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SPECTROPHOTOMETRIC RESULTS FROM THE *COPERNICUS* SATELLITE. IV. MOLECULAR HYDROGEN IN INTERSTELLAR SPACE

L. SPITZER, J. F. DRAKE, E. B. JENKINS, D. C. MORTON, J. B. ROGERSON, AND D. G. YORK
Princeton University Observatory
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ABSTRACT

Strong H_2 lines are measured in all 11 reddened stars $[E(B-V)>0.10]$ observed; the fraction f of hydrogen gas in molecular form exceeds 10^{-1}. In eight out of nine unreddened stars $[E(B-V)<0.05]$ there is no trace of H_2 absorption, with f less than 10^{-7}. In two stars of intermediate reddening f is between 10^{-5} and 10^{-6}. The relatively large column densities in higher rotational levels, up to $J=5$ or 6, correspond to excitation temperatures mostly between 150° and 200°; the ratios of ortho-hydrogen $(J=1)$ to para-hydrogen $(J=0)$ correspond to lower temperatures, averaging about 80°. Measures of two HD lines in nine stars indicate a ratio of HD to H_2 equal to about 10^{-6}; correction for the more rapid disruption of HD molecules, in the absence of effective optical shielding by many other such molecules, indicates that one HD molecule is formed and dissociated for about every 200 H_2 molecules.

Subject headings: abundances — interstellar matter — molecules, interstellar — spectra, ultraviolet — spectrophotometry

I. INTRODUCTION

The detection and measurement of interstellar H_2 absorption lines in the spectra of early-type stars has been a primary objective of the Princeton telescope-spectrometer, which was optimized for performance in the region between 1000 and 1200 Å. Measures of these lines in ξ Per and δ Sco have been reported recently by Carruthers (1970) and Smith (1973), respectively. This *Letter* reports such measures in 15 stars, with upper limits in eight stars.

II. ABUNDANCE OF H_2

Interstellar H_2 molecules are predominantly in the two lowest rotational levels, $J=0$ (para-hydrogen) and $J=1$ (ortho-hydrogen). The determination of N_J, the column density per cm^2 in the line of sight from the Earth to a star, is in principle straightforward for these two J-values, since the lines produced are generally on the square-root section of the curve of growth, with wings extending over an angstrom or more. Measures of $R(0)$ and $R(1)$ were made on U2 scans, described in Paper I. The values of N_J were adjusted to give the best fits to the observed profiles, with the usual damping formula used for $\phi(\Delta\nu)$, the profile of τ_ν (Spitzer 1968, eq. [2-43]). In the course of this fit the continuum was also adjusted. Since the wings of $R(0)$, $R(1)$, and $P(1)$ overlap to some extent, at least two of these lines were considered simultaneously for each vibrational band analyzed. The quality of fit obtained is indicated in figure 1, where the triangles and squares denote the computed profiles for the $R(0)$ and $R(1)$ lines, respectively, in the 1–0 band in ξ Per.

The electronic and vibrational oscillator strengths and damping constants used were taken from Allison and Dalgarno (1970), with the rotational oscillator strengths taken from Spitzer, Dressler, and Upson (1964). Since these lines are much wider than the instrumental width and are fully saturated at the center, the measured count at the center was taken equal to the background level of stray light plus phototube dark

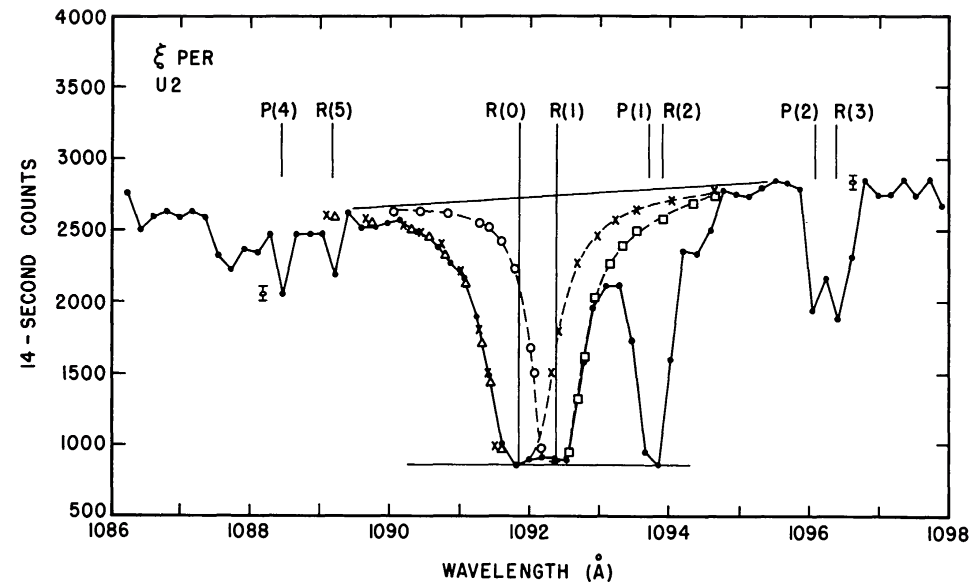

FIG. 1.—Profile fitting of H_2 lines in U2 scan of ξ Per. The theoretical profile of the $R(0)$ line in the 1–0 vibrational branch is indicated with crosses, obtained with the straight continuum and the flat background level shown. The open circles show a similar profile for $R(1)$. The triangles show the final profile of $R(0)$ when the circles for $R(1)$ are used as a continuum, and the assumed column density is decreased by about 15 percent, while the squares show the analogous profile for $R(1)$. The $P(4)$ and $R(5)$ lines at shorter wavelengths arise from the 2–0 vibrational band. Laboratory wavelengths are less than the indicated values by 0.33 Å.

count. For the narrower lines the U1 scans were also used in the background determination. The resultant values of N_0 and N_1 are listed in table 1. Except in the few cases indicated, several different vibrational bands were used, and the column densities averaged. The average deviations from the mean ranged up to a maximum of 16 percent for HD 21278, where strong narrow stellar lines made profile fitting difficult, but were generally much less, averaging about 7 percent. For those stars in which only the 1–0 band was used the maximum error is estimated not to exceed 25 percent.

For two of the three Orion stars the H_2 lines showed no wings, and the curve of growth was used to determine column densities. Details will be published elsewhere, but results are summarized here. In ζ Ori measures of five $R(0)$ lines were available, with oscillator strengths ranging over a factor of 13. The equivalent widths did not agree with the theoretical curve computed for a Maxwellian velocity distribution with any value of b (see Paper II); determinations of b from each pair of adjacent lines gave values increasing from 1.6 km s^{-1} for the two weakest lines up to 3.6 km s^{-1} for the strongest pair, with log N_0 decreasing from 15.2 to 14.5. As pointed out in Paper II, this is the result anticipated when a number of unequal clouds are present. The column density for this star in table 1 is somewhat uncertain, and may be regarded as a lower limit. For δ Ori the lines were weaker (W_λ between 2 and 7 mÅ), and the one value of b obtainable was 0.7 km s^{-1}. While $R(1)$ and $P(1)$ in these stars appear relatively strong, the data do not permit a determination of N_1.

The column densities for atomic H, given in column (7) of table 1, were taken in part from a detailed analysis (Jenkins 1971) of Lα profiles obtained with sounding rockets; in other cases N(H I) was found from approximate measured widths of the Lα line at half maximum depth on U2 scans. Values of f, the fraction of hydrogen nuclei in molecular form in the interstellar gas, are given in the last column. For stars of spectral type B3 or later, stellar absorption is likely to dominate the Lα

TABLE 1

H_2 COLUMN DENSITIES

Star	$E(B-V)$	Log N_0	Log N_1	Log $N_{J,m}$	J_m	Log N(H I)	f
ζ Per	0.33	20.29*	20.39*	14.98	4	20.78	0.59
ξ Per	0.32	20.28*	20.21*	13.89	6	20.92	0.46
ε Per	0.10	19.59	19.56	13.40	5	20.56	0.30
δ Per	0.03	18.91	19.18	15.06	4	(20.18)	(0.24)
HD 21278	0.10	19.45	19.38	14.26	5	(20.74)	(0.16)
α Cam	0.32	19.81*	19.94*	14.58	5	20.72	0.37
139 Tau	0.14	19.49	19.79	13.93	5	20.77	0.24
ζ Ori	0.09	15.2	...	...	3	20.26	1.8×10^{-5}
δ Ori	0.07	14.1	...	13.20	4	20.11	1.9×10^{-6}
λ Ori A	0.12	19.34	19.02	13.79	5	20.72	0.11
ζ Oph	0.32	20.46*	20.10*	13.59	6	20.61	0.67
γ Ara	0.09	19.08	19.24	...	...	20.58	0.13
67 Oph	0.12	20.35*	20.00*	...	...	(20.74)	(0.54)
59 Cyg	0.19	18.94	19.18	13.50	5	20.26	0.21
10 Lac	0.11	19.12	19.26	13.45	5	20.84†	0.082

* Only one line used for this determination.
†Lα scan lost in transmission; value taken from Savage and Jenkins (1972).

profile, and for these stars N_H, the column density of hydrogen nuclei, was set equal to $5\times10^{21}\ E(B-V)$, following Savage and Jenkins (1972); the corresponding values of $N(\text{H I}) = (1-f)N_H$ and of f are given in parentheses.

In stars which showed no trace of any of the H_2 lines, approximate upper limits on the equivalent widths were obtained from U1 scans, in the manner described in Paper V below (with $M = 4$); the stray light was assumed to equal 0.30 times the observed continuum, an approximate mean value for this wavelength region. The corresponding upper limits on N_0, the column density in the $J = 0$ level, are given in table 2, together with values of N(H I) and f_{max} determined as in table 1. The spectral types and colors for the unreddened stars α Eri, δ Per, υ Sco, and λ Sco were provided by Morgan (1972).[1]

Tables 1 and 2 indicate an enormous variation in $N(H_2)$ between different stars, correlated roughly with color excess. All stars with $E(B-V) > 0.10$ show strong H_2 absorption, with f exceeding 0.10; except for δ Per, all stars with $E(B-V) < 0.05$ show no H_2 features, with f less than 10^{-7}. This behavior provides qualitative confirmation of the theory by Hollenbach, Werner, and Salpeter (1971), who find that absorption of the Lyman bands by H_2 molecules and grains in the outer layers of a cloud shields the inner molecules from dissociation by ultraviolet light. As a result, f at the cloud center should be a strong function of τ_V, the optical depth to the cloud center in visible light [about half of $3E(B-V)$] through the cloud. They find that f increases from 10^{-7} for $\tau_V = 0$ up to 0.9 or more if τ_V exceeds unity. However, the observed concentration of f to very high and very low values seems more extreme, perhaps, than predicted by their theory.

III. ROTATIONAL EXCITATION OF H_2

Equivalent widths were measured for a substantial number of H_2 lines from rotationally excited molecules. The maximum value of J for which $R(J)$ or $P(J)$ showed a measurable equivalent width was denoted by J_m, and the column density for molecules in this rotational state, by $N_{J,m}$. The values of $N_{J,m}$ in table 1 have been computed on the assumption that the lines are formed on the linear portion of the curve of

[1] We are much indebted to Dr. Morgan for these important data.

TABLE 2

UPPER LIMITS ON H_2 COLUMN DENSITIES

Star	Spectral Type	$E(B-V)$	Log $(N_0)_{max}$	Log N(H I)	f_{max} ($\times 10^8$)
α Eri	B3 IV	0.03	12.51	(20.17)	(4.3)
γ Peg	B2 IV	0.01	12.81	20.20	8.0
σ Sgr	B2.5 V	0.03	12.63	20.58	2.3
τ Sco	B0 V	0.05	12.54	20.58	1.8
υ Sco	B2 IV	0.02	12.66	20.28	4.8
λ Sco	B1.5 IV	0.02	12.40	19.90	6.2
α Pav	B2.5 V	0.02	12.90	(20.00)	(16.0)
α Gru	B7 IV	0.02	12.95	(20.00)	(18.0)

growth, and are thus lower limits. However, these lines are so weak that if the Doppler velocity parameter b, defined in Paper II above, is taken to be as low as 3 km s^{-1}, $N_{J,m}$ is increased by at most 30 percent over the values given in table 1, except in the case of α Cam, where the increase of N_J is by a factor 10. Photometric uncertainties are more serious for these relatively weak lines, with equivalent widths mostly between 3 and 5 mÅ, and individual values of $N_{J,m}$ may well be in error by as much as 50 percent.

The excitation energy, E_J, of level J is given approximately by

$$E_J = 0.0073\ J(J+1)\ \text{eV}. \tag{1}$$

Radiative transitions between levels of even and odd J are strictly forbidden, and even collisional transitions occur very rarely, if at all, in the interstellar gas. If it is assumed that the molecules are formed initially with a Boltzmann distribution of E_J at some formation temperature T_f, and cascade down to the $J = 0$ or 1 levels, the observed ratio of N_1 to N_0 can be used to determine T_f, using the computations by Spitzer *et al.* (1964). The values of T_f found from table 1 range between 55° and 115°, averaging about 80°.

Transitions among levels of even J or of odd J can be produced by collisions, and will occur slowly by spontaneous emission. Thus the rotational temperature, T_r, for the higher values of J should depend on the local kinetic temperature and density of the gas. The values of T_r corresponding to the ratio $N_{J,m}/N_0$ (or $N_{J,m}/N_1$ if J_m is odd) in table 1 are mostly between 150° and 200°, significantly higher than the mean temperature of about 80° found in the 21-cm absorption studies (Hughes, Thompson, and Colvin 1971; Radhakrishnan *et al.* 1972).

To obtain more detailed information, the curve of growth may be used to give N_J for all the excited rotational levels observed. If a separate curve is plotted for each J, using $P(J)$ and $R(J)$ from bands with different oscillator strengths, the horizontal shifts required to fit a pair of curves together gives the difference in the log $N(J)$ values. A preliminary such curve for ξ Per agrees with the theoretical curve for a single cloud with a Maxwellian distribution of velocities and $b = 4.3$ km s^{-1}. The resultant values of N_J/g_J drop steeply with J up to $J = 3$, corresponding to a rotational temperature of about 100°; the statistical weight, g_J, equals $2J + 1$ and $3(2J + 1)$ for J even and odd, respectively. The drop in N_J/g_J from $J = 3$ to $J = 6$ is much slower, corresponding to a rotational temperature of some 300°, as though a small fraction of the cloud were at this higher temperature. The resultant infrared radiation comes mostly from the $J = 2$ level, with an emissivity of about 10^{-26} ergs cm^{-3} s^{-1} per H atom, about equal to the energy input generally assumed for H I regions.

A relatively large density may be required to account for the excitation of the higher rotational levels, whose radiative lifetimes (Spitzer 1949; Dalgarno and Wright 1972) decrease about as $1/J^5$, equaling 10^8 seconds for $J = 5$. If radiative de-excitation is assumed to be no more rapid than collisional de-excitation, the density required must be at least 10^3 cm^{-3}.

IV. ABUNDANCE OF HD

Equivalent widths of either or both of the HD lines at 1054.29 and 1066.27 Å, the $R(0)$ lines of the 4–0 and 3–0 bands, respectively, were measured in the more reddened stars, giving values ranging from 6 mÅ in ϵ Per up to 41 mÅ in α Cam. Column densities obtained for the HD molecules in the $J = 0$ level, using again the f-values tabulated by Allison and Dalgarno (1970), and assuming unsaturated lines, are shown in table 3. No $R(1)$ or $P(1)$ lines from HD were observed, consistent with the short lifetime (4.0×10^7 s) for the $J = 1$ level (Dalgarno and Wright 1972). To obtain the overall ratio of HD to H_2 molecules, these HD column densities have been divided by the sum of N_0 and N_1 in table 1 to give the third column in table 3. These are minimum estimates, since saturation could increase N(HD) above the value computed from the linear curve of growth; if b is as low as 3 km s^{-1}, the value of N(ND) in ζ Oph and ζ Per is increased by an order of magnitude, with even larger increases for α Cam and 10 Lac. Evidently the ratio of HD to H_2 molecules is about 10^{-6} or more.

The detection of the HD lines confirms the presence of deuterium in interstellar space found by radio astronomers, with DCN reported by Jefferts, Penzias, and Wilson (1973) and the 91.6-cm D line possibly detected by Cesarsky, Moffet, and Pasachoff (1973). The ratio of roughly 10^{-6} for the abundance of HD relative to H_2 shown in table 3 above is related only indirectly to the relative abundance of deuterons and protons in the interstellar gas, since the probabilities both of molecule formation and of molecule disruption may differ for the two species. The disruption rate by ultraviolet radiation should be much greater for the HD molecule because of the weakness of the HD lines; there is little shielding of the molecule by absorption in the Lyman lines. To correct for this effect we may multiply $N(H_2)$ by a shielding correction factor, equal to the reduction in the rate of ultraviolet disruption of the H_2 molecules because of the absorption in the Lyman lines. This factor has been evaluated for the $R(0)$ line of the 10–0 band, using equation (A6) from the Appendix by Hollenbach *et al.*, and taking the optical depth halfway through the cloud; the corrected ratios are listed in the fourth column of table 3. The $R(1)$ and $P(1)$ lines, whose inclusion would increase this correction factor by at most 21 percent, have been ignored; higher rotational levels have a much smaller effect. If it is assumed that the HD lines are saturated, then N(HD) must also be multiplied by a corresponding shielding correction factor; however, the resultant decrease is slightly more than offset by the increase

TABLE 3

HD COLUMN DENSITIES

Star	Log N(HD)	Log $\frac{N(HD)}{N(H_2)}$	Log Corr. Factor	Log $\left[\frac{N(HD)}{N(H_2)}\right]_{corr}$
ζ Per	14.30	−6.35	−3.96	−2.39
ξ Per	14.15	−6.40	−3.97	−2.43
ϵ Per	13.57	−6.31	−3.64	−2.67
HD 21278	14.06:	−5.66:	−3.58	−2.08:
α Cam	14.49	−5.68	−3.73	−1.95
139 Tau	13.84	−6.12	−3.58	−2.54
ζ Oph	14.23	−6.40	−4.06	−2.34
59 Cyg	13.86	−5.52	−3.32	−2.20
10 Lac	14.41	−5.09	−3.41	−1.68

of the computed N(HD) if the lines are assumed saturated, and we ignore this effect, which could increase slightly the computed abundance of deuterium.

The corrected values in the last column of table 3 give the relative numbers of HD and H_2 molecules disrupted by ultraviolet photons per unit time, and must equal, of course, the ratio of the corresponding formation rates. If these formation rates were proportional to the relative abundances of D and H atoms, the values in this last column would equal the ratio of N(D) to N(H) in the gas. The average ratio of about 5×10^{-3}, which is in qualitative agreement with the high DCN abundance found by Jefferts *et al.,* is more than an order of magnitude greater than the ratio 2×10^{-4} observed on the Earth. While computation of the shielding correction factor depends on the geometry, it appears unlikely that the computed values could be incorrect by an order of magnitude. However, it seems not unlikely that the rate of formation on grains may be different for HD and H_2 and other formation processes may be involved (e.g., exchange interactions between D atoms and H_2 molecules).[2] While this particular reaction is unimportant at the low kinetic temperatures of clouds, further analysis is evidently needed to obtain the ratio of deuterons to protons in the interstellar gas.

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[2] We are indebted to Dr. R. McCray and Dr. Winifred Morton for pointing out the possible importance of this reaction, and for discussing its rate coefficient.