THE ASTROPHYSICAL JOURNAL, 271:L95–L99, 1983 August 15

INTERSTELLAR C_2 MOLECULES IN A TAURUS DARK CLOUD

L. M. HOBBS
Yerkes Observatory, University of Chicago
JOHN H. BLACK
Harvard-Smithsonian Center for Astrophysics
AND
EWINE F. VAN DISHOECK
Sterrewacht-Huygens Laboratorium
Received 1983 March 7; accepted 1983 April 20

ABSTRACT

Five relatively strong interstellar absorption lines of the (2–0) Phillips band of C_2 near λ8760 are detected in the spectrum of HD 29647, a late B star which lies behind a substantial part of the Taurus molecular cloud complex about 20′ from TMC-1. In combination with newly determined oscillator strengths, the observations yield a column density $N(C_2) \approx 9 \times 10^{13}$ cm^{-2}, which is comparable to those of widely distributed molecules like CH and H_2CO. Theoretical models of the observed C_2 rotational level populations indicate a kinetic temperature $T = 14^{+8}_{-5}$ K and a mean density $n \lesssim 10^3$ cm^{-3}. A narrow, anomalously strong, stellar Mn II line yields for HD 29647 a projected rotational velocity $v \sin i \lesssim 7$ km s^{-1} and is explained by previous identifications of HD 29647 as a Hg-Mn peculiar star. Similar spectra of ν Cyg and ο And give an upper limit $W_\lambda \leq 1.6$ mÅ on all interstellar C_2 lines in the (2–0) band, toward both stars.

Subject heading: interstellar: molecules

I. INTRODUCTION

The heavily reddened, late B star HD 29647 lies behind a substantial part of one of the darkest regions of the nearest molecular cloud complex, the dark clouds in Taurus, which are located at a distance of about 140 pc (e.g., Elias 1978). The peak of the radio line emission of the largest known interstellar molecule, HC_9N, lies within the dense cloud core TMC-1, about 20′ (0.8 pc) from the line of sight to this star (Broten *et al.* 1978; MacLeod, Avery and Broten 1979). At a visual magnitude $V = 8.3$, HD 29647 is bright enough to provide an exceptional opportunity for the study of relatively dense interstellar matter by means of its absorption lines in the ultraviolet and visual regions of the spectrum. Observations of interstellar Na I and K I have been reported by Crutcher (1980), and the unusual UV extinction curve has been discussed by Seab, Snow, and Joseph (1981), who discovered the virtual absence of an interstellar 2200 Å feature in the star's spectrum.

We report here the detection of five relatively strong interstellar absorption lines of C_2 toward HD 29647 in the (2–0) Phillips band near 8760 Å, as well as stringent upper limits on the C_2 absorption toward two lightly reddened stars, ν Cyg and ο And. The former result constitutes the first detection of several lines of C_2 in a genuine dark cloud. The rotational populations of C_2 depend upon the local physical conditions and can be used as diagnostics of the density and temperature of the gas and of the intensity of the interstellar radiation field. Furthermore, C_2 is the simplest carbon chain molecule, and studies of its abundance may help to identify the processes responsible for the observed high abundances of the large cyanopolyyne molecules in Taurus (cf. Bujarrabal *et al.* 1981).

II. OBSERVATIONS AND RESULTS

The spectrum of HD 29647 shown in Figure 1 was obtained on 1982 November 4 in a 4 hr exposure with the Reticon detector, echelle grating, and coudé spectrograph at the 2.7 m reflector of the McDonald Observatory. An instrumental resolution (FWHM) of 0.20 Å, or 6.8 km s^{-1}, was set by choosing a slit width corresponding to 1″.5 on the sky. The observations of ν Cyg and ο And described below were obtained with a 1″.0 slit, which gave a higher resolution of 0.13 Å, or 4.5 km s^{-1}. Other features of the instrumental setup were as described for earlier C_2 observations (Hobbs 1981). The full wavelength interval covered by the exposure was about 30 Å, of which only the most important part is shown in Figure 1. The rms fluctuation of the data points outside the absorption lines in Figure 1 about the continuum level of unity is 1.2%, which corresponds to a signal-to-noise ratio of 83. This combination of photo-

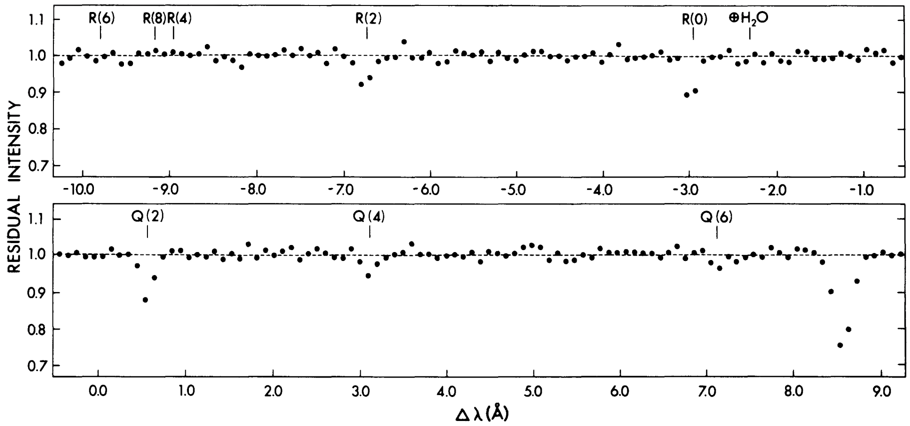

FIG. 1.—The region of the (2–0) Phillips band of C_2 near λ8760 in the spectrum of HD 29647. The data points are spaced by 0.099 Å, or 3.38 km s^{-1}, or half a resolution element. The wavelength scale is a heliocentric one measured from the position of the $Q(2)$ line. The broad wing of the stellar Paschen line of H I at λ8750 has been divided out. The known telluric line of H_2O at 8758.466 Å, slightly longward of $R(0)$, is too weak to be detected.

metric accuracy and resolution gives an equivalent width $W_\lambda \leq 5$ mÅ at a 2 σ detection limit.

Six lines, all having widths comparable to the instrumental resolution, are seen in Figure 1; the equivalent widths of the five interstellar lines of C_2 are included in Table 1. The lines arising from the lowest levels $J = 0$ and 2 are stronger than their counterparts toward ζ Oph, ζ Per, and o Per by an order of magnitude or more. The resulting column densities $N(J)$ given in Table 1 are based on the assumption that the lines are completely unsaturated. The good agreement between the two values of $N(2)$ obtained respectively from the $R(2)$ and $Q(2)$ lines, which are the two strongest C_2 lines, supports this assumption. The values of $N(2)$ imply an equivalent width for the unobserved $P(2)$ line at 8766.031 Å of 4 mÅ, consistent with the 2 σ upper limit of 5 mÅ. The profiles of the narrowest CO rotational lines in adjacent dense cores (Myers, Linke, and Benson 1983) and of widespread H_2CO lines in Taurus (Sume, Downes, and Wilson 1975) show very narrow widths, $b = 0.3$ km s^{-1}. If the C_2 lines are equally narrow, then curve-of-growth effects will increase the total column density of C_2 in Table 1 by a factor of about 1.8. This possibility cannot be excluded by the present data. Within the uncertainties, the limits on the strengths of the $R(4)$ and $R(6)$ lines are consistent with the measured strengths of the stronger $Q(4)$ and $Q(6)$ lines respectively. The total column density of C_2 derived from the five detected lines is $N(C_2) = 8.8 \times 10^{13}$ cm^{-2}.

The column densities derived here are based upon an oscillator strength for the 2–0 band of $f_{20} = 1.7 \times 10^{-3}$. This value is obtained from a recent *ab initio* theoretical calculation (van Dishoeck 1983) and exceeds the value frequently adopted previously by about 30% (e.g., Hobbs and Campbell 1982). Some uncertainty surrounds the transition moment and *f*-values for the Phillips system of C_2. The results adopted here are confirmed by independent theoretical calculations (Pouilly *et al.* 1983; Buenker 1983) and are consistent with some of the

TABLE 1

C_2 LINES TOWARD HD 29647

	R(J)			Q(J)			THEORY
J	λ(Å)	W_λ(mÅ)	$N(J)$ (10^{13} cm^{-2})	λ(Å)	W_λ(mÅ)	$N(J)$ (10^{13} cm^{-2})	$N(J)$ (10^{13} cm^{-2})
0..........	8757.686	21	1.8	...	...	...	1.84
2..........	8753.949	17	3.7	8761.194	21	3.7	3.73
4..........	8751.685	≤ 5	≤ 1.3	8763.751	12	2.1	2.10
6..........	8750.848	≤ 5	≤ 1.4	8767.759	7	1.2	1.10
8..........	8751.486	≤ 5	≤ 1.5	8773.221	≤ 5	≤ 0.9	0.61
Total							10.4

existing experimental results. The discrepancy between our values and the lower f-values suggested by recent lifetime measurements (Erman *et al.* 1982) and inferred from an analysis of solar absorption lines (Brault *et al.* 1982) is discussed by van Dishoeck (1983).

The rest wavelengths in air of the C_2 lines (Table 1) have been derived from recent laboratory results of Chauville, Maillard, and Mantz (1977). The local standard of rest (LSR) radial velocity of the absorbing molecules deduced from the five lines is 6.3 ± 0.8 km s^{-1}, which can be compared with the values near 5.3 km s^{-1} found from radio observations of H_2CO (Sume, Downes, and Wilson 1975) and with the value 5.9 km s^{-1} found for the long carbon-chain molecules in TMC-1 (e.g., Snell *et al.* 1981).

The strongest feature seen in Figure 1, which shows $W_\lambda = 63$ mÅ and lies at a slightly longer wavelength than the $Q(6)$ line, can be identified as the stellar Mn II line at 8769.175 Å, which arises from the transition $3d^5 5s\ ^7S_3$ to $3d^5 5p\ ^7P_3$ (Corliss and Sugar 1977). The width of the stellar line only marginally exceeds those of the essentially instrumentally broadened interstellar lines; therefore, the projected rotational velocity of HD 29647 is $v \sin i \lesssim 7$ km s^{-1}. An upper limit on the strength of the same stellar Mn II line in the spectrum of 20 Tau, a sharp-lined B7 III star, is $W_\lambda \lesssim 10$ mÅ (Hobbs 1979). The unexpectedly great strength of Mn II λ8769 in the spectrum of HD 29647 is explained, however, by the discovery (Straizys *et al.* 1982; Abt 1983) that HD 29647 is a Hg-Mn peculiar star (e.g., Preston 1974; Morgan, Abt, and Tapscott 1978). Straizys *et al.* give an equivalent spectral type of B5 for HD 29647; Dr. Abt has kindly informed us that he finds a spectral type of B7 III-IVp, with abnormally strong lines of Hg and Mn and weak lines of He. If $A_V/E_{B-V} \lesssim 4$ (§ III), then this latter spectral type and the color excess $E_{B-V} = 1.0$ given by Seab, Snow, and Joseph (1981) indeed place HD 29647 at $d \gtrsim 140$ pc (§ I). The heliocentric and LSR radial velocities of HD 29647 derived from the Mn II line in Figure 1 are +18 and +8 km s^{-1} respectively.

Similar observations of ν Cyg and of o And at higher resolution and higher photometric accuracy give the negative result $W_\lambda \leq 1.6$ mÅ (2 σ) for all lines of the (2–0) band toward both stars. This unambiguous result fails to confirm the strong interstellar C_2 lines reported by Cosmovici and Strafella (1981) toward both stars, which would have required ratios $N(C_2)/E(B-V)$ exceeding those observed toward any other star by at least an order of magnitude.

III. DISCUSSION

The observed C_2 population distribution toward HD 29647 is shown in Figure 2 as the ratio of the various column densities relative to that of $J = 2$, *versus* the rotational excitation energy. Thermal population distributions for $T = 10$ and $T = 20$ K appear as straight, dashed lines. The column densities in $J = 0$ and $J = 2$ are characterized by a low excitation temperature, $T_{\rm rot} = 17$ K, but no single temperature describes all of the rotational populations. This rotational temperature is

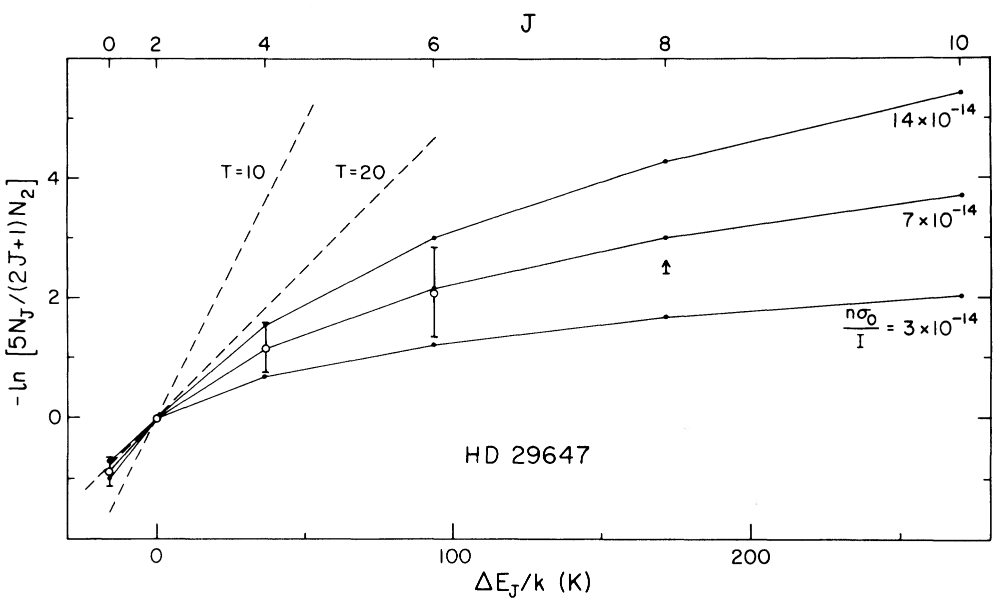

FIG. 2.—The distribution of rotational populations in C_2 toward HD 29647 relative to that of the $J = 2$ level, as a function of rotational excitation energy. Thermal population distributions at $T = 10$ and 20 K are indicated by dashed lines, and theoretical distributions are shown as solid curves for $T = 14$ K and several values of the excitation parameter $\xi = n\sigma_0/I$.

much lower than those found for C_2 in the well-studied clouds toward ζ Oph and ζ Per (Hobbs and Campbell 1982).

Chaffee *et al.* (1980) pointed out that absorption of background starlight by the Phillips system lines can excite C_2 radiatively and lead to nonthermal population distributions. Van Dishoeck and Black (1982) discussed the excitation processes of C_2 in detail and found that the observed population distributions in diffuse clouds could be described well by a combination of radiative excitation and collisional excitation at a kinetic temperature that was generally lower than the rotational excitation temperature. The theoretical analysis provides relative rotational populations for a given kinetic temperature T and excitation parameter $\xi = n_c\sigma_0/I$, where n_c is the density (cm^{-3}) of collision partners in the cloud and I is the scaling factor for the interstellar radiation field as given by van Dishoeck and Black (1982). The collisional cross section, σ_0, is poorly known, but its value has been calibrated with models of diffuse clouds to be $(2 \pm 1) \times 10^{-16}$ cm^2 (van Dishoeck and Black 1982, 1983).

The theoretical treatment has been applied to the present data, with an approximate adjustment by a factor of 1.35 in the scaling of the radiation field to accommodate the new Phillips band oscillator strengths. The best fitting theoretical distribution (Fig. 2) has $T = 14$ K and an excitation parameter $\xi = n_c\sigma_0/I = 7 \times 10^{-14}$ cm^{-1}, which corresponds to $\xi = 1.0 \times 10^{-13}$ cm^{-1} in the tables of van Dishoeck and Black (1982). This theoretical distribution, scaled to the observed value of $N(2)$, is tabulated in the last column of Table 1, where the total column density $N(C_2) = 1.04 \times 10^{14}$ cm^{-2} includes the higher, unobserved levels. If we take $\sigma_0 = 2 \times 10^{-16}$ cm^2 and assume $I = 1$, then $n_c = 350$ cm^{-3} in the cloud toward HD 29647. The 2 σ error limits allow a range of derived parameters, $9 < T < 22$ K and $4 \leq 10^{14}\xi \leq 15$, corresponding to $n_c = 200$–750 cm^{-3} under the above assumptions. The value of T is well constrained and is in harmony with temperatures inferred from radio molecular line observations of the Taurus molecular cloud (Bujarrabal *et al.* 1981). The value of ξ could be better defined by improved measurements of the populations in $J = 4$ and $J = 6$, or by the detection of lines originating from $J > 6$. Recent estimates of the density from radio observations indicate $n_c = (5$–$10) \times 10^4$ cm^{-3} for the dense core TMC-1 (Schloerb, Snell, and Young 1983; Tölle *et al.* 1981) but suggest the presence of a lower density envelope with $n_c \approx 10^3$ cm^{-3} in the foreground (Langer *et al.* 1978; Tölle *et al.* 1981). The density obtained from our C_2 observations 20′ from TMC-1 is in agreement with that of the low-density envelope. Densities higher than 10^4 cm^{-3} would be consistent with the observed C_2 populations only if the near-infrared radiation field were enhanced by a factor $I \gtrsim 20$. HD 29647 itself could account for such an enhancement only if all of the interstellar C_2 were within 0.5 pc of the star, in which case the gas temperature would be expected to be higher as well. Since there is no other indication of a strong infrared source, we consider $I \approx 1$ more likely. In an extensive, independent study of the interstellar matter toward HD 29647, Crutcher (1983) deduces a density $n(H_2) = 800$ cm^{-3} and a temperature $T = 10$ K, which are in agreement with our results here.

It is not certain how much of the dark cloud material is actually in front of HD 29647. The color excess $E(B - V) = 1.0$ is not extraordinarily large, nor are the central depths of the diffuse interstellar bands large for a reddened star;[1] however, the absence of a 2200 Å feature in the ultraviolet extinction curve indicates that the grains in this direction are abnormal (Snow and Seab 1980) and suggests that use of a normal extinction/gas ratio will yield only a lower limit to the total column density of interstellar gas. The detection of the interstellar H_2O ice band in absorption at 3.1 μm (Goebel 1983) suggests that the grains have large mantles and that a large amount of foreground interstellar matter is present. The column density of C_2 toward HD 29647 is about 6 times larger than those observed toward stars with $E(B - V) \approx 0.3$. In four diffuse clouds where both C_2 and H_2 have been observed, the mean relative abundance of C_2 is $N(C_2)/N(H_2) = 4.5 \times 10^{-8}$ (Hobbs 1979, 1981; Chaffee *et al.* 1980; Hobbs and Campbell 1982; van Dishoeck and de Zeeuw 1983), if small theoretical corrections for unobserved levels of C_2 and small adjustments for the new oscillator strengths are included. If we take this ratio as a representative upper limit for the Taurus cloud, then $N(H_2) > 2 \times 10^{21}$ cm^{-2} toward HD 29647. Although some molecules, notably NH_3 and the cyanopolyynes, appear to be highly localized in the dense cores in Taurus (Tölle *et al.* 1981), the fact that C_2 is comparable in abundance to the broadly distributed molecules CH and H_2CO (Hjalmarson *et al.* 1977; Sume, Downes, and Wilson 1975) suggests that HD 29647 does indeed lie behind most, if not all, of the molecular cloud.

We are grateful to Dr. R. L. Kurucz for making available his spectral synthesis of Sirius, which suggested the identification of the Mn II line. This work was supported by the National Aeronautics and Space Administration through grant NGR 14-001-147 (L. M. H.), by the National Science Foundation through grant AST-81-14718 (J. H. B.), and by the Netherlands Organization for the Advancement of Pure Research (ZWO; to E. F. v. D.).

[1]HD 29647 is identified as BD +25°723 in Table 1 of Snow (1973).

REFERENCES

Abt, H. A. 1983, private communication.
Brault, J. W., Delbouille, L., Grevesse, N., Roland, G., Sauval, A. J., and Testerman, L. 1982, *Astr. Ap.*, **108**, 201.
Broten N. W., Oka, T., Avery, L. W., MacLeod, J. M., and Kroto, H. W. 1978, *Ap. J. (Letters)*, **223**, L105.
Buenker, R. J. 1983, private communication.
Bujarrabal, V., Guélin, M., Morris, M., and Thaddeus, P. 1981, *Astr. Ap.*, **99**, 239.
Chaffee, F. H., Jr., Lutz, B. L., Black, J. H., Vanden Bout, P. A., and Snell, R. L. 1980, *Ap. J.*, **236**, 474.
Chauville, J., Maillard, J. P., and Mantz, A. W. 1977, *J. Molec. Spectrosc.*, **68**, 399.
Corliss, C., and Sugar, J. 1977, *J. Phys. Chem. Ref. Data*, **6**, 1253.
Cosmovici, C. B., and Strafella, F. 1981, *Astr. Ap.*, **98**, 408.
Crutcher, R. M. 1980, *Ap. J.*, **239**, 549.
______. 1983, preprint.
Elias, J. H. 1978, *Ap. J.*, **224**, 857.
Erman, P., Lambert, D. L., Larsson, M., and Mannfors, B. 1982, *Ap. J.*, **253**, 983.
Goebel, J. H. 1983, *Ap. J. (Letters)*, **268**, L41.
Hjalmarson, Å., Sume, A., Ellder, J., Rydbeck, O. E. H., Moore, E. L., Huguenin, G. R., Sandqvist, Åa., Lindblad, P. O., and Lindross, P. 1977, *Ap. J. Suppl.*, **35**, 263.
Hobbs, L. M. 1979, *Ap. J. (Letters)*, **232**, L175.
______. 1981, *Ap. J.*, **243**, 485.
Hobbs, L. M., and Campbell, B. 1982, *Ap. J.*, **254**, 108.
Langer, W. D., Wilson, R. W., Henry, P. S., and Guélin, M. 1978, *Ap. J. (Letters)*, **225**, L139.
MacLeod, J. M., Avery, L. W., and Broten, N. W. 1979, *Ap. J.*, **233**, 584.
Morgan, W. W., Abt, H. A., and Tapscott, J. W. 1978, *Revised MK Spectral Atlas for Stars Earlier than the Sun* (Yerkes Observatory, University of Chicago and Kitt Peak National Observatory).
Myers, P. C., Linke, R. A., and Benson, P. J. 1983, *Ap. J.*, **264**, 517.
Pouilly, B., Robbe, J. M., Schamps, J., and Roueff, E. 1983, *J. Phys. B*, **16**, 437.
Preston, G. W. 1974, *Ann. Rev. Astr. Ap.*, **12**, 257.
Schloerb, F. P., Snell, R. L., and Young, J. S. 1983, *Ap. J.*, **267**, 163.
Seab, C. G., Snow, T. P., and Joseph, C. L. 1981, *Ap. J.*, **246**, 788.
Snell, R. L., Schloerb, F. P., Young, J. S., Hjalmarson, Å., and Friberg, P. 1981, *Ap. J.*, **244**, 45.
Snow, T. P., Jr. 1973, *Ap. J.*, **184**, 135.
Snow, T. P., Jr., and Seab, C. G. 1980, *Ap. J. (Letters)*, **242**, L83.
Straizys, V., Glagolevskii, Y. V., Romanyuk, I. I., and Bychkov, V. D. 1982, *Soviet Astr. Letters*, **8**, 96.
Sume, A., Downes, D., and Wilson, T. L. 1975 *Astr. Ap.*, **39**, 435.
Tölle, F., Ungerechts, H., Walmsley, C. M., Winnewisser, G., and Churchwell, E. 1981, *Astr. Ap.*, **95**, 143.
van Dishoeck, E. F. 1983, *Chem. Phys.*, in press.
van Dishoeck, E. F., and Black, J. H. 1982, *Ap. J.*, **258**, 533.
______. 1983, in preparation.
van Dishoeck, E. F., and de Zeeuw, T. 1983, *M.N.R.A.S.*, in press.

JOHN H. BLACK: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

L. M. HOBBS: Yerkes Observatory, University of Chicago, Williams Bay, WI 53191

EWINE F. VAN DISHOECK: Sterrewacht-Huygens Laboratorium, Postbus 9513, 2300 RA Leiden, The Netherlands