ORFEUS-I Observations of Molecular Hydrogen in the Galactic Disk

W. Van Dyke Dixon, Mark Hurwitz, and Stuart Bowyer

Space Sciences Laboratory and Center for EUV Astrophysics,
University of California, Berkeley, California 94720-5030, U.S.A.

Abstract. We present measurements of interstellar H_2 absorption lines in the continuum spectra of seven early-type stars in the Galactic disk at distances between 1 and 4 kpc. The spectra, obtained with the Berkeley EUV/FUV spectrometer on the ORFEUS telescope in 1993 September, have a resolution of 3000 and statistical signal-to-noise ratios between 20 and 80. We determine column densities for each observed rotational level and derive mean excitation temperatures and proton density limits for the H_2 clouds along each line of sight. The gross properties of the H_2-bearing clouds (e.g., column density, spatial density, cloud size) are consistent with those derived from *Copernicus* observations, though our lines of sight are much longer, with lower average reddenings and neutral gas densities. We find that the molecular fraction of the neutral hydrogen remains ~ 0.1 out to distances of 4 kpc in the Galactic disk.

1 Introduction

The hydrogen molecule (H_2) plays a central role in a variety of processes that significantly influence the chemical and physical state of the interstellar medium (ISM). From observations by *Copernicus* and other spacecraft-borne observatories, a picture has emerged in which the bulk of interstellar H_2 lies in clouds with densities between ~ 10 and a few 1000 cm^{-3}, diameters less than a few tens of parsecs, and column densities $\gtrsim 10^{20}$ cm^{-2}, which allow the rapid formation of H_2 on dust grains and provide self-shielding against dissociating photons (Wilson and Walmsley 1989). In order to determine whether this model, developed from observations of relatively nearby stars ($d \lesssim 1$ kpc), holds in other parts of the Galactic disk, we observed seven disk stars ($|z| < 300$ pc) at distances out to 3.9 kpc using the Berkeley spectrometer on the ORFEUS[1] telescope in 1993 September.

[1] Based on the development and utilization of ORFEUS (Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometers), a collaboration of the Astronomical Institute of the University of Tübingen, the Space Astrophysics Group of the University of California at Berkeley, and the Landessternwarte Heidelberg.

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Table 1. Target Summary

HD	l	b	Sp. Type	$E(B-V)$	d (pc)	$v \sin i$ (km s^{-1})	T (s)	S/N[a]	Ref.
41161	165.0	+12.9	O8 V	0.20	1253	300	814	45.2	1,2
54911	229.0	−3.1	B1 III	0.14	1893	100:	2462	78.0	1,3
93129a	287.4	−0.6	O3 If*	0.54	3470	120	3045	36.2	4,5
94493	289.0	−1.2	B0.5 Iab/Ib	0.20	3327	145	1528	34.9	1,3
99857	294.8	−4.9	B1 Ib	0.33	3058	180	1383	22.3	1,3
99890	291.8	+4.4	B0.5 V:	0.24	3070	180	2532	39.7	1,3
104705	297.5	−0.3	B0 III/IV	0.26	3898	215	1788	36.3	1,3

[a]Statistical signal-to-noise ratio in a 0.2 Å bin averaged over the 1045–1060 Å band. References: (1) Fruscione et al. 1994; (2) Jenkins 1978; (3) Savage and Massa 1987; (4) Walborn 1973; (5) Gies 1987.

2 Observations and Data Reduction

With an effective area of about 4 cm^2 and a resolution $\lambda/\Delta\lambda = 3000$ between 390 and 1170 Å, the Berkeley spectrometer is ideally suited for absorption-line studies of bright, far-UV sources. Far-UV spectra of seven disk stars (Table 1) were obtained on the ORFEUS-I mission. We model their interstellar absorption features using an ISM line-fitting package written by M. Hurwitz and V. Saba. Given the column density, Doppler broadening parameter, and relative velocity of a given species, the program computes a Voigt profile for each line, convolves the lines with a Gaussian to the instrument resolution, and uses the result as a transmission function by which to scale the model continuum. Where available, we use the Doppler parameters, relative velocities, and relative column densities of the principal Na I absorption components (Sembach et al. 1993; Walborn 1982). Otherwise, we assume a single absorption component with a Doppler parameter $b = 5$ km s^{-1}. We adopt 0.31 Å as the FWHM of the instrument point-spread function. Reference spectra selected from the *Copernicus* Spectral Atlas (Snow and Jenkins 1977) provide an estimate of the stellar continuum. Column densities derived for the $J'' = 0$ to 5 rotational levels of H_2 are presented in Table 2. We estimate uncertainties of 0.2 dex for $J'' = 0$ to 3 and 0.5 dex for $J'' \geq 4$.

3 Analysis

The mean excitation temperature of the clouds along each line of sight can be derived from the column densities $N(0)$ and $N(1)$ using the relation

$$\frac{N(1)}{N(0)} = \frac{g_1}{g_0} \exp\left(\frac{-E_{01}}{kT_{01}}\right) = 9 \exp\left(\frac{-170\ \mathrm{K}}{T_{01}}\right) \qquad (1)$$

Table 2. Column Densities

HD	N(H I)[a]	$N(H_2)$	$N(0)$	$N(1)$	$N(2)$	$N(3)$	$N(4)$	$N(5)$	T_{01}[b] (K)	n[c] (cm^{-3})
41161	21.01	20.0	19.7	19.7	17.6	17.6	15.0	14.2	77	16
54911	21.13	19.6	19.3	19.3	17.4	16.9	14.5	13.9	77	8
93129a	21.40	20.1	19.7	19.9	17.2	16.9	15.9	16.1	98	6
94493	21.11	20.1	19.7	19.8	17.7	16.2	15.0	15.1	86	13
99857	21.31	20.2	19.8	20.0	18.5	18.2	16.2	15.4	97	9
99890	20.93	19.6	19.2	19.3	17.7	17.6	16.0	14.7	86	11
104705	21.11	20.0	19.7	19.7	17.5	16.6	14.6	...	77	13

Note.—All column densities are given as logarithms. Units are cm^{-2}.
[a] N(H I) from the compilation of Fruscione et al. 1994, except for HD 93129a, which is from Taresch et al. 1997.
[b] Mean H_2 excitation temperature derived from $N(1)/N(0)$; see Sec. 3.
[c] Lower limit to cloud proton (H I + $2H_2$) density; see Sec. 3.

(Shull and Beckwith 1982). We can estimate the proton (H I + $2H_2$) volume density n by assuming

$$\left(\frac{n}{50 \text{ cm}^{-3}}\right)^2 \simeq \left[\frac{N(\text{H}_2)}{10^{19} \text{ cm}^{-2}}\right] \left(\frac{T}{80 \text{ K}}\right)^{-1} \left[\frac{N(\text{H I})}{10^{20} \text{ cm}^{-2}}\right]^{-2} \tag{2}$$

(Reach et al. 1994). The resulting densities are lower limits, because an unknown fraction of N(H I) lies outside of the H_2-bearing clouds. The temperatures and density limits presented in Table 2 are consistent with the values derived from *Copernicus* observations (Savage et al. 1977; Jura 1975).

4 Conclusions

Our data reflect the trends among $N(H_2)$, $E(B-V)$, the molecular fraction $f = 2N(\text{H}_2)/[N(\text{H I})+2N(\text{H}_2)]$, and the total hydrogen column $N(\text{H I}+\text{H}_2) = N(\text{H I})+2N(\text{H}_2)$ established by Savage et al. (1977; see their Figs. 4–6), indicating a common mechanism for H_2 production. From our column densities $N(\text{H}) = 1-3\times10^{21}$ cm^{-2} and proton densities $n \gtrsim 10$ cm^{-3}, we estimate path lengths (cloud diameters) on the order of tens of parsecs, consistent with standard models. The molecular fraction f remains ~ 0.1 out to distances of 4 kpc in the Galactic disk (Fig. 1). These results are not entirely expected, as our observations probe sight lines of exceptionally low average density: $N(\text{H I} + \text{H}_2)\ /\ d$ is only about 0.2 cm^{-3}, and the mean reddening $\Sigma E(B-V)/\Sigma r = 0.11$ mag kpc^{-1}. Our results are consistent with a model in which a significant fraction of the neutral ISM is confined to the small, low-density molecular clouds, even along low-density lines of sight.

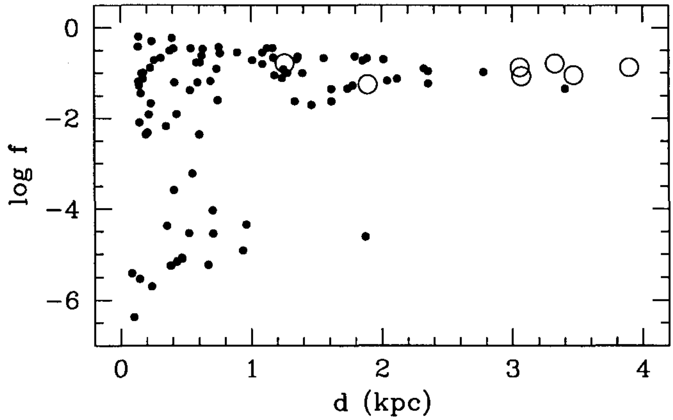

Fig. 1. The molecular fraction f plotted against stellar distance. Solid circles represent *Copernicus* observations (Savage et al. 1977), while the open circles are from this work. We find that $f \sim 0.1$ out to large distances in the disk.

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