EQUIVALENT WIDTH OF INTERSTELLAR MOLECULAR LINES

IV: *Analyses of the Line Spectrum of H_2 in the Interstellar Spectrum of δ Scorpii*

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Abstract. We have made an analysis of the observed equivalent widths of the lines of Lyman and Werner bands by Smith. The H_2 column densities of 3×10^{19} to 10^{20} and the excitation temperature of 80 to 150 K satisfy the observations. This temperature refers to the kinetic temperature. We have also discussed the importance of getting the excitation temperature from lines of H_2 and other heteronuclear diatomic molecules for the same star and from different regions of space.

1. Introduction

The lines of H_2 molecule in the UV region of the spectrum was first observed by Carruthers (1970) in the star ξ Per. However, the resolution of the spectrum was not enough to resolve into individual rotational lines. The observation of individual rotational lines of H_2 are very essential as it will give directly a measure of the kinetic temperature (Krishna Swamy and Tarafdar, 1972a, b; called Papers I and II). Recently Smith (1973) has observed the lines of H_2 in the star δ Scorpii. He was able to measure the equivalent width of $P(1)$ line and the total equivalent width of the blended feature of $R(0)$ and $R(1)$ lines in a number of bands of the Lyman series. In addition he has also measured the equivalent widths of the $R(1)$ line and the blended feature of $R(0)$ and $Q(1)$ lines of the (0–0) band of the Werner series. In the present paper, we would like to analyse these measured equivalent widths along the lines of our earlier papers (Papers I and II).

2. Calculation and Results

The method of calculation of the equivalent width of molecular lines have been described in detail in earlier papers (Papers I and II). The number densities involved are such that the equivalent width lies on the damping portion of the curve of growth. Therefore, one can use the asymptotic expression for the calculation of the equivalent widths. The total oscillator strengths for the lines of Lyman and Werner bands have been determined using the vibrational oscillator strengths of Allison and Dalgarno (1970) and Hönl-London factor of Schadee (1964). The life time of the various levels are also those of Allison and Dalgarno (1970). The total equivalent width of the blended feature of $R(0)$ and $R(1)$ lines has been calculated following Paper I as

$$W_T = [W(R(0))^2 + W(R(1))^2]^{1/2}. \tag{1}$$

In Figures 1 and 2, we have shown the observed equivalent widths of Smith for the blended feature and the $P(1)$ line along with the error bars. One finds from Equation (1) and the asymptotic expression for the damping portion of the curve of growth, that the total equivalent width of the blended feature is independent of the temperature T and the velocity parameter b. Therefore, from Figure 1, we can get only an estimate
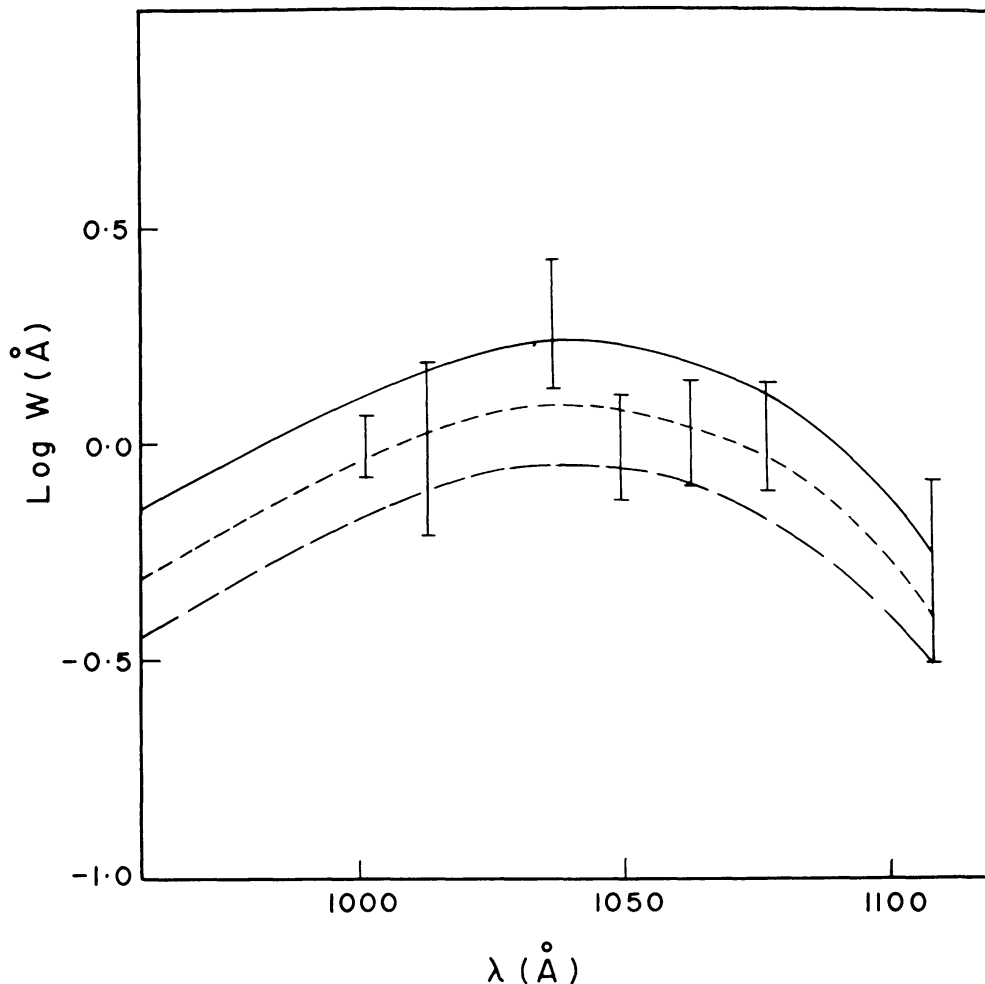

Fig. 1. Comparison of the total observed equivalent width of the R(0) and R(1) lines (lines with error bars) with those of calculated values. Continuous, dashed and long dashed curves refer to N_{total} of 10^{20}, 5×10^{19} and 3×10^{19} cm^{-2} respectively.

of the column density of H_2. The calculated curves covering the range of observations are also shown in Figure 1. The calculated curve for $n(H_2) \approx 5 \times 10^{19}$ cm^{-2} gives reasonably a good fit with the observations. Having fixed the column density of H_2 from the blended feature, we can now make an estimate of the excitation temperature from the $P(1)$ line. From Figure 2, we find that the minimum and maximum excitation temperatures are about 80 and 150 K with a mean around 100 K, corresponding to the column densities of Figure 1. Using $n(H) = 1.5 \times 10^{21}$ cm^{-2} (Smith, 1973) and the present number density of H_2, we get $n(H_2)/n(H) \approx 0.02$ to 0.07. The number

density obtained here is in agreement with the values of Smith. However, the excitation temperature as given by Smith is roughly a factor of three smaller than the present values. In this connection, it might be pointed out that a comparison of the shape of the calculated curve with the observed one as has been done here is more meaningful
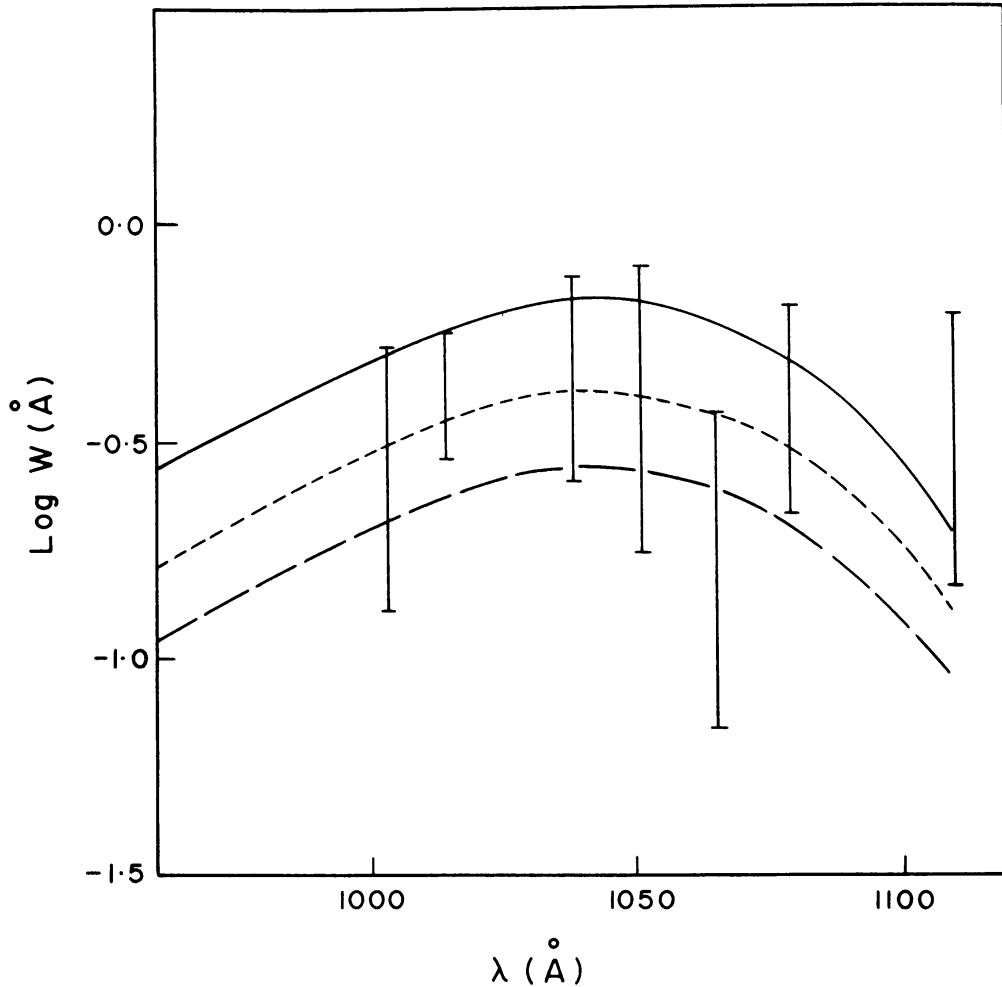

Fig. 2. Comparison of the observed equivalent width of the $P(1)$ line (lines with error bars) with those of calculated values. Continuous, dashed and long dashed curves refer to 10^{20}, 150 K; 5×10^{19}, 100 K and 3×10^{19}, 80 K, respectively.

and reliable than comparing at each wavelength. In addition to the Lyman band, Smith (1973) has also observed $R(1)$ line and the blended feature of $R(0)$ and $Q(1)$ lines of (0–0) band of the Werner system. In Table I, we have given the observed equivalent widths along with the calculated values for the excitation temperature and column densities of Figures 1 and 2. The agreement is not bad considering the fact that only one band has been observed and in addition error is quite large. It may also be pointed out that for the excitation temperature around 100 K lots of rotational lines of HD should be observable (Paper II). One might also be able to observe the lines of D_2 in regions of high H_2 column density, if $D_2/H_2 \sim 10^{-8}$. This means that

TABLE I

Comparison of the observed and calculated equivalent widths of (C − X) band of H_2 for $n(H_2) = 3 \times 10^{19}$, $T = 80$ K and $n(H_2) = 10^{20}$, $T = 150$ K

Line	Band	Ranges of equivalent widths in Å	
		Observed	Calculated
$R(1)$	(0–0)	0.11 to 0.71	0.44 to 1.0
$R(0)$ } $Q(1)$ }	(0–0)	0.29 to 0.88	1.1 to 1.9

these lines should be looked for in the star ξ Per, where $n(H_2) \approx 10^{21}$ cm^{-2} (Paper II; Carruthers, 1970).

As was pointed out in Paper II, the population of the rotational levels of H_2, HD or D_2 molecules cannot be controlled by radiation but by the collision processes. This is due to the fact that the dipole moments of these molecules are zero. Therefore the excitation temperature ~ 100 K, that has been deduced from Figure 2, essentially refers to a kinetic temperature. It may be noted that the excitation temperature obtained for H_2 lines is vastly different from that obtained from other heteronuclear diatomic molecules, which give $T \sim 3$ K (Field and Hitchcock, 1966; Thaddeus and Clauser, 1966; Paper I). Unfortunately at the present time we do not have detailed rotational line observations of H_2 and other heteronuclear diatomic molecules arising out of the same region in order to make an estimate of the excitation temperature and to see whether the two are different. Presently available observations seems to indicate different excitation temperatures for H_2 and other heteronuclear diatomic molecules. If future observations confirm this, then it will raise some important questions: like, how lines arising from the same region can have different excitation temperatures. One possibility is that they are produced in different clouds of different temperatures. Alternatively it may be due to Non-LTE Processes which results in two excitation temperatures in the same cloud. If latter is the case, then either the excitation process of the two types of molecules under consideration are different or somehow in the formation process, H_2 attains a higher temperature compared to heteronuclear molecules. In fact, they may give some clues about the formation of these molecules. Therefore it is utmost important to make detailed line observations of H_2 and other heteronuclear diatomic molecules arising for same star and from different regions of space.

Note added in proof: Reference may be made to the more recent work of the Princeton group obtained from Copernicus satellite on H_2 and other molecules (*Astrophys. J Letters* **181**, L116 and L122).

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