton 1978). The echelle grating (79 rulings per mm) was used in 54th and 53rd order for the CH^+ and CH lines, respectively, giving dispersions of 0.636 Å mm^{-1} and 0.653 Å mm^{-1}, respectively. The entrance slit to the spectrograph was set at 220 μm, corresponding to a resolution of 2.2 km s^{-1} at 4300 Å.

The data were reduced with a least-squares program which produced flat continua. The program also removed the remaining fixed pattern noise of the Reticon array, which was not divided out by the Reticon software package (Vogt, Tull, and Kelton 1978) from the raw data. The root mean square error ϵ_{rms} in the continuum of each spectrum was determined over an interval of 50 diodes. The calculated value for ϵ_{rms} typically corresponded to a ratio of signal-to-noise of 100. The conditions were least favorable during the observations of o Per, producing the noisiest spectra.

The measured equivalent widths are presented in the second column of Table 1. The stated errors are determined from the noise in the continuum over the full width of the line. The third column lists previous determinations for the equivalent widths; the superscripts in this column indicate the reference. The present photoelectric results are lower than the corresponding photographic ones, but are within the range of values determined in all previous work. The discrepancy between the two observational techniques has been discussed by Hobbs (1973) with regard to his photoelectric measurements.

The cores of the absorption lines were fitted by Gaussian line profiles. A confidence at the 95% level from a χ^2 test was adopted for each final fit. The absorption feature for CH toward ξ Per was the only one that could not be fitted with a single Gaussian of a width not too different from that deduced for CH^+ in this direction. However, two components separated by 4–5 km s^{-1} adequately describe the line. The fitted curves were used to derive the velocity of the line centers, the Doppler width parameters, and the respec-

TABLE 1

RESULTS FOR CH^+ AND CH

Molecule	W_λ(mÅ) This Work	W_λ(mÅ) Previous Work	v_{LSR}(km s^{-1})	b_D(km s^{-1})
		ζ Persei		
CH^+..........	2.6±0.9	2,[1] 3.2,[2] 5.4[3]	7.7±0.1	1.2±0.3
CH...........	15.9±2.9	8,[4] 20.6[1]	8.1±0.1	1.9±0.1
		o Persei		
CH^+..........	5.1±2.7	8.6[1]	6.1±0.1	2.0±0.2
CH...........	11.2±4.9	14,[4] 20.3[1]	7.7±0.4	2.5±0.5
		ξ Persei		
CH^+..........	17.8±2.1	18.2,[5] 25,[2,6] 27,[1] 32[3]	2.0±0.1	3.6±0.2
CH no. 1......	3.1±2.1	{8,[5] 11[1]	0.3±0.1	2.5±0.3
CH no. 2......	6.3±2.5		4.7±0.5	3.1±0.5

REFERENCES.—(1) Chaffee 1974; (2) Hobbs 1973; (3) Rogerson *et al.* 1959; (4) Dunham 1941; (5) Frisch 1972; and (6) Cohen 1973.

tive errors; the curves do not reproduce the wings well and thus were not used to determine the equivalent widths. Figures 1–3 show both the observed lines and the fitted Gaussians toward ζ Per, *o* Per, and ξ Per, respectively. The spectra labeled (*a*) are the CH^+ results; those labeled (*b*) are the corresponding CH results. The actual data are represented by filled circles, and the fitted Gaussians are the solid curves. The dashed curves are the adopted continua. In each of the plots, the normalized intensity is the ordinate, while

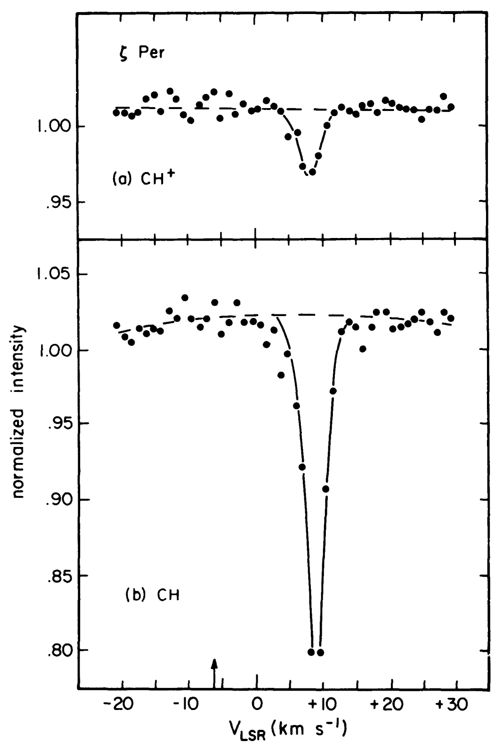

FIG. 1.—Normalized intensity for absorption lines of CH^+ and CH toward ζ Per are plotted against the velocity in the local standard of rest—(*a*) the CH^+ spectrum; (*b*) CH spectrum. The filled circles represent the observations, while the solid curves are the fitted Gaussians. The dashed lines are the adopted continua. The arrow on the velocity scale indicates the zero in heliocentric velocity.

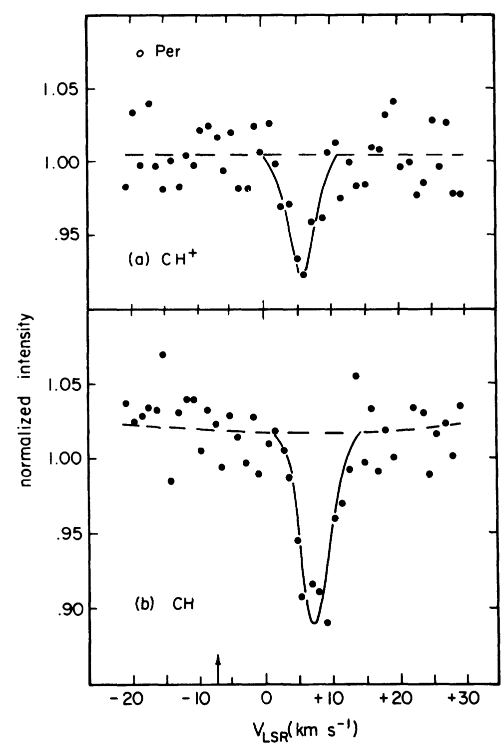

FIG. 2.—Same as Fig. 1 for the line of sight toward *o* Per.

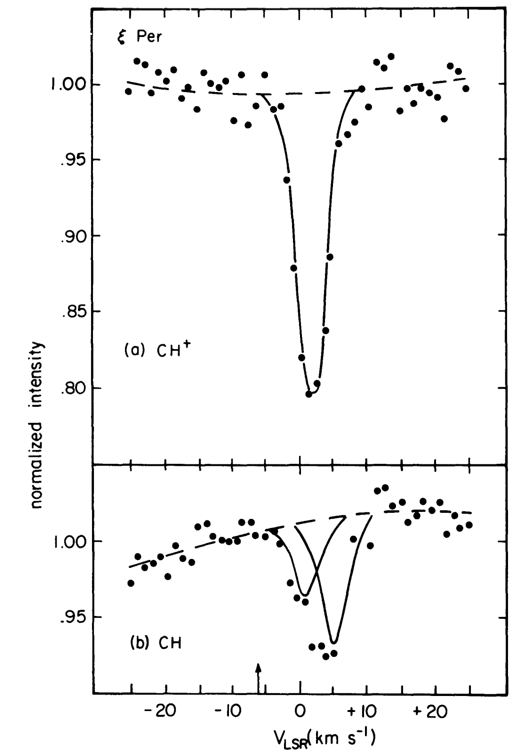

FIG. 3.—Same as Fig. 1 for the line of sight toward ξ Per.

the velocity with respect to the local standard of rest is the abscissa. The arrow indicates the zero for heliocentric velocity.

The centers of the fitted lines yielded velocities in the frame of the local standard of rest ($v_{\rm LSR}$). These velocities are shown in the fourth column of Table 1. A possible shift (at 2 σ level) is found between the two molecular lines for the direction toward ζ Per. (Stronger evidence for two components in this direction are presented in § III.) For the other two lines of sight, the CH feature appears redshifted with respect to the CH^+ feature. In the direction of ξ Per there are two CH components; the CH^+ feature is believed to be associated with the component at higher velocity. The low-velocity component of CH has a radial velocity similar to the rim 21 cm emission which lies in the direction of ξ Per (Sancisi 1974) and probably represents an unrelated cloud in the line of sight. The results of Hobbs (1973) for this direction indicate a velocity for the CH^+ line approximately midway between our CH^+ feature and our high-velocity component of CH. Considering the velocity resolution of the spectrograph, the two CH^+ features are likely the same; the two values for $v_{\rm LSR}$ produce a small range in the velocity shift. The velocity structure seen toward *o* and ξ Per, and possibly ζ Per, indicates that CH^+ and CH reside in different gaseous components of a specific cloud.

All velocity components found here have a corresponding component in K I (λ7699) (see Hobbs 1974); the Na I (λλ5890, 5891) lines are too saturated for a comparison. Hobbs (1973) also noted the agreement in velocities for CH^+, Na I, and Ca II toward ζ Per. Toward *o* Per the K I feature has a shoulder on the blue side of the line, indicating the presence of two velocity components. Similar velocities are expected because shielded regions protect both atoms with ionization potentials less than 13.6 eV and molecules from processes involving photodestruction (e.g., Federman *et al.* 1980).

The Doppler width parameters for each line are shown in the last column of Table 1. The values for $b_{\rm D}$ for the molecular gas toward all three directions agree with the values deduced from data of the unsaturated *U* lines of Na I (Chaffee 1974; de Boer and Pottasch 1974; Crutcher 1975). However, since sodium has a mass twice that of CH, a higher temperature is indicated by the atomic data. The apparent broadening of the atomic lines probably is related to the fact that the two velocity components seen in the present observations were not resolved in the atomic studies.

III. DISCUSSION

Elitzur and Watson (1978, 1980) have suggested that CH^+ is formed in hot postshock gas via the reaction

$$C^+ + H_2 \rightleftarrows CH^+ + H - 0.4\ \text{eV} .$$

At a temperature of a few thousand degrees, typical for hot postshock gas, this reaction proceeds to the right and produces sufficient CH^+ to reproduce observations. For other molecules incorporating heavy atoms, the chemical reaction network of the steady state models adequately describes their abundances as arising from the cold postshock region.

The chemical model of EW has several observational consequences. Foremost, a shift in the velocity of molecular lines relative to the CH^+ line is expected. A typical shock velocity (v_s) for neutral gas interacting with stellar winds or expanding H II regions is 10 km s^{-1}; the expected shift between the lines is $\frac{1}{4}\, v_s$, or 2–3 km s^{-1}. Since the production of CH^+ is dependent on temperature, the equivalent width of the CH^+ feature would be proportional to both v_s and $b_{\rm D}$.

Observations toward the Per OB2 association tend to confirm the predictions of the model. Atomic hydrogen emission at 21 cm toward the Per OB2 association (Sancisi 1974) shows the presence of an expanding shell along the line of sight. The atomic gas which has a velocity similar to the velocities reported here for CH^+ and CH is centered on a dust complex. The part of the shell represented by this gas is receding from the Sun. For flow away from the Sun, the model of EW predicts that the CH line should be redshifted relative to the CH^+ line. In § II, evidence was presented for such a shift toward *o*, ξ, and possibly ζ Per. Furthermore, the velocity for the CH line agrees with other molecular observations of the dust cloud toward these stars. These were observations of emission from OH and CH (Sancisi *et al.* 1974) and CO (Sargent 1979).

The results of Table 1 show a correlation between $W_\lambda(CH^+)$ and $\Delta v_{\rm LSR} = |v_{\rm LSR}(CH) - v_{\rm LSR}(CH^+)|$. The weakest CH^+ feature is found toward ζ Per, where the shift in velocity is $\sim$0.5 km s^{-1}; the strongest feature, that toward ξ Per, is shifted by 2–3 km s^{-1}. In fact, when the shifts are translated into shock velocities, the variation of W_λ (CH^+) with v_s is in good agreement with the analytical results of Elizur (1980). Therefore, the small velocity shift seen toward ζ Per is not a geometrical effect, but is due to the shock being weaker in this direction. Additional evidence for a weaker shock there comes from the fact that the postshock gas appears to be less dense toward ζ Per. (The strength of an isothermal shock is proportional to the enhancement in density, assuming the preshock densities are similar.) From studies with the *Copernicus* satellite (Savage *et al.* 1977), the column density of protons is the same for the three directions considered here. The dust cloud seen toward the Per OB2 association, where molecular emission is observed at radio wavelengths, extends over the lines of sight of o and ξ Per, but not of ζ Per. It is suggested that the dust complex was formed by the passage of a moderately strong shock ($v_s \approx 10$ km s^{-1}).

An inspection of Table 1 reveals that $W_\lambda(CH^+)$ also varies with b_D. If the Doppler width parameter for the CH^+ lines is solely due to thermal motion, temperatures ranging from 1000 to 10,000 K are obtained. Such values for the temperature are consistent with the model of EW for the chemistry. The smallest value is from the line toward ζ Per, while the largest is from that toward ξ Per. This result again suggests that the shock is strongest in the direction of ξ Per. The Doppler width parameters for species in the cold gas may be similar to those for CH^+ because turbulence has developed downstream from the shock.

Absorption lines of OH at 1222 Å and 3078 Å have been detected toward ζ and o Per (Smith and Snow 1979, and references therein). The equivalent widths measured toward o Per are approximately twice as large as those toward ζ Per. Therefore, W_λ(OH) varies in a manner similar to $W_\lambda(CH^+)$ for these two directions (see Table 1), indicating that a substantial fraction of OH formed in the hot postshock gas via

$$O + H_2 \rightarrow OH + H - 0.4 \text{ eV} .$$

When the shock velocities deduced from the present observations are used to compare the OH observations with the analytical results of Elitzur (1980), good agreement again is obtained.

The observed column densities of molecular hydrogen toward ζ, o, and ξ Per are 4.7×10^{20}, 4.1×10^{20}, and 3.4×10^{20} cm^{-2}, respectively (Savage *et al.* 1977). The equivalent widths listed in Table 1 for CH vary with $N(H_2)$ [for the optically thin lines of CH, $W_\lambda(CH) \propto N(CH)$], where $N(X)$ denotes column density of species X. Federman *et al.* (1980) suggested that such a correlation arises because the two molecules coexist in diffuse clouds (in the cold postshock gas of EW). The equivalent width of CH^+ does not depend on $N(H_2)$; cooling through collisions with H_2 removes the dependence of $N(CH^+)$ on $N(H_2)$ (see eq. [10] of EW).

In conclusion, interstellar CH lines were found to be redshifted with respect to CH^+ lines toward stars in the Per OB2 association. The present results confirm many predictions of the chemical model of EW for CH^+ production in shocked gas. The shocked gas is flowing away from the Sun; observations of a shell of atomic hydrogen expanding toward the association (Sancisi 1974) substantiate this finding. The velocity of the CH line agrees with that for other molecular lines observed in this direction. Additional evidence to support the model comes from the correlation of $W_\lambda(CH^+)$ with both the velocity of the shock and the Doppler width parameter.

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