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ROTATIONAL FINE-STRUCTURE LINES OF INTERSTELLAR C_2 TOWARD ZETA PERSEI

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ABSTRACT

We have detected nine of the rotational fine-structure lines of the 2–0 band of the Phillips system of interstellar C_2 toward ζ Persei with the McDonald Observatory 2.7 m telescope's coudé echelle spectrograph and Reticon detector. The equivalent widths of the lines yield values of $N(C_2) = 1.2 \times 10^{13}$ cm^{-2} and $T_{rot} = 97$ K. These values are compared with 1.4×10^{13} and 45 K predicted by the detailed model of the cloud by Black, Hartquist, and Dalgarno.

We discuss the apparent discrepancy in the observed and predicted cloud temperature by suggesting that the level populations of C_2 have been altered from those expected in pure thermal equilibrium by radiative pumping through the Mulliken and Phillips systems. Although not all of the physical constants required to calculate this effect in detail are known, arguments based on reasonable estimates of their values suggest that radiative pumping can, indeed, produce a rotational temperature of 97 K even though the kinetic temperature of the cloud is significantly lower than this value.

Subject headings: interstellar: abundances — interstellar: molecules — stars: individual

I. INTRODUCTION

That diatomic molecular carbon can be produced in diffuse interstellar (IS) clouds through gas phase reactions was first suggested by Dalgarno and Black (1976) wherein C_2 results from the same chain of reactions which produces CH and CH^+—two of the most frequently observed IS molecules. In their scheme C_2 is a product of the dissociative recombination of C_2H^+ which itself is formed in a series of reactions beginning with C^+ and H_2.

Since that paper, detailed models of two of the best-studied diffuse IS clouds have appeared—ζ Ophiuchi (Black and Dalgarno 1977, hereafter BD) and ζ Persei (Black, Hartquist, and Dalgarno 1978, hereafter BHD)—in which column densities of many molecules, whose formation is possible through gas phase reactions, are predicted. For ζ Oph BD pointed out that of the unobserved IS molecules whose existence they predict, one of the most likely to be detectable is C_2, which, although it exhibits no radio spectrum, has lines in the near-infrared.

Initial attempts to detect C_2 toward these two clouds failed (Lutz, Souza, and Chaffee 1977) because the lines are weak, and the Phillips system, which contains the strongest predicted lines of C_2, lies in a region for which conventional two-dimensional detectors have both low quantum efficiency and high noise.

In an effort to detect a higher column density of C_2 than that expected in diffuse clouds, Souza and Lutz (1977) obtained echelle spectra of Cyg OB2 No. 12, a star with $A_V = 10$, and detected the $R(2)$ and $Q(2)$ rotational fine-structure lines of the (1–0) Phillips band. In a similar, but unsuccessful, search for C_2 toward ζ Oph, Lutz and Souza (1977) suggested that because C_2 is similar in its structure to H_2 the population of its rotational fine-structure levels should be thermalized, thus allowing an estimate of the cloud temperature to be obtained from the relative strengths of lines from at least two different J levels.

The $R(0)$ line of the Mullikan band at $\lambda 2312$ was detected by Snow (1978) toward ζ Oph, and shortly thereafter the $Q(2)$ line of the 2–0 Phillips band was detected toward the same star (Chaffee and Lutz 1978) at roughly the strength predicted by BD's model.

BHD's model of the ζ Per cloud indicated that the $R(2)$ and $Q(4)$ lines of the 2–0 Phillips band might be detectable at the 1 mÅ level, and if both could be measured with sufficient accuracy, an independent determination of the cloud temperature could be obtained. It was with these considerations in mind that we selected ζ Per as a star of which to obtain high signal-to-noise (S/N) spectra to search for lines of the 2–0 Phillips band.

II. THE OBSERVATIONS

To obtain the necessary observations we require a unique combination of an extremely mechanically stable, high resolution ($\mathscr{R} = 10^5$) spectrograph and a detector with high quantum efficiency in the near-infrared, itself sufficiently stable to produce very high S/N spectra in a reasonable amount of telescope time. A system which meets all of our requirements is the Reticon system on the coudé echelle spectrograph of the McDonald 2.7 m telescope, and this instrument was used for the present program. It has been described in detail by Vogt, Tull, and Kelton (1978) and will be reviewed only briefly here. The instrument consists of a 20 cm beam coudé echelle spectrograph with an unintensified 1024B Reticon photodiode array as the detector. The array is cooled to $-140 \pm 0.25°$ C to eliminate thermal leakage and to allow the near elimination of the every-other-diode fixed pattern signal which exists with these devices. The array consists of 1024 discrete photodiodes, each 610 μm $\times$ 25.4 μm with effectively no interdiode dead space. At λ8755, the wavelength region of the 2–0 Phillips band, the spectrograph produces a nominal reciprocal dispersion of 1.3 Å mm^{-1}, and for our experiment we used a 50 μm slit projected onto the array, yielding a resolution of 66 mÅ ($\mathscr{R} = 1.3 \times 10^5$). An interference filter with FWHM = 14 Å centered at λ8756 was used to isolate the echelle order of interest. The Reticon has a readout noise of 600 *e-h* pairs, and thus to achieve the highest detective quantum efficiency (DQE), sufficiently long exposures must be taken before readout so that this noise is small compared to the shot noise of the incident photons. Finally, in order to minimize the fixed pattern signal, continuous lamp exposures are taken with very high S/N after each night's observing, which are used to normalize the stellar exposures.

Three exposures totaling 8 hours of observing time over two nights (1978 November 18, 19) were added to produce the final spectrum. The individual exposures were shifted with respect to each other by the difference of the geocentric velocity of ζ Per between exposures, thus registering the IS lines but broadening any telluric lines in the sum.

The summed spectrum was processed using the fast Fourier transform spectral reduction program (REDUCER) developed for use at Kitt Peak for solar data (Brault and White 1971). At the high S/N level some fixed pattern signal remains even after normalization by the continuous lamp exposure and appears as a spike at the appropriate frequency in the transform of the spectrum. We have thus filtered the spectrum by removing all Fourier components at or above the fixed pattern fundamental frequency. We have also rectified the spectrum by the measured shape of the interference filter.

The upper portion of Figure 1 shows the top 2% of the rectified observed spectrum with $\times$'s marking the actual sample points. The higher noise at the long wavelength end of the spectrum results from the filter transmission rolloff. The lower portion of Figure 1 shows the processed data on the same scale, and the locations of the lines of the 2–0 Phillips band are marked with their rest wavelengths.

Some of the remaining noise in the processed spectrum may be systematic as a result of interference fringes caused by the blocking filter or of weak lines of the 7–3 Meinel band of telluric OH airglow which exist in this spectral region. The dashed line in the lower spectrum in Figure 1 is our eye estimate of the continuum level, and the measured equivalent widths are given in Table 1. We estimate an uncertainty of 15% in these values, the major source of this uncertainty being the location of the continuum. Both $R(10)$ and $R(12)$ are suspect, and we have not used their strengths for any of the analysis below.

Two solar spectra taken with the McMath telescope were used to reconstruct the telluric water vapor spectrum in this region. From the Kitt Peak library of solar spectra two photoelectric scans taken a few minutes apart near sunset were subtracted to produce a difference spectrum. The air mass difference between solar scans was 7 air masses, so that the telluric lines are strong in the difference spectrum whereas solar features disappear. The only telluric line of sufficient strength to be detected in our spectrum lies at λ8758.423 and is identified in Figure 1. That it is indeed telluric is indicated by its asymmetry which results from our having registered the spectra to the IS lines.

This H_2O line serves as our fiducial mark for the measurement of the heliocentric radial velocity of the C_2 lines. A quadratic dispersion solution was fit to

TABLE 1

SUMMARY OF C_2 OBSERVATIONS TOWARD ZETA PERSEI

$\lambda_{(\mathrm{air})}$	Line	W_λ (mÅ)	$f(10^{-3})$	$N_J(10^{12})$	ln $[N_J/(2J+1)]$	chE_J/k	N_T (10^{13})	log N_T
8757.66	R (0)	0.57	1.35	0.62	27.15	0	1.17	13.07
8752.92	R (2)	1.06	0.54	2.90	27.09	16	1.28	13.11
8761.16	Q (2)	1.19	0.68	2.60	26.98	16	1.15	13.06
8751.64	R (4)	0.82	0.45	2.69	26.42	52	0.96	12.98
8763.69	Q (4)	1.49	0.68	3.25	26.61	52	1.16	13.06
8750.82	R (6)	1.01	0.42	3.60	26.35	109	1.61	13.21
8751.43	R (8)	0.37	0.40	1.38	25.12	188	1.05	13.02
8753.56	R (10)	0.23:	0.39	0.88:	24.46:	286	...	...
8757.10	R (12)	0.35:	0.38	1.37:	24.73:	406	...	...

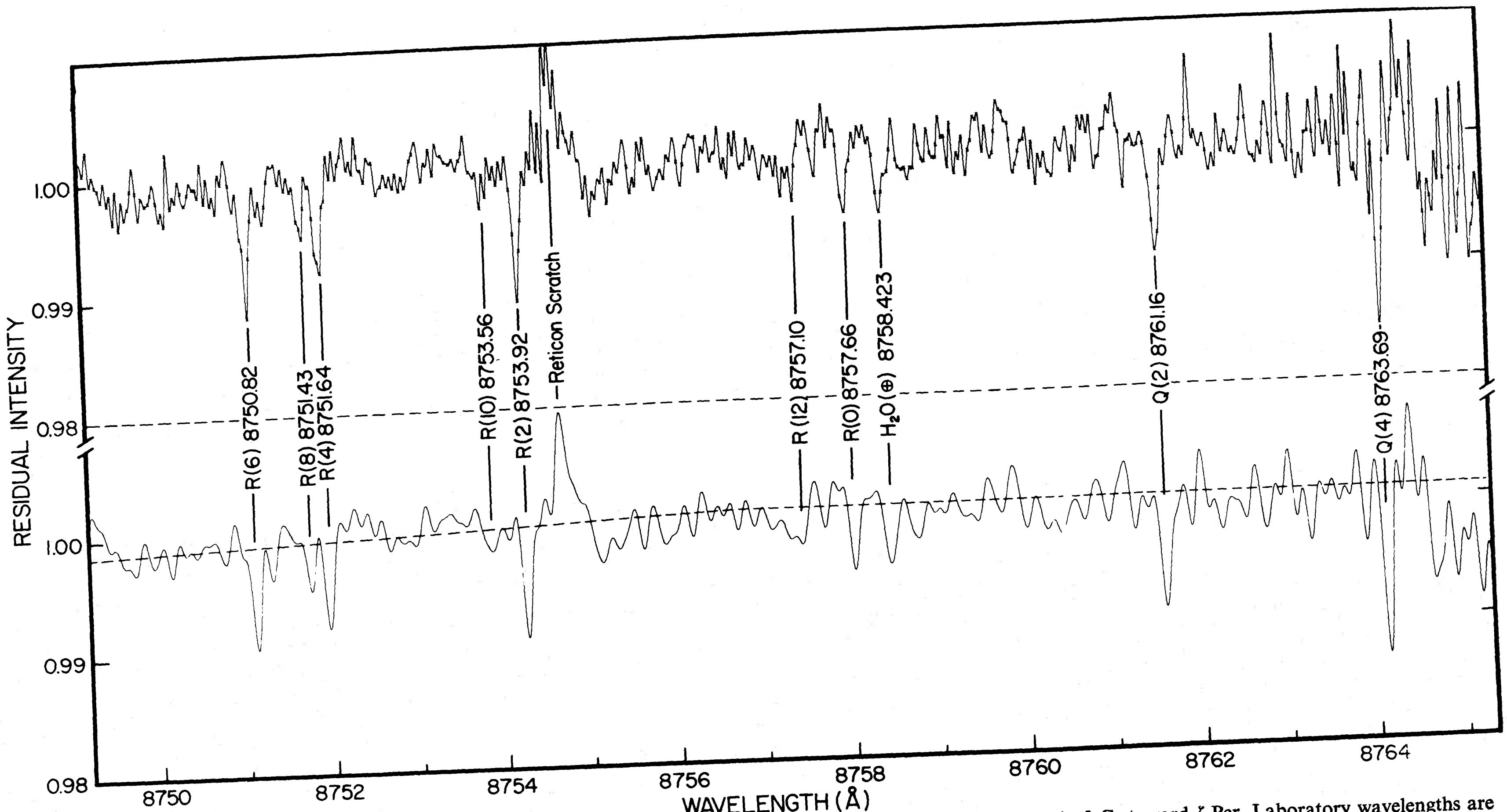

FIG. 1.—Raw data (*upper curve*) and smoothed spectrum (*lower curve*) for interstellar lines of the 2–0 Phillips band of C_2 toward ζ Per. Laboratory wavelengths are given on the abscissa.

the observed C_2 lines and this function was used to predict the position of the H_2O feature. The difference between the observed and predicted positions yields the radial velocity of the IS features. From this analysis we find that $v_{\text{helio}}(\zeta \text{ Per}) = +15 \pm 0.6 \text{ km s}^{-1}$, consistent with the cloud velocity observed for the other atomic and molecular constituents (see Marschall and Hobbs 1972; Chaffee 1974).

III. C_2 OSCILLATOR STRENGTHS AND COLUMN DENSITIES

To determine the total column density of C_2 along the line of sight toward ζ Per and to derive the rotational temperature we have used a number of well-established approximations. First, we assume that the Born-Oppenheimer approximation of the separability of molecular wave functions is sufficiently accurate that the line f-values are given directly by the product of the band f-value, f(2–0), and the relative line strength as determined from the usual Hönl-London factors for a $^1\Pi$–$^1\Sigma$ transition (Herzberg 1950).

Second, we assume that this principle of separability is sufficiently valid so that the f-value of the 2–0 band can be obtained by scaling the measured f-value of the 0–0 band

$$f(2\text{–}0) = f(0\text{–}0)\left[\frac{\nu(2\text{–}0)q(2\text{–}0)}{\nu(0\text{–}0)q(0\text{–}0)}\right], \quad (1)$$

where $\nu(v'\text{–}0)$ and $q(v'\text{–}0)$ are the band origins and Franck-Condon factors, respectively. Values for $\nu(v'\text{–}0)$ were taken from the spectroscopic analysis of Phillips (1948), while those for $q(v'\text{–}0)$ were taken from the tabulation of Halman and Laulicht (1965).

The value for f(0–0) is not well determined—only two absolute measurements have been reported in the last decade: 4×10^{-3} by Cooper and Nicholls (1975) (hereafter CN) based on integrated band intensities observed at low resolution, and 2.5×10^{-3} by Roux, Cerny, and d'Incan (1976) (hereafter RCd'I) obtained from high resolution line intensities.[1] Of these we have chosen to use the value of RCd'I. This selection is somewhat subjective since different techniques were used, both of which have difficult absolute calibration problems. However, an independent astrophysical measurement based on equivalent width measurements in the solar spectrum by Lambert and Mallia (1974) yielded a value of $f(0\text{–}0) = 2.7 \times 10^{-3}$, while the average value of relative measurements since 1965 (see RCd'I for a summary) is near 2×10^{-3}.

The third assumption in our analysis is that of linearity of column density with equivalent width, though certainly for lines this weak no saturation effects are present.

The adopted f-values and deduced column densities are given in Table 1.

IV. ROTATIONAL TEMPERATURE OF C_2

If the populations of the rotational levels are all characterized by a single, unique temperature, then their distribution is described by a Boltzmann function:

$$N_J = (2J + 1)(N_T/Q_r) \exp(-E_J hc/kT_{\text{rot}}), \quad (2)$$

where N_J is the population in level J, having an energy E_J above level $J = 0$, Q_r is the partition function at temperature T_{rot}, h, c, and k are the usual physical constants, and N_T is the total abundance of C_2 in all levels. We assume here and in the following discussion that relative column densities and relative volume densities can be used interchangeably.

If equation (2) is valid, a plot of $\ln[N_J/(2J + 1)]$ versus $-E_J hc/k$ results in a linear relationship with a slope of $1/T_{\text{rot}}$. Figure 2 illustrates this diagram based on the column densities and energy levels in Table 1—the latter computed from the rotational constants of Marenin and Johnson (1970). Since we consider $R(10)$ and $R(12)$ as only marginally detected, we did not use them to determine the temperature, but they are displayed in the figure. The error bar represents the $\pm 15\%$ equivalent width uncertainty we estimated to arise from the uncertainty in the continuum location.

The best fit of the data to equation (2) yields a rotational temperature of 97 ± 10 K. Using this temperature, we have computed the partition function, Q_r, using the full summation

$$Q_r = \sum_{J_{\text{even}}} (2J + 1) \exp(-E_J hc/kT_{\text{rot}}) = 18.85 \quad (3)$$

to a convergence of better than 0.05%. In Table 1 we list our estimates of N_T calculated for each J level

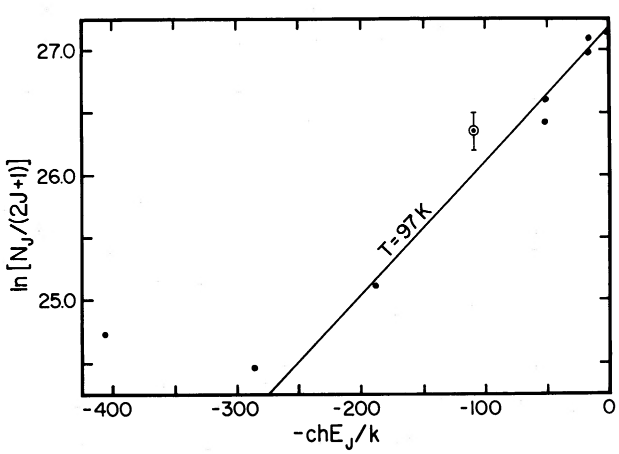

FIG. 2.—Determination of C_2 rotational temperature for the ζ Per cloud.

[1] There is an inconsistency between the values of f(0–0) and its equivalent transition dipole moment $\Sigma |R_e|^2$ reported by RCd'I. Presumably this inconsistency results from the use of an incorrect statistical weight for the lower $X\,^1\Sigma_g^+$ state in converging f(0–0) to $\Sigma |R_e|^2$ for their comparison. Based on their estimated oscillator strength of $f(0\text{–}0) = 2.5 \times 10^{-3}$, the transition dipole moment should be $\Sigma |R_e|^2 = 0.25$ a.u. A similar error exists in their table summarizing the Phillips band f-values in their conversion from CN's transition dipole moment to its equivalent band oscillator strength. Consquently the value $f(0\text{–}0) = 1.8 \times 10^{-3}$ ascribed by RCd'I to CN should be replaced by the value reported here—$f(0\text{–}0) = 4 \times 10^{-3}$. A concerted effort aimed at obtaining an independent and accurate f-value is certainly needed.

population based on this partition function and equation (2). The mean value of $\log N_T$ (excluding $R(10)$ and $R(12)$) is 13.07 ± 0.03 ($1\ \sigma$).

V. COMPARISON OF OBSERVATIONS WITH THEORY

BHD have presented a detailed model of the diffuse interstellar cloud in the line of sight to ζ Per. This model reproduces the observed concentrations of H_2, HD, CO, CH, CN, and OH, and predicts a column density of $1.4 \times 10^{13}\ \mathrm{cm^{-2}}$ for C_2 for a photodissociation rate of $10^{-10}\ \mathrm{s^{-1}}$. This prediction is in harmony with the present observations.

The observations of the abundance and rotational populations of H_2 require a two-component model with most of the molecules confined to a cold core having a kinetic temperature of 45 K and a total density $[n(\mathrm{H}) + 2n(\mathrm{H_2})]$ of $267\ \mathrm{cm^{-3}}$—the former value in apparent conflict with the present observations.

The rotational temperature which we have determined from our observations of the C_2 molecule is a good measure of the kinetic temperature of the gas if inelastic collisions with the abundant species (i.e., H and H_2) dominate the statistical equilibrium of rotational populations. However, at least two other mechanisms can, in principle, affect the rotational populations: spontaneous radiative transitions between levels, and absorption and fluorescence in electronic systems.

As emphasized by Lutz and Souza (1977), spontaneous radiative transitions between rotational levels of C_2 occur only by quadrupole interactions with very small probabilities because the molecule is a symmetric, homonuclear species with a small rotational constant. Although the quadrupole moment of C_2 in the $X\,^1\Sigma_g{}^+$ ground state is not known, it is reasonable to expect transition probabilities $A < 10^{-13}\ \mathrm{s^{-1}}$ (Lutz, Souza, and Chaffee 1977) for rotational transitions. Inelastic collisions with H and H_2 are almost certainly more rapid than spontaneous radiation, even at IS densities and temperatures.

Absorption and fluorescence in the Phillips and Mulliken systems, on the other hand, *can* compete with collisions in redistributing rotational populations. It is not possible to predict precisely the relative contributions of collisional and radiative processes, but the following preliminary analysis provides a qualitative interpretation of the observed rotational populations.

A full treatment of the rotational populations of C_2 resembles the corresponding analysis of H_2 (Black and Dalgarno 1976). The IS absorption lines of C_2 remain unsaturated throughout diffuse clouds so that the effects of radiative transfer in the lines are unimportant. Cross sections for rotationally inelastic collisions involving C_2 are unknown, and can be only estimated. The effects of absorption and fluorescence can, however, be calculated explicitly. Virtually every absorption in an electronic system is followed by a downward transition to some level of the ground electronic state, and the final rotational quantum number is frequently different from the initial one. If the fluorescent transition is to a vibrationally excited level, the rotational distribution is further modified by a cascade through quadrupole rotation-vibration transitions.

The populations of rotational levels of the $X\,^1\Sigma_g{}^+$ state in statistical equilibrium are related by

$$N_J[R_J + C(J, J+2) + C(J, J-2)] = r_J + N_{J-2}C(J-2, J) + N_{J+2}C(J+2, J)\,, \quad (4)$$

where R_J is the rate ($\mathrm{s^{-1}}$) of absorptions out of level J, r_J is the rate ($\mathrm{cm^{-3}\ s^{-1}}$) at which fluorescence and cascade populate level J, and $C(J, J')$ is the rate ($\mathrm{s^{-1}}$) at which collisions populate level J' from level J. Equation (4) ignores quadrupole rotational transitions and collisional transitions involving changes in quantum number $|\Delta J| > 2$.

R_J is given by

$$R_J = \frac{\pi e^2}{mc} I \sum_k f_k \phi(\lambda_k)\,, \quad (5)$$

where f_k is the oscillator strength and λ_k is the wavelength of each possible absorption line k arising in level J. The radiation field is characterized by a flux $I\phi$ in photons $\mathrm{cm^{-2}\ s^{-1}\ Hz^{-1}}$, which is the same function described by BD except that the dimensionless scaling factor I is retained explicitly. The rate r_J is exactly analogous to the term $q_0(J)$ in the analysis of H_2 level population of Black and Dalgarno (1976), and both it and R_J are proportional to the factor I.

A simple model of the collisional process is assumed in which all the rate coefficients scale in proportion to a constant cross section σ and to the statistical weights. Thus the frequency of downward transitions $2 \rightarrow 0$ is

$$C(2, 0) = (8kT/\pi\mu)^{1/2} n_c \sigma = 10^4 T^{1/2} n_c \sigma \quad \mathrm{s^{-1}}\,, \quad (6)$$

for H_2–C_2 collisions, where n_c is the effective density of collision partners (H and H_2). The rates scale as

$$C(J+2, J) = \frac{2J+1}{2J+5} C(J, J-2) \quad (7)$$

for all other de-excitations, and as

$$C(J, J+2) = \frac{2J+5}{2J+1} C(J+2, J) \exp\,[-\Delta E(J+2, J)/kT] \quad (8)$$

for all upward transitions, where $\Delta E(J', J)$ is the difference in energy between levels J' and J. It is possible to estimate the relative influence of collisions and of radiative processes by solving equation (4) in the form

$$N_J R_J - Y_J = N_{J-2}C(J-2, J) + N_{J+2}C(J+2, J) - N_J[C(J, J-2) + C(J, J+2)] \quad (9)$$

for each J at a variety of temperatures, assuming plausible values of I and $n_c\sigma$, and adopting observed populations N_J.

In order to calculate the radiative rates, we have adopted the corrected dipole transition moment of RCd'I for the Phillips system and the oscillator strength of Smith (1969) for the Mulliken system.[2] Franck-Condon factors of Spindler (1965) and Nicholls (1965) are used for the Phillips and Mulliken systems, respectively. The former Franck-Condon factors are very similar to more recent results of Dwivedi *et al.* (1978) for small v and J. The intensity of the ultraviolet system $F\,^1\Pi_u \leftarrow X\,^1\Sigma_g^+$ (Herzberg, Lagerqvist, and Malmberg 1969) has not been measured, and we have assumed simply that $\Sigma\,|R_e|^2 = 0.44$ a.u. (appropriate for a strong Rydberg transition), and that the Franck-Condon factors are $q(0, 0) = q(1, 1) = 0.50$.[3] Energy levels and transition wavelengths are calculated using molecular constants of Marenin and Johnson (1970) for the X and A states, of Landsverk (1939) for the D state, and of Herzberg, Lagerqvist, and Malmberg (1969) for the F state. Given the values $N_J R_J$ and these molecular data, the evaluation of the r_J for direct fluorescence without cascade is straightforward (see Black and Dalgarno 1976).

In the adopted radiation field, $R_J = 8.3 \times 10^{-10}\,I$ s^{-1} for all $J \lesssim 20$. For excitation temperatures in the range $40 < T_{\rm rot} < 100$ K, about 60% of the total fluorescence is directly to levels of $X\,^1\Sigma_g^+(v = 0)$. The rotation-vibration cascade that modifies the rest of the fluorescence cannot be specified precisely; however, each episode of absorption and fluorescence followed by cascade probably tends to shift the rotational distribution toward higher J.

To see if absorption and fluorescence could account for our value of $T_{\rm rot}$ and BHD's kinetic temperature, we use in equation (9) the rotational populations N_J given by $T_{\rm rot} = 97$ K, and ask what range of $T_{\rm kin}$ is allowed. Initially we note that no plausible solutions exist for $T_{\rm kin} > 97$ K. Second, if $T_{\rm kin} = T_{\rm rot}$, then by definition the radiative processes do not affect the populations.

For kinetic temperatures in the range $20 \leq T \leq 96$ K, the derived ratio $n_c\sigma/I$ is $4.0 \times 10^{-15} \leq n_c\sigma/I \leq 5.0 \times 10^{-13}$ cm^{-1}. If we take as a reasonable upper limit for the cross section of C_2 its classical geometrical value ($\sigma \lesssim 5 \times 10^{-16}$ cm^2) and we accept $I = 1$ as inferred by BHD and assume that $n_c \approx 100$ cm^{-3} as implied by the H_2 observations, then $n_c\sigma/I < 5 \times 10^{-14}$ cm^{-1}, and kinetic temperatures higher than 80 K can be excluded.

Plausible values of the fluorescence-cascade rates can be found for any smaller temperature. In particular, with $T_{\rm kin} = 40$ K and $n_c\sigma/I = 5 \times 10^{-15}$ cm^{-1}, an adequate solution of the statistical equilibrium can be found in which the rotational populations are characterized by a *single rotational temperature* but are significantly affected by radiative pumping. The probabilities of populating level J by fluorescence and cascade can be represented by the ratio r_J/R_J, and typical values of this ratio are presented in Table 2 for the case $T_{\rm rot} = 97$ K, $T_{\rm kin} = 40$ K, and $n_c\sigma/I = 5 \times 10^{-15}$ cm^{-1}.

The above analysis does not permit the exclusive determination of I, n_c, and $T_{\rm kin}$ from observations of C_2 because of lack of knowledge of the behavior of the collisional cross sections and of the details of the radiative cascade. We can assert with some confidence, however, that radiative effects are important in determining rotational populations in C_2 under reasonable assumptions concerning densities, radiation fields, and cross sections. Thus a uniform rotational temperature is not necessarily a direct measure of the kinetic temperature. Reliable calculations of the excitation cross sections and of the array of rotation-vibration transition probabilities would constrain the analysis sufficiently that C_2 could be used as an accurate diagnostic probe of diffuse clouds.

As discussed above, it is also important to have reliable oscillator strengths for the Phillips, Mulliken, and $F\,^1\Pi \leftarrow X\,^1\Sigma_g^+$ systems of C_2. The observed strengths of the 2–0 Phillips lines imply equivalent widths of 2–5 mÅ for the $R(0)$ through $R(6)$ lines of the 0–0 band of the Mulliken system (λ2313) toward ζ Per, assuming that the oscillator strength is as large as that measured by Smith (1969). Lines of the 0–0 and 1–0 bands of the $F \leftarrow X$ system could have equivalent widths as large as 1 mÅ if the oscillator strength is as large as assumed above.

TABLE 2

FLUORESCENCE AND CASCADE IN C_2

J	N_J[a]	r_J/R_J[b] (fluorescence only)	r_J/R_J[c] (fluorescence plus cascade)
0	0.0532	0.0291	0.0345
2	0.2266	0.1255	0.2193
4	0.2800	0.1602	0.2863
6	0.2240	0.1349	0.2332
8	0.1309	0.0844	0.1372
10	0.0583	0.0409	0.0612
12	0.0202	0.0157	0.0212
Sum	0.9932	0.5907	0.9929

[a] Relative populations at $T_{\rm rot} = 97$ K.

[b] Fluorescent probability depends only upon the initial populations (i.e., $T_{\rm rot}$) and the oscillator strengths.

[c] This solution for the fluorescence/cascade probabilities is based upon $T_{\rm kin} = 40$ K, and $n_c\sigma/I = 5 \times 10^{-15}$ cm^{-1}.

[2] In the literature there exist two laboratory measurements of the transition dipole moment for the Mulliken system: $\Sigma\,|R_e|^2 = 0.42$ a.u. by Smith (1969), and 0.13 a.u. by CN (1975). Because of the difficult problems associated with absolute calibration of the shock-tube method, we prefer to use the value obtained by Smith using the lifetime technique. However, this bias is somewhat subjective, and a laboratory project of high priority should be a redetermination of this f-value, perhaps in conjunction with the remeasurement of that of the Phillips band.

[3] The value of $\Sigma\,|R_e|^2$ used for the ultraviolet system is based on an order-of-magnitude estimate of an f-value for a "typical" Rydberg-type transition, of which the *uv* system appears to be an example (Herzberg, Lagerqvist, and Malmberg 1969): $f(0\text{–}0) \approx 0.1$. The Franck-Condon factor is estimated from the value for the 0–0 band sequence of the Phillips system which has a similar change of equilibrium internuclear distance associated with the transition. However, the *uv* system contributes only weakly to the radiative pumping, and consequently the calculations are relatively insensitive to these selections.

If better molecular data were available, observations of C_2 could be used to extract information about densities, temperatures, and radiation fields in IS clouds. Although the C_2 lines observed so far are extremely weak, because they lie in the near infrared the potential exists for using them to probe regions of much higher extinction than can be observed in ultraviolet lines of H_2.

V. SUMMARY

We summarize below the key results of the present paper:

1. We have detected IS C_2 in the direction of ζ Persei and have identified nine rotational lines of the 2–0 band of the Phillips system near λ8755.
2. Analysis of these observations yields a total C_2 column density of 1.2×10^{13} cm^{-2} with $T_{\rm rot} = 97$ K.
3. A preliminary investigation of the processes which are likely to affect the rotational equilibrium indicates that a uniform rotational temperature is not necessarily a direct measure of the kinetic temperature and that radiative pumping is important in determining the rotational population distribution of C_2.
4. In the ζ Persei cloud our calculations further indicate that the kinetic temperature is less than 80 K, but because of a lack of knowledge of the behavior of the collisional cross sections and of the details of radiative cascade they cannot further specify a unique determination of T, n_c, and I. However, within the range allowed, adequate solutions can be found for our results to be consistent with the model of BHD.

Note added in preparation.—As this paper was in its final iteration, we received a preprint from Dr. L. M. Hobbs, reporting the detection of the $R(0)$, $Q(2)$, and $Q(4)$ lines of the 2–0 Phillips band toward ζ Per. His observational errors considerably exceed ours, but within these errors, the deduced values of $N(C_2)$ and $T_{\rm rot}$ from the two investigations agree.

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