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THE INTERSTELLAR MOLECULAR HYDROGEN OBSERVED IN THE ULTRAVIOLET SPECTRUM OF DELTA SCORPII

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by

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Received:_____

I

ABSTRACT

Molecular hydrogen bands of the Lyman and Werner systems have been observed in the ultraviolet, interstellar spectrum of δ Sco. The average molecular column density is 3.5 (+2.2, -0.9) x 10^{19} cm^{-2}, and the average temperature of the gas of which the molecules are part is 47°K. Minimum and maximum gas temperatures are 25 and 98°K respectively. The observed column density of hydrogen atoms is (1.5 ± 0.5) x 10^{21} cm^{-2}, and hence, the ratio of the number of hydrogen atoms in molecular form to the total number of hydrogen atoms in either atomic or molecular form is 0.044 (+0.070, -0.018).

II

In the recent past considerable work has been expended on the subject of interstellar molecular hydrogen. If found to be generally present in interstellar clouds the molecule could play an important role in star formation and perhaps comprise a significant portion of the "missing hydrodynamic mass". In addition, the molecular spectrum would reflect sensitively the temperature of the gas which included the molecules through the population of the lowest rotational levels of the ground state. Unfortunately, the only spectral regions where there is a strong possibility of finding molecular hydrogen signatures are well away from visible wavelengths in the infrared and vacuum ultraviolet. Only one positive detection of interstellar molecular hydrogen has been reported, namely that of Carruthers (1970), in which a rather large (0.38) abundance ratio of atoms in molecular form to all atoms was found. However, on June 8, 1972 using rocket techniques, an ultraviolet spectrogram of δ Sco was obtained by this laboratory which exhibited ten bands of the Lyman system ($B\ ^1\Sigma_u^+ \leftarrow X\ ^1\Sigma_g^+$) and one band of the Werner system ($C\ ^1\Pi_u^\pm \leftarrow X\ ^1\Sigma_g^+$) arising, presumably, in one or two clouds along the line of sight. The results of this observation are reported in this letter.

The spectrogram, recorded on Kodak 101-01 by a one meter Wadsworth-type spectrograph, extended from 980 to 1400Å with a dispersion of 4.5Å mm^{-1} and a resolution of about 0.2Å. The spectrogram was somewhat under-exposed thereby yielding a poor characteristic signal-to-noise ratio. However, the main stellar features as well as the molecular bands can be easily identified. A microdensitometer trace of the spectrogram was made and a wavelength scale established by fitting the appropriately identified features on the trace to the stellar lines of H I (1025.72Å), He II (1084.98Å) and C III (1175.7Å). Consistency checks made with other lines indicate that the scale is accurate to $\pm$ 0.1Å.

A smaller portion of the microdensitometer trace covering the interval from 984 to 1114Å is shown in Figure 1. Relative flux falues are plotted on the ordinate and wavelengths are plotted on the abscissa. The molecular features are indicated by vertical lines which are labeled according to the branch and the rotational quantum number of the ground state. Each band is identified by the vibrational quantum number, v', of the upper state. The essential spectral information is tabulated in Table 1 where column one contains the vibrational quantum numbers, v', column two the branch identifications and rotational quantum numbers, and column three the transition wavelengths. Table 1 also contains in column four the equivalent widths of the features in every band except those associated with v' = 1, 6 and 9. In these cases determination of equivalent widths was omitted because of the apparently dominant contribution of Lβ to the feature at 1025Å(v' = 6) or because the background noise was considered excessive (v' = 1 and 9). The quoted uncertainties are a best estimate of the error incurred in locating the background continuum. In the case of the Lyman bands the R(0) and the R(1) lines are blended whereas the P(1) line is sufficiently isolated from the first two lines to be considered single. As will be pointed out later no lines arising from the ground state, J = 2 level were definitely observed, and thus each band consists of only three lines. The same is true for the v' = 0 Werner band except in this case the R(0) line coincides to within 0.02Å with the Q(1) line whereas the R(1) line is isolated.

Other lines which may be present at wavelengths close to the molecular lines are indicated. All of these competing lines are likely to be present, but the extent to which they affect the contour of the molecular lines is difficult to estimate. The validity of the identification must be based on the excellent correlation between the spectral features and the known wavelengths of the molecular lines.

With these data an attempt was made to derive the column density of hydrogen molecules utilizing the curve of growth method. It was assumed that all of the molecules were located in one cloud. The results of Marschall and Hobbs (1972), who obtained a 0.01Å resolution, δ Sco spectrum of the interstellar Ca II K-line, indicate that there are in fact, two components, but that one is definitely predominent. Oscillator strengths and Einstein spontaneous emission probabilities were taken from the work of Cartwright and Drapatz (1970). The turbulence parameter, $b = (2kT/Am_o)^{1/2}$, where Am_o is the mass of the molecule and k is the Boltzmann constant, was assumed to be 1.5 km s^{-1}. The equivalent width of the lines fell well up on the square root portion of the curve of growth where radiation damping is the only significant cause of line broadening. Thus, assumptions as to the turbulence parameter and the distribution of molecules between the two observed interstellar clouds are unimportant.

The derived hydrogen molecule column density depends on the assumed temperature of the cloud, that is on the distribution of ground state molecules in the J = 0 and J = 1 rotational levels. Since for each value of v' there two features, one, a blend of lines arising from both the J = 0 and J = 1 ground state levels, and another, a single line arising from the J = 1 level only, one can in principle find a temperature consistent with the observations. The procedure, then was to first assume a cloud temperature and calculate the relative populations of the J = 0 and J = 1 levels under the assumption the J = 2 level is not significantly populated. A curve of growth was then computed from which the column density of hydrogen molecules in both J = 0 and J = 1 levels could be determined. Similarly, another curve of growth for single lines was used to determine the column density of hydrogen molecules in the J = 2 level only, and the column densities so determined should be consistent with the temperature assumed at the start. If not, a better guess of the temperature was made, and the procedure was repeated.

The bands where v' = 5 and 6 were not considered useful for determining column densities because other lines (identified in Figure 1) seemed to make a large, indeterminate contribution to the absorption features.

The uncertainties may be used to yield a good minimum temperature value. They may not be used to indicate a maximum temperature since their magnitude permits unreasonably high temperatures. Due to the noisey character of the data the fact that a single line (P(1) in the Lyman bands and R(1) in the Werner band) is seen at all implies a minimum temperature of 20°K. The results of these computations are presented in Table 2. Again, the v' quantum number is listed in column one, while the hydrogen molecule column density, N, the cloud temperature, T, and the minimum cloud temperature, T_{min}, are listed in columns two, three, and four respectively. Eliminating the largest and smallest value of N an average of the remaining five values yields a column density of 3.5 (+2.2, -0.9) 10^{19} cm^{-2}. The corresponding average of T and T_{min} is 47°K and 25°K respectively.

A maximum temperature can be estimated by looking for lines which originate in the J = 2 level of the ground state. Such a search gave negative results in that no correlation was found between observed features and calculated wavelengths. Instead, an rms equivalent width of the background was estimated and multiplied by a signal-to-noise ratio of 2 yielding a minimum detectable equivalent width of 0.14Å. This value is reasonable if a correlation between line positions and absorption features exists. The corresponding column density of molecules in the J = 2 level is 3.9 x 10^{17} cm^{-2}. Considering this value in conjunction with the average value of N determined above (3.5 x 10^{19} cm^{-2}) it appears that the temperature beyond which lines originating in the J = 2 level could have been observed is 98°K.

The column density of atomic hydrogen as measured in this observation by the interstellar Lα line is (1.5 ± 0.5) 10^{21} cm^{-2}. This value is in good agreement with that found by Savage and

Jenkins (1972), that is 1.25×10^{21} cm^{-2}. The proportion of molecular hydrogen to the total amount of hydrogen in atomic or molecular form is 0.022. Or, about 4.4 (+7.0, -1.8)% of the total number of hydrogen atoms in the line of sight is in molecular form. This is a small figure compared to the 38% found by Carruthers (1970) in his ξ Per observation.

It is somewhat difficult to compare these results with the theoretical estimates of Hollenbach, Werner and Salpeter (1971) because of both the idealized nature of their cloud models and the observational unknowns. For example, if it is assumed that the line of sight passes through the center of a spherical cloud with a total mass of $500M_{\odot}$ we should expect on the basis of a total visual extinction of $0^{m}.51$ appropriate to δ Sco that about 23% of all hydrogen atoms should be in molecular form. If the cloud mass were $2000M_{\odot}$, the other conditions remaining the same, 8.6% of all hydrogen atoms should be in molecular form which is considerably closer to the value reported here. However, the line of sight very likely does not pass through the center of the cloud, but instead through regions which are less shielded from the interstellar radiation field. Also δ Sco is in a close grouping of hot B-type stars, the II Sco association, which may produce an ultraviolet radiation field significantly in excess of the values deduced by Habing (1968) which Hollenbach et al., used in their calculations. Both of these possibilities would reduce the proportion of molecular to atomic hydrogen.

Similarly, the results of Carruthers show that the ratio of hydrogen atoms present in molecular form to the total number of hydrogen atoms is less by a factor of two than that estimated by Hollenbach et al., for the case of a $500M_{\odot}$ cloud. The reasons may be the same. However, since ξ Per is a "run-away" star and is presently about 80pc away from the II Per association from which it came (Blaauw, 1961) the ultraviolet radiation field near the cloud may be of less influence that in

the case of δ Sco. Furthermore, in terms of the II Per association age ξ Per may have just arrived in the neighborhood of the cloud so that its radiation field would have had little time to affect the equilibrium abundance of molecular hydrogen in the cloud.

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TABLE 1

MOLECULAR HYDROGEN ABSORPTION LINES OBSERVED IN THE INTERSTELLAR SPECTRUM OF δ SCO

v' (v"=0)		λ (Å)	Equivalent Width (Å)	v' v"=0		λ (Å)	Equivalent Width (Å)
0	R(0)	1108.13	0.59(+0.23, -0.27)	5	R(0)	1036.55	2.16(+0.50, -0.82)
	R(1)	1108.63			R(1)	1037.15	
	P(1)	1110.07	0.40(+0.23, -0.25)		P(1)	1038.16	0.57(+0.19, -0.31)
1	R(0)	1092.20	---	6	R(0)	1024.37	---
	R(1)	1092.71			R(1)	1024.99	
	P(1)	1094.06	---		P(1)	1025.94	---
2	R(0)	1077.14	1.02 (+0.36, -0.23)	7	R(0)	1012.81	1.02(+0.49, -0.40)
	R(1)	1077.70			R(1)	1013.44	
	P(1)	1078.93	0.40(+0.26, - 0.18)		P(1)	1014.33	0.39(+0.17, -0.10)
3	R(0)	1062.88	1.18(+0.22, -0.37)	8	R(0)	1001.83	1.02(+0.14, -0.17)
	R(1)	1063.46			R(1)	1002.46	
	P(1)	1064.61	0.22(+0.17, -0.15)		P(1)	1003.30	0.37(+0.15, -0.24)
4	R(0)	1049.37	1.02(+0.22, -0.27)	9	R(0)	991.38	---
	R(1)	1049.96			R(1)	992.02	
	P(1)	1051.04	0.47(+0.31, -0.29)		P(1)	992.81	---
				0	R(0)	1008.55	0.52(+0.36, -0.23)
					R(1)	1008.54	
					P(1)	1009.81	0.39(+0.32, 0.28)

NOTE: The first 10 entries are bands of the Lyman system; the last entry (to the right) is the only observed band of the Werner system.

TABLE 2

MOLECULAR HYDROGEN COLUMN DENSITIES AND INTERSTELLAR CLOUD TEMPERATURES

v' v" = 0	Column Density ($\times 10^{19}$ cm^{-2})	T ^{o}K	T_{min} ^{o}K
0	6.4(+15.4, -4.8)	900	31
2	4.4(+6.6, -2.0)	51	28
3	5.5(+4.1, -3.4)	32	20
4	2.0(+1.4, -1.0)	66	24
7	2.6(+5.7, -1.8)	45	28
8	2.8(+1.2, -0.8)	41	26
0	0.55(+1.07, -0.39)	86	26

NOTE: The first 6 entries are associated with bands of the Lyman system, the last entry with the only observed band of the Werner System.

Figure Caption

(For letter entitled "Interstellar Molecular Hydrogen Observed In the Ultraviolet Spectrum of Delta Scorpii" by A. M. Smith)

Fig. 1. - Spectrum of δ Sco. Vertical lines indicate laboratory measured wavelengths of H_2 molecular transitions as well as transitions in various atoms and ions. Numbers in parentheses indicate the atomic or ionic excitation. For the meaning of other symbols see text.

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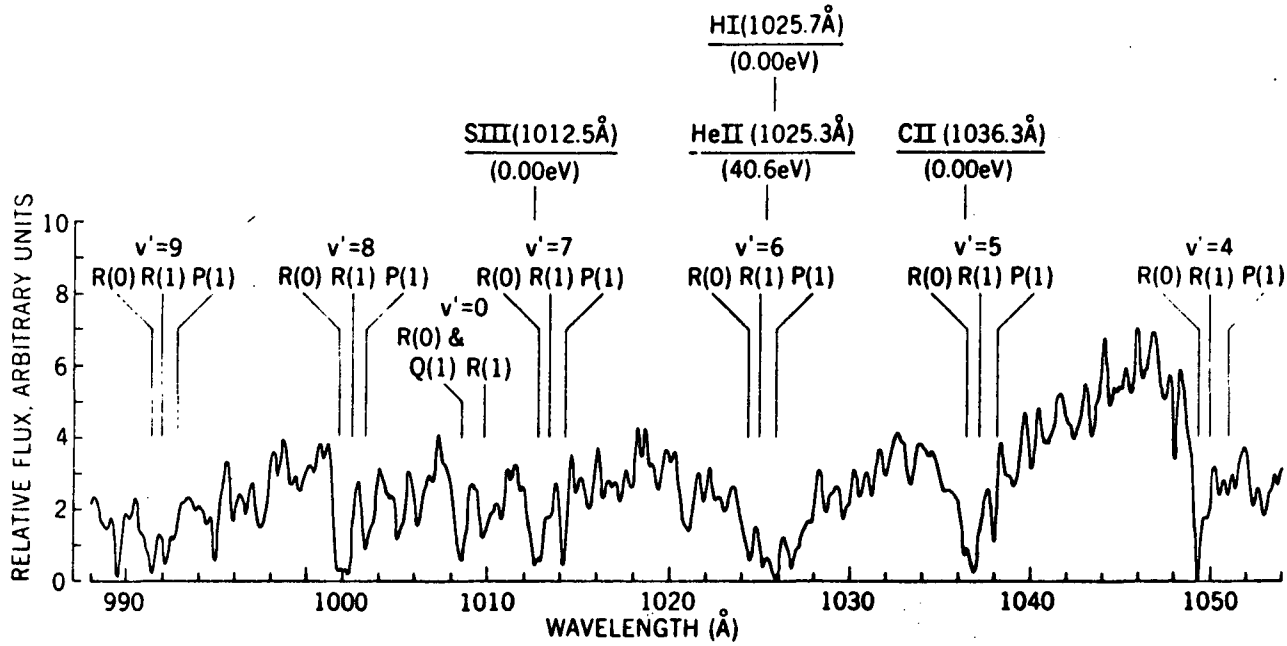
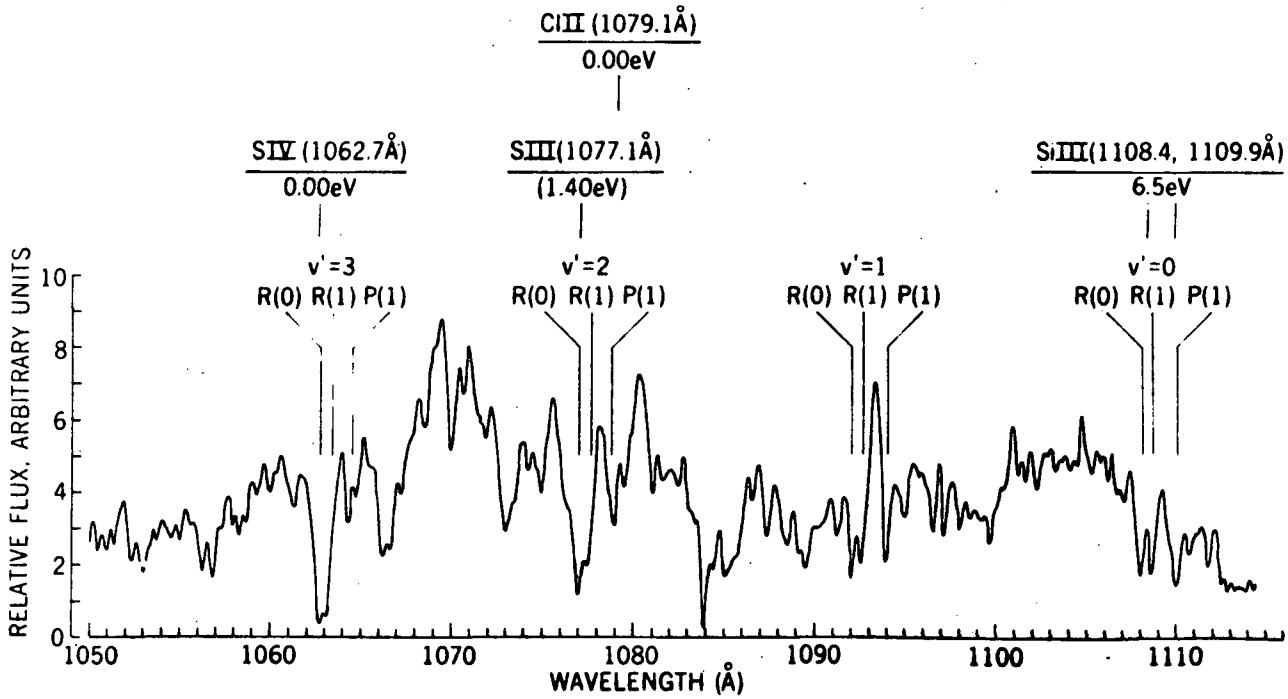

HI(1025.7Å)
(0.00eV)
SIII(1012.5Å)
(0.00eV)
HeII (1025.3Å)
(40.6eV)
CII (1036.3Å)
(0.00eV)
v'=9
R(0) R(1) P(1)
v'=8
R(0) R(1) P(1)
v'=7
R(0) R(1) P(1)
v'=0
R(0) &
Q(1) R(1)
v'=6
R(0) R(1) P(1)
v'=5
R(0) R(1) P(1)
v'=4
R(0) R(1) P(1)
RELATIVE FLUX, ARBITRARY UNITS
WAVELENGTH (Å)


CIII (1079.1Å)
0.00eV
SIV (1062.7Å)
0.00eV
SIII(1077.1Å)
(1.40eV)
SiIII(1108.4, 1109.9Å)
6.5eV
v'=3
R(0) R(1) P(1)
v'=2
R(0) R(1) P(1)
v'=1
R(0) R(1) P(1)
v'=0
R(0) R(1) P(1)
RELATIVE FLUX, ARBITRARY UNITS
WAVELENGTH (Å)

12

Fig. 1