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ROCKET OBSERVATION OF INTERSTELLAR MOLECULAR HYDROGEN

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ABSTRACT

The Lyman resonance-absorption bands of interstellar molecular hydrogen have been observed in the far-ultraviolet spectrum of the star ξ Persei. The column density of H_2 is estimated to be about 1.3×10^{20} cm^{-2}. The column density of interstellar atomic hydrogen, determined from the Lα absorption line in the same spectrum, is about 4.2×10^{20} cm^{-2}. Hence, in this line of sight, where visual total extinction by dust is about 1 mag, nearly half of the total hydrogen may be in molecular form. This is in agreement with theoretical predictions.

Theoretical studies of photodissociation processes (Solomon; see Field, Somerville ,and Dressler, 1966; Stecher and Williams 1967) and previous rocket observations (Carruthers 1967; Smith 1969, 1970) have shown that molecular hydrogen is not present in appreciable amounts in the general interstellar medium. However, much evidence has accumulated which indicates that molecular hydrogen is the major constituent of the gas in dark dust clouds, where the catalyzed recombination of hydrogen atoms on dust grains predominates over photodissociation of molecules by stellar ultraviolet radiation. (A review of this evidence is presented by Carruthers 1970.) Theoretical studies by Solomon and Wickramasinghe (1969) and by Hollenbach, Werner, and Salpeter (1970) have predicted the ratio of molecular to atomic hydrogen to be expected in various concentrations of dust and gas. These studies have indicated that, in dust clouds where the total visual extinction of starlight exceeds about 1.5 mag, the hydrogen should be mostly molecular.

An all-reflecting electronographic spectrograph and ultraviolet photometers, which were flown previously to observe the Orion region (Carruthers 1969*a*, *b*, *c*), were flown again on an Aerobee-150 rocket from White Sands Missile Range on 1970 March 13. The rocket attitude-control system was programmed to point the instruments toward the stars ϵ Per, ξ Per, ζ Per, and S Mon. However, because of a lower-than-expected peak altitude and other problems, useful spectra were obtained only for the first two targets. The spectra covered the wavelength range 1000–1500 Å for ϵ Per (B0.5 V, $m_V = 2.89$) and 1000–1400 Å for ξ Per (O7, $m_V = 4.06$). The spectral resolution obtained was about 2 Å.

Figure 1 (Plate L1) shows a flight spectrum of ξ Per, made with a 12-second exposure time. Comparison with laboratory spectra made with the same instrument, using a hydrogen-filled absorption cell and argon-continuum light source, reveals the presence of lines in the stellar spectrum matching the 0–0, 1–0, and 2–0 vibrational transitions of the Lyman resonance series ($B\,^1\Sigma_u \leftarrow X\,^1\Sigma_g$). Other strong lines in the stellar spectrum, at wavelengths below the useful range of the laboratory spectrum, match the expected wavelengths of the 3–0 through 7–0 Lyman-band absorptions. The only other lines apparent in this wavelength range of the spectrum are the Lβ line at 1026 Å, due to interstellar atomic hydrogen, and the O VI resonance doublet (rest wavelengths 1032 and 1038 Å). At longer wavelengths appear the Lα line of interstellar atomic hydrogen at 1216 Å and the N V resonance doublet (rest wavelengths 1239 and 1243 Å), which exhibits a strong P Cygni profile.

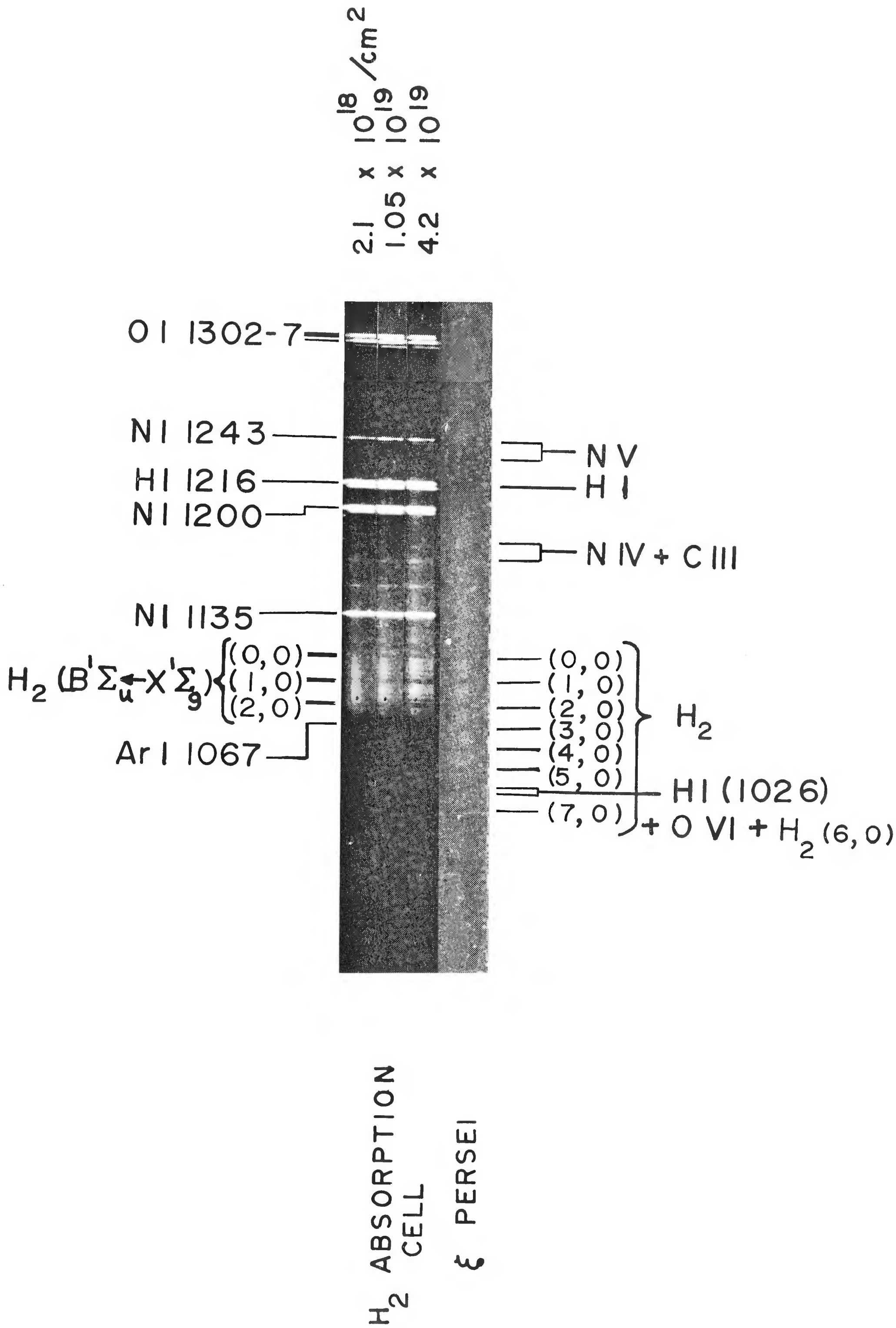

FIG. 1.—Comparison of laboratory spectra, made with a hydrogen-filled absorption cell and argon-continuum light source, with flight spectrum of ξ Per.

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Figure 2 shows densitometer tracings of both the ξ Per spectrum in the wavelength range of the H_2 absorptions and the absorption cell spectrum made with a column density $N_{H_2} = 4.2 \times 10^{19}$ cm^{-2}. Table 1 lists the measured equivalent widths of the 0–0 through 4–0 bands in the stellar spectrum, and of the 0–0 through 2–0 bands in the laboratory spectrum. Also are listed the theoretical equivalent widths calculated by Spitzer, Dressler, and Upson (1964) for a gas temperature of 100° K. Although there is some redistribution in the rotational-level populations at higher temperatures, this probably has little effect on the total equivalent widths of the complete bands. It is seen that the integrated equivalent widths measured in the laboratory are somewhat less than expected theoretically for the same column density, but the deviation is within the range consistent with the errors of measurement in the laboratory spectra and the uncertainties in the theoretical estimates. Also, the summation of theoretical equivalent widths neglects the overlapping of line profiles at high column densities.

The column density of H_2 in the direction of ξ Per was estimated by assuming that the line profile is determined by natural broadening ($W \propto \sqrt{N}$) and comparing the

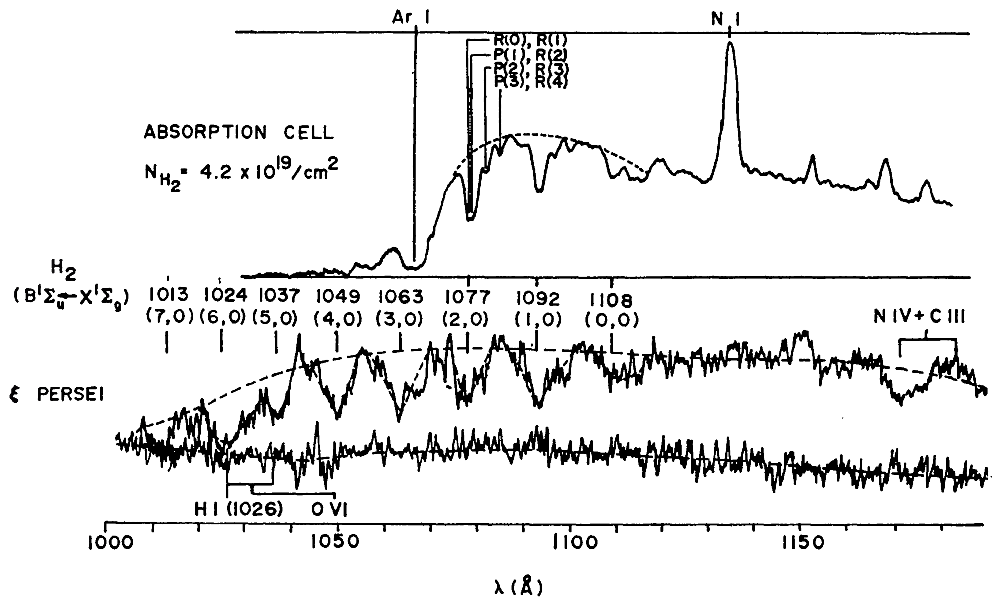

FIG. 2.—Microdensitometer tracings of laboratory absorption-cell spectrum and ξ Per spectrum

TABLE 1

EQUIVALENT WIDTHS OF H_2 LYMAN BANDS

			THEORETICAL* (T=100° K, 3.1×10^{19} cm^{-2})			
v'–v''	ξ PERSEI	LABORATORY (4.2×10^{19} cm^{-2})	R(0)	R(1)	P(1)	Total
0–0.......	1.9±1.0	1.0±0.3	0.38	0.40	0.27	1.05
1–0.......	3.8±1.5	2.1±0.5	0.77	0.81	0.54	2.12
2–0.......	4.3±1.5	2.1±0.5	1.15	1.21	0.81	3.17
3–0.......	5.3±1.5	...	1.43	1.51	1.01	3.95
4–0.......	4.2±1.5	...	1.57	1.66	1.11	4.34

* Spitzer *et al.* (1964).

equivalent widths measured in the stellar spectrum and in the laboratory spectrum. This comparison gives a column density of

$$N_{H_2} = 1.3(+0.9, -0.65) \times 10^{20} \text{ cm}^{-2}$$

in the direction of ξ Per. Because of the low intensity of the continuum in the stellar spectrum, grain-noise fluctuations introduce uncertainties of the order of ± 30 percent into the equivalent-width measurements (see Table 1), which gives rise to the uncertainty in column density of $(+70, -50)$ percent.

The quality of the stellar spectrum is not adequate to provide a definite indication of the temperature of the interstellar H_2, or of the ratio of ortho-hydrogen to para-hydrogen. In the laboratory spectrum, the two strongest features in each band (which are themselves just barely resolved, see Figs. 1 and 2) are due respectively to the $R(0) + R(1)$ and $P(1) + R(2)$ lines. The interstellar lines are of such strength that, for each, the core is as broad as the combined width of the two features in the laboratory spectrum. Therefore, the $R(0)$ line cannot be separated from the $R(1)$, $P(1)$, and $R(2)$ lines. However, since no features are seen in the stellar spectrum corresponding to the $P(2), R(3), \ldots,$ features seen in the laboratory spectrum, it can at least be stated that the observed features are not inconsistent with a low temperature of the absorbing interstellar hydrogen.

The Lα absorption line can be used to determine the column density of interstellar atomic hydrogen by the relationship (Morton 1967)

$$N_H = 1.871 \times 10^{18}(W_{1216})^2 .$$

The measured equivalent width (see Fig. 3) is $15(\pm 3)$ Å, a value giving a column density $N_H = 4.2(+1.9, -1.5) \times 10^{20}$ cm^{-2}. Hence, nearly half of the total hydrogen in the line of sight to ξ Per may be in molecular form.

Ground-based studies of ξ Per indicate that it is reddened by interstellar dust; the observed $(B - V) = +0.01$ (Iriarte *et al.* 1965) whereas the intrinsic $(B - V)$ for an O7 star is -0.32 (Johnson 1963). Hence, the color excess $E(B - V) = 0.33$. Assuming the ratio of total to selective extinction to be the generally observed value of 3.0 (Sharpless 1963), we find a visual total extinction of about 1 mag. Hollenbach *et al.* (1970) calculate that, for typical interstellar clouds, the molecular-hydrogen content does, in fact, become comparable with the atomic-hydrogen content at a visual extinction of 1 mag. Hence, the present observation is in agreement with theoretical predictions.

The interstellar Lα line was also measured in ϵ Per (Fig. 3), and an equivalent width of $7.7(\pm 1.0)$ Å was found, giving a column density $N_H = 1.1(\pm 0.3) \times 10^{20}$ cm^{-2}. No definitely identifiable absorptions due to H_2 were found. Although this spectrum was much stronger than that of ξ Per, the many more stellar lines present in this wavelength range tended to obscure the interstellar H_2 lines. However, it appears that the column density of H_2 in the line of sight to ϵ Per is less than in the direction of ξ Per by considerably more than the factor of 4 ratio of atomic-hydrogen column densities. For ϵ Per, $(B - V) = -0.18$ (Iriarte *et al.* 1965), whereas the intrinsic color of a B0.5 V star is $(B - V) = -0.28$ (Johnson 1963), giving $E(B - V) = 0.10$ and $A_V = 0.30$. According to the curves of Hollenbach *et al.* (1970), this is well below the amount of extinction at which appreciable conversion of atomic to molecular hydrogen is expected.

The star ξ Per is a member of the ζ Persei association, which is about 300 pc distant from Earth (Underhill 1966). If ϵ Per is assumed to have the intrinsic absolute visual magnitude of a typical B0.5 V star, i.e., about -4.0 (Underhill 1966), its distance is estimated to be between 100 and 150 pc. This indicates that the volume density of atomic hydrogen between ϵ Per and ξ Per is somewhat greater than between ϵ Per and Earth. Even this latter concentration, however, is greater than in the direction of Orion, where the same or only slightly greater column densities are observed over a distance of more than 400 pc (Morton 1967; Carruthers 1969*b*). The corresponding volume densities are approximately 0.1 cm^{-3} in the direction of Orion, 0.3 cm^{-3} in the direction of ϵ Per, and 0.6 cm^{-3} between ϵ Per and ξ Per.

Chemical-abundance arguments lead to the relationship (Heiles 1969)

$$N_{\text{H}} > 8 \times 10^{20} A_V$$

between the total column density of hydrogen atoms (single or in molecules) and the

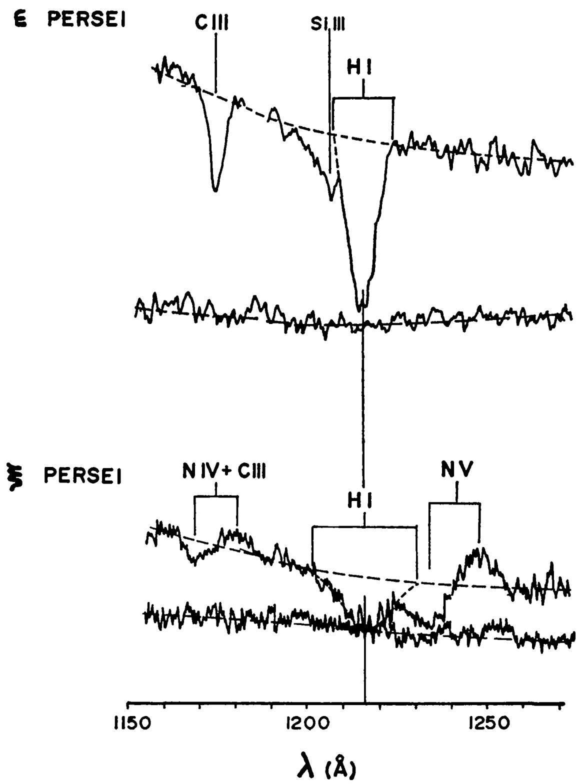

FIG. 3.—Microdensitometer tracings of spectra of ϵ and ξ Per in the vicinity of the Lα interstellar absorption line.

visual extinction due to dust. This is in fair agreement with our observation of ξ Per. However, in the case of ϵ Per, where we observe only one-fourth as much atomic hydrogen as toward ξ Per (and no molecular hydrogen), this relationship indicates a deficiency of hydrogen relative to dust. Since the reddening and the atomic-hydrogen column densities of typical Orion stars (such as η Ori, B0.5 V) are about the same as for ϵ Per, this indicates that the ratio of hydrogen to dust may actually be higher in dense dust clouds than in the general interstellar medium. Further observations, particularly of stars intermediate in reddening between ϵ Per and ξ Per, should help resolve this question.

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