ROTATIONAL FINE STRUCTURE LINES OF INTERSTELLAR C_2 TOWARD ζ PERSEI

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ABSTRACT

We have detected 9 of the rotational fine structure lines of the 2-0 Phillips band of interstellar C_2 toward ζ Persei using the Tull spectrograph and Reticon detector on the 2.7 m telescope at the McDonald Observatory. These data yield a total C_2 column density of 1.2×10^{13} cm^{-2} and a rotational temperature of 97 K compared to 1.4×10^{13} cm^{-2} and 45 K predicted by the detailed model of the cloud by Black, Hartquist and Dalgarno. We suggest that radiative pumping through the Mulliken and Phillips systems has modified the C_2 level populations in such a way as to produce an observed rotational temperature which exceeds that arising in pure thermal equilibrium.

I. INTRODUCTION

In their discussion of the formation of interstellar (IS) molecules through gas phase reactions, Dalgarno and Black (1976) showed that C_2 can be produced through the same chain of reactions which produces CH and CH^+--the two most frequently observed IS molecules in the optical window. They suggested that C_2 is produced by the dissociative recombination of C_2H^+ which itself is formed in a series of reactions beginning with C^+ and H_2.

Recently, detailed models have appeared for the diffuse IS clouds toward ζ Oph (Black and Dalgarno 1977) and ζ Per (Black, Hartquist, and Dalgarno 1978, hereafter BHD). BHD predict column densities of many as yet unobserved molecules of which C_2 seemed the most likely to exhibit lines of sufficient strength to be detected with present techniques.

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The IS R(2) and Q(2) lines of the 1-0 Phillips band were first detected by Souza and Lutz (1977) toward VI Cyg No. 12, a star reddened by nearly 10 magnitudes. They suggested that because C_2 and H_2 have a similar molecular structure, the relative strengths of C_2 fine structure lines arising from different J levels can be used to estimate the cloud temperature just as in the case of H_2.

BHD's model predicts that the R(2) and Q(4) lines of the 2-0 Phillips band of C_2 might be of sufficient strength to be detected optically toward ζ Per, and the present observations were undertaken to search for these lines.

II. OBSERVATIONS AND C_2 ROTATIONAL TEMPERATURE AND COLUMN DENSITY

Spectra were obtained with the Tull spectrograph and the direct illuminated Reticon (Vogt, Tull and Kelton 1978) on the McDonald Observatory 2.7 m telescope. A total of 8 hours of integration over two nights were used to produce the final spectrum. The data were smoothed using the Fourier filtering techniques described by Brault and White (1971), and the smoothed data are displayed below the raw data in figure 1. Q(4) has an equivalent width of 1.49 mA and is the strongest feature in the spectrum. We consider R(10) and R(12) only marginally detected, and we have not used them in our analysis. The weakest line we have used is R(8) with an equivalent width of 0.37 mA.

We have adopted the f-values suggested by Roux, Cerny and d'Incan (1976) to calculate the C_2 column density for each line in figure 1. From the relative line strengths we have determined that the C_2 rotational temperature is 97 ± 10 (1σ) K. Using this temperature we have computed the appropriate partition function which allows the total C_2 column density to be calculated from the strength of any line. The 7 C_2 lines in figure 1 yield a mean column density of $N(C_2) = 1.17 \pm .08$ (1σ) x 10^{13} cm^{-2}.

III. IMPLICATIONS OF INTERSTELLAR C_2 OBSERVATIONS

The model of the ζ Per diffuse cloud presented by BHD predicts that if C_2 arises in gas phase reactions it should have a column density of 1.4 x 10^{13} cm^{-2}, a prediction in remarkably good agreement with the observed value. Observations of the rotational line strengths of H_2, on the other hand, are best explained by a two component model of the cloud with most of the molecules confined to a cold core having a kinetic temperature of 45 K. A rotational temperature this low is inconsistent with the C_2 observations, but the rotational and kinetic temperatures will be the same only if inelastic collisions with the abundant species (i.e. H and H_2) dominate the statistical equilibrium of rotational levels. Both spontaneous radiative transitions and absorption and fluorescence in electronic systems can alter the rotational populations and could explain a disparity between the observed rotational temperature and the actual kinetic temperature of the cloud.

A reasonable estimate of the probability of spontaneous radiative transitions between rotational levels of C_2 suggests that inelastic collisions with H and H_2 are almost certainly more rapid than spontaneous radiation even at IS densities and temperatures. Thus such transitions can not produce a rotational temperature which differs from the kinetic temperature of the cloud.

On the other hand, absorption and fluorescence in the Phillips and Mulliken systems can compete with collisions in redistributing rotational populations, and calculating these populations for C_2 resembles the corresponding analysis for H_2 (Black and Dalgarno 1976). 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 through quadrupole rotation-vibration transitions.

We have assumed that the level populations of C_2 are in statistical equilibrium and have considered collisional and radiative transitions in our analysis. Cross sections for rotationally inelastic collisions involving C_2 are unknown and can be only estimated, but the effects of absorption and fluorescence can be calculated explicitly.

The results of such an analysis do not permit the exclusive determination of the characteristics of the radiation field, the number densith of collision partners and the kinetic temperature from observations of C_2 because of our lack of knowledge of the collisional cross sections and of the details of the radiative cascade. However, under reasonable assumptions of these quantities, a reasonable solution of the statistical equilibrium equation can be found in which the rotational populations are characterized by a single rotational temperature which differs significantly from the kinetic temperature because of radiative pumping.

When better molecular data become available, observations of C_2 can be used to extract information about densities, temperatures and radiation fields in IS clouds. Although the C_2 lines observed so far are very 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 the ultraviolet lines of H_2.

This paper was extracted from a much more detailed one which has been submitted for publication to the *Astrophysical Journal*.

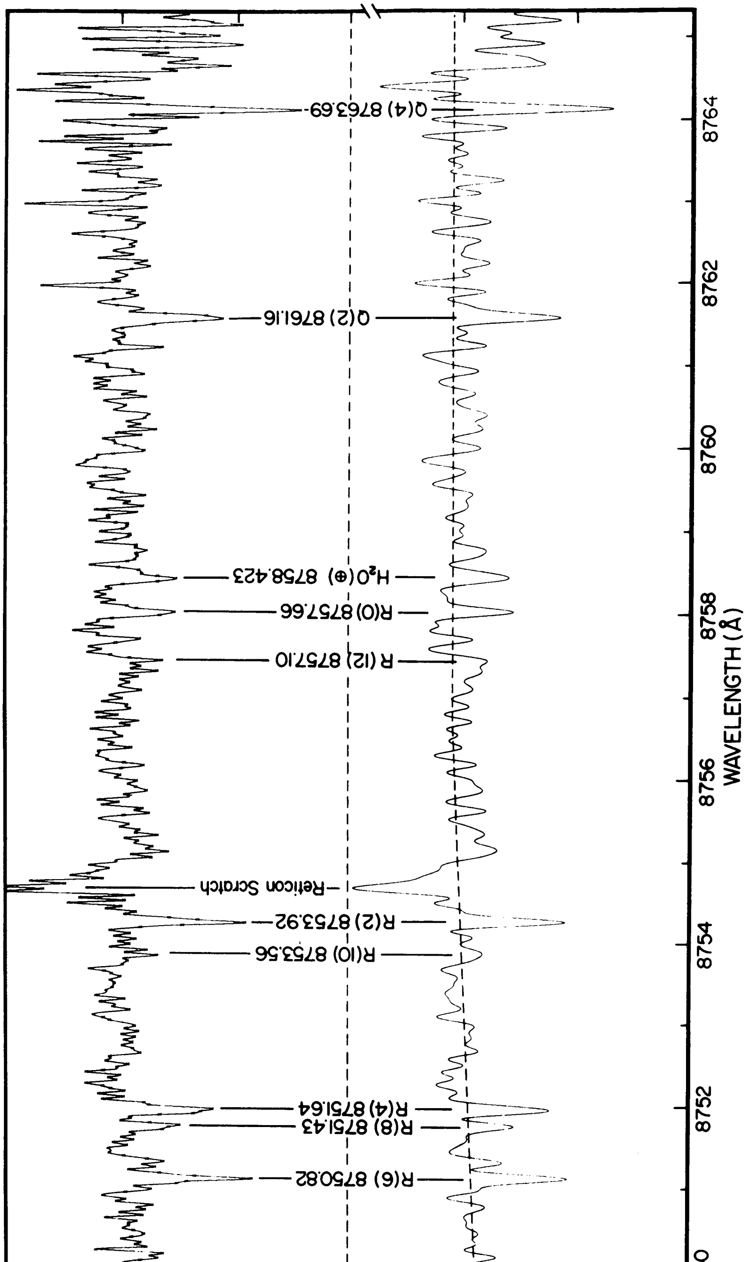

Figure 1. Fine structure lines of the 2-0 Phillips system toward ζ Per: raw data (upper curve) and processed data (lower curve).

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DISCUSSION FOLLOWING CHAFFEE

Thaddeus: Does a plot of log intensity vs rotational energy give a simple linear relationship for your C_2 data, characteristic of thermal equilibrium? If so, it would seem to me that the details of the C_2 collisions with H or H_2 are not an important consideration.

Chaffee: The relationship *is* a simple linear one, but one of the main points of our paper is that it is possible for such a relationship to obtain even when the actual kinetic temperature differs significantly from the measured rotational temperature. In the diffuse cloud toward ζ Persei radiative pumping and collisions are of nearly equal importance in determining the C_2 level populations, and the combined effect still produces a linear relationship for log intensity versus rotational energy. The slope of this relationship gives a temperature that is more than a factor of two higher than the actual kinetic temperature of the cloud.

Carruthers: Have you looked for C_2 towards ζ Ophiuchi?

Chaffee: Yes. The Q(2) line of the 2-0 Phillips band was detected, and reported in Ap.J. 1978, 221, L91. The column density of C_2 is again in good agreement with the Black and Dalgarno model.

Lutz: I want to remark that in addition to this C_2 detection in ζ Per and to Chaffee's and my detection in ζ Oph, Souza and I have confirmed the presence of C_2 in the VI Cyg cloud and, based on six rotational lines, have found an excitation temperature of 45 K. We have also detected C_2 in the ρ Oph cloud - in HD147889 - at a rotational temperature of 60 K. This latter result was based on four lines.