A SEARCH FOR INTERSTELLAR MOLECULES IN THE SPECTRA OF HIGHLY REDDENED STARS*

D. Lien,[1] D. Buhl,[2] R.M. Crutcher,[1] B. Donn,[2]
A.M. Smith,[3] L.E. Snyder,[1] L.J. Stief[2]

ABSTRACT

The dark cloud in the line of sight towards X Persei has been searched for the molecular species OH, CH_2, HCl, CO and C_2 using the IUE satellite. We have detected CO, with a column density of $5 \times 10^{15} cm^{-2}$ and $1 \times 10^{14} cm^{-2}$ for ^{12}CO and ^{13}CO, respectively. We have placed upper limits on the log of the column densities of OH, CH_2 and HCl of 14.0, 12.8, and 12.3, respectively. Radio observations toward X Persei give a factor of 4 greater column density in CO, and a velocity width in the cloud containing the CO of 2 km/s, FWHM. Log N(OH) = 13.8 from radio data, which is consistent with our upper limit. We also have apparently detected the $F^1\pi_u - X^1\Sigma_g^+$ transition of C_2 at 1341Å. The equivalent widths of the C II lines are great enough to place them on the damping portion of the curve of growth. The derived column density of carbon implies a C/H ratio of 2/3 the solar value.

INTRODUCTION

Most molecules of astrophysical interest have electronic transitions in the spectral region covered by the International Ultraviolet Explorer Satellite (IUE). Because of this, we have undertaken the analysis of high dispersion spectra of ten stars embedded in or behind dark interstellar clouds which are known to contain strong lines of CH and CH^+ from optical studies (ref 1). These stars were observed in October, 1978, January, 1979, and March, 1980. The initial data reduction was done using the GSFC PDP 11/40 Forth Reduction System, set up by D. Klinglesmith. From this preliminary overview of all the data, we decided to analyze in detail only one star, and then return to the others. With this in mind, we spent the March 1980 observing run observing the chosen star in order to build up the total signal-to-noise ratio of the stacked data. This star, to which all further discussion is directed, is X Persei (HD 24534).

X Persei is a 6th magnitude O or B emission star. It has recently been identified with the X-ray source 3U 0352 + 30 (ref 2), and has a Vsini of about 500 km/s (ref 3). The broad stellar lines are easily distinguishable from the narrow interstellar lines. There is no indication in any of our data for a stellar wind or super-surface emission features.

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1. Department of Astronomy, University of Illinois

2. Laboratory for Extraterrestrial Physics, GSFC

3. Laboratory for Astronomy and Solar Physics, GSFC

Copernicus observations (ref 2) of the atomic and diatomic hydrogen lines give the total hydrogen column density toward X Persei as 2.4 x 10^{21}cm^{-2}, with a fractional abundance of H_2 of 0.9, and an associated kinetic temperature derived from the first two rotational levels of H_2 of 71°K.

DATA REDUCTION

There are two main problems associated with the identification and subsequent analysis of weak interstellar lines: the noise and the background.

As the system stands, the ITF should remove all systematic tube defects, and hence all remaining noise should be random. Due to Pixel-ITF mismatching and possible time-dependent spots, this is not the case. In order to detect such non-random noise, we have found that sequential observations of the same star in the same camera should be taken with the star positioned at alternate ends of the large aperture for each exposure. This places a given spectral feature at different physical locations on the tube face for each exposure. The plotted results then show a wavelength shift between exposures, whereas any non-random noise feature will appear at the same wavelength. An example of this effect is shown in Figure 1. With this procedure, tube defects cannot be interpreted as weak lines.

When the gross spectrum is divided by the extracted background, a noisy straight line results. This implies that there are data mixed in with the background (e.g. order overlap). To correct for this problem, we assume that the background is of the form $B_T = C + (B_0 - C)f$, where B_0 is the observed background at a given wavelength, B_T is the "true" background at that point, and C and f are empirically derived constants. An example of this is shown in Figure 2, where B_0, B_T and C are shown, and f = 0.6. We chose this value of C because at the edge of the order there are very little data, hence that value of the background probably represents the component due to thermal noise and any reading induced noise. A best-fit value for f is found by varying the value of f and subtracting B_T from the gross spectrum until the equivalent widths of the same line in two different orders are equal. Thus C is a constant for each order, and f is a constant for the spectrum. We find that f = 0.6 reproduces equivalent widths between orders within 5%, and between exposures within 10%.

After the proper background for each spectrum has been subtracted from the gross spectrum for a given order, spectra are stacked after shifting each to the same radial velocity, at the wavelength of interest. All equivalent widths and line profiles are extracted from this stack. For X Persei, there are 6 spectra, shifted and stacked as described above.

RESULTS

Radio observations of the CO 1-0 rotational transition obtained by one of us (RMC) have been analyzed assuming LTE. We find $T_{01} = 5^{\circ}$K, a velocity width of 2 km/s FWHM, and a ^{13}CO column density of 4.2 x 10^{14}cm^{-2}. Assuming a ^{12}CO/^{13}CO ratio of 40 gives the column density of ^{12}CO as 1.8 x 10^{16}cm^{-2}. Subsequent analysis in this section will assume a velocity width of 2 km/s, and a rotation temperature for CO of 5° K. This may not be a valid assumption when comparisons between atomic and molecular column densities are made; however, it is adequate as a first approximation.

We have observed the v" = 0 progression of the Fourth Positive system of CO through v' = 12 for ^{12}CO. Observations of the 1-0 rotational transition and the 2-0 vibrational band of the A-X system are shown in figure 3 for ^{12}CO and ^{13}CO. We have done an initial analysis of the system assuming that only the first four rotational levels are populated, at a rotation temperature of 5°K. For each frequency over the band, we then calculate the optical depth contributed at that frequency by each of the nine transitions from the four levels, assuming that a Voigt profile describes the line. Under these assumptions, we find the column density of ^{12}CO to be about 5 x 10^{15}cm^{-2}, and the column density of ^{13}CO to be about 1 x 10^{14}cm^{-2}. These values compare favorably with the column densities derived from radio observations; reasons for the small differences may be due to the assumption of a thermal population of the rotational levels (which strongly affects the saturation of the UV CO lines), and the larger beamwidth of the radio measurement. It seems reasonable that the cloud is completely in front of the star.

We have made a detailed search for OH (1222Å), HCL (1290Å), and CH_2 (1416Å), and report that none of these molecules were detected above the 5 mÅ level. This puts upper limits on the logarithm of the column densities for these molecules at 14.0 (.004), 12.3 (.16), and 12.8 (.05), respectively. The numbers in parentheses are the oscillator strengths (ref 5,6,7). These limits are derived assuming that the molecular line is optically thin.

One of us (RMC) has detected the 1667 MHz radio OH line toward X Persei. He finds log N(OH)=13.8, which is consistent with our upper limit.

We have apparently detected the $F^1\pi_u - X^1\Sigma^+$ system of C_2 (ref 8), of which we have observed the 0-0 vibrational band at 1341 Å. The D-X system in the ultraviolet has previously been reported (ref 9). Since C_2 does not have a permanent electric dipole moment, transitions between rotational levels are forbidden; hence, there is expected to be a thermal population of the ground state rotational levels. The resultant profile due to the convolution of lines arising from these rotational levels with the response of the IUE spectrograph should show the transition as a broad profile, with a possible separation of the bands. This is about what we observe, as shown in Figure 4. We are in the process of modeling the C_2 line in much the same way as described for the CO lines.

The C II doublet at 1334Å, 1335Å is important not only as an indicator of the total hydrogen density (ref. 4), but also the abundance of this dominant species can provide some information about the composition of the dust. The equivalent widths of the two lines toward X Persei are 267 and 172 mÅ, for the 1334Å and 1335Å lines, respectively. For a velocity parameter, b, of 5 km/s or less, this puts the 1334Å line on the damping part of the curve of growth, thus making it independent of the exact velocity dispersion, providing it is less than about 5 km/s. This implies a column density of C (assuming most carbon is C II) of 5.6 x 10^{17}cm^{-2}. For a total hydrogen column density of 2.4×10^{21}, this implies a C/H ratio of 2.3×10^{-4} or about 2/3 the solar value. Formal errors have not been worked out, but errors in the exact placement on the curve of growth do not change by more than ±.15 in dex. The kinetic temperature based on the relative populations of the fine structure levels of C II is 55°K, which agrees favorably with the kinetic temperature of 71°K derived from the relative populations of the $J = 0$ and $J = 1$ levels of H_2. This implies that collisions dominate the de-excitation of the excited fine structure level of C II, and puts the brunt of the cooling on H_2 and other molecules.

SUMMARY

We have observed a total of ten stars with both the SWP and LWR cameras of the IUE in both high and low dispersion. We have chosen one star, X Persei (HD 24534, 6.0 BE), to analyze in detail.

Our ultraviolet observations of the column densities of CO match those derived from the radio to within a factor of 4, with the difference probably due to the larger beam size of the radio measurement and the assumption of a thermal population in the rotational levels of CO.

We give upper limits to the log column densities for OH, HCl, and CH_2 of 14.0, 12.3 and 12.8, respectively, and report the identification of the $F^1\pi_u - X^1\Sigma_g^+$ system of C_2. We find the carbon abundance to be about solar, with a possible depletion of about a factor of 2. We feel that with the proper precautions concerning both noise and correct background, the IUE can effectively be used for some studies of interstellar molecules.

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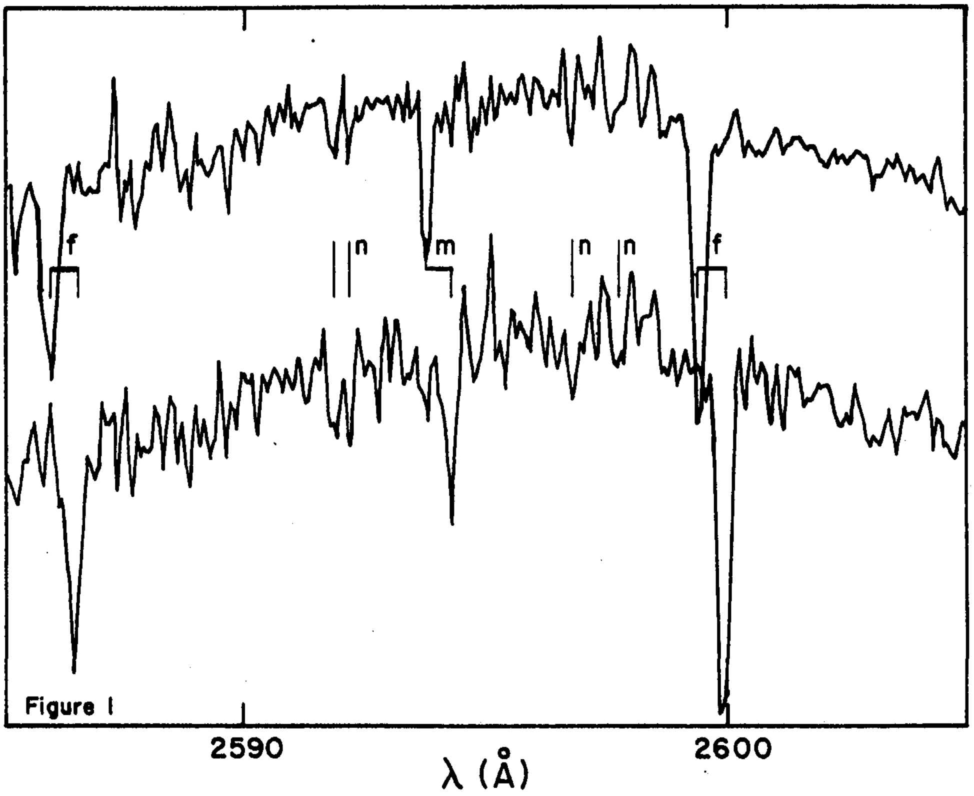


1. During sequential observations of the same star, if the star is shifted in the large aperture, spectral lines shift, but systematic noise does not; f indicates lines due to FeII, m indicates lines due to MnII, and n indicates systematic noise features on the tube.

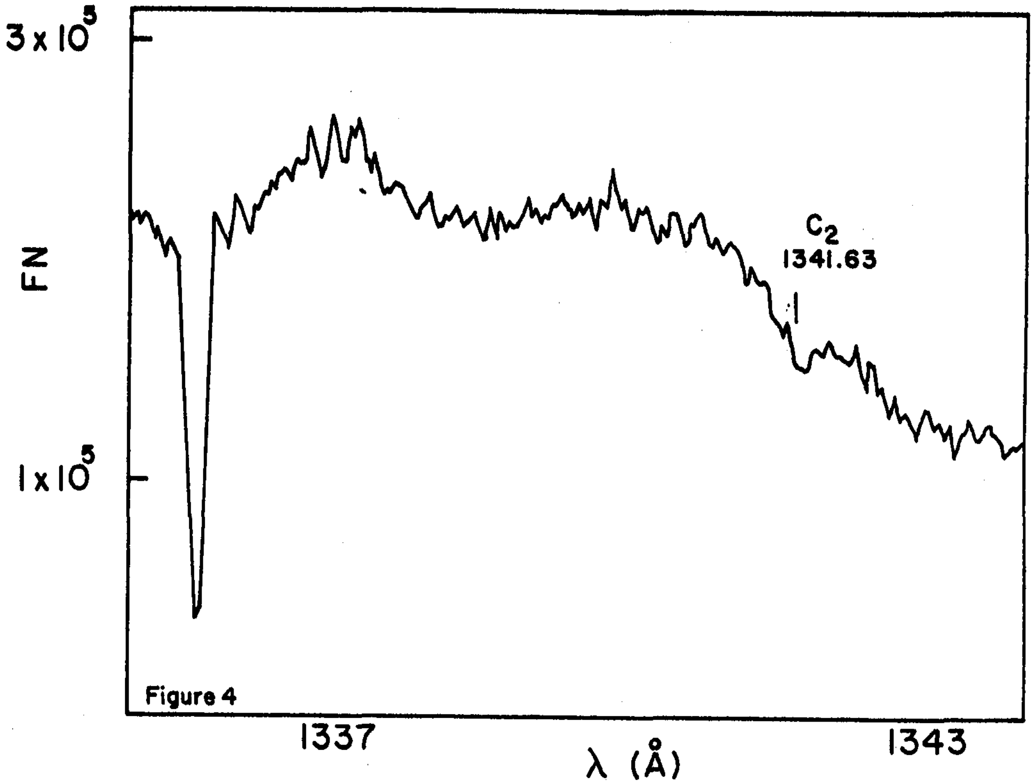
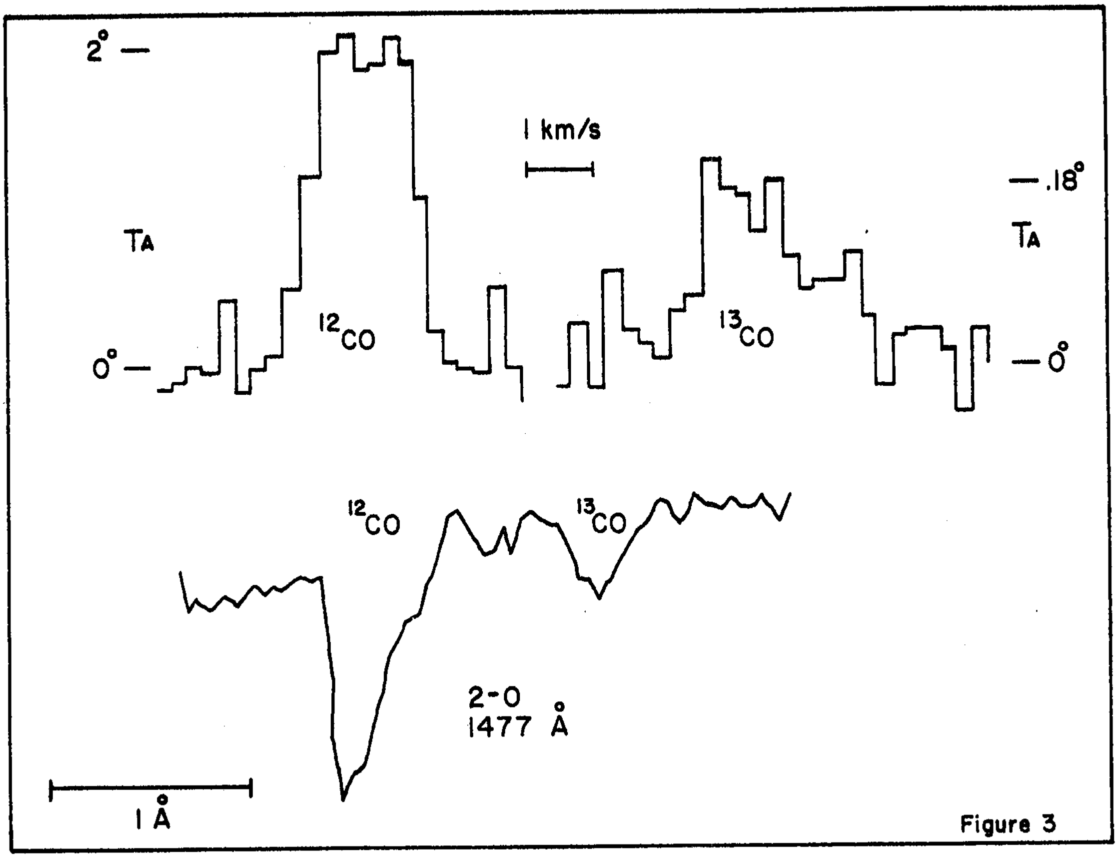
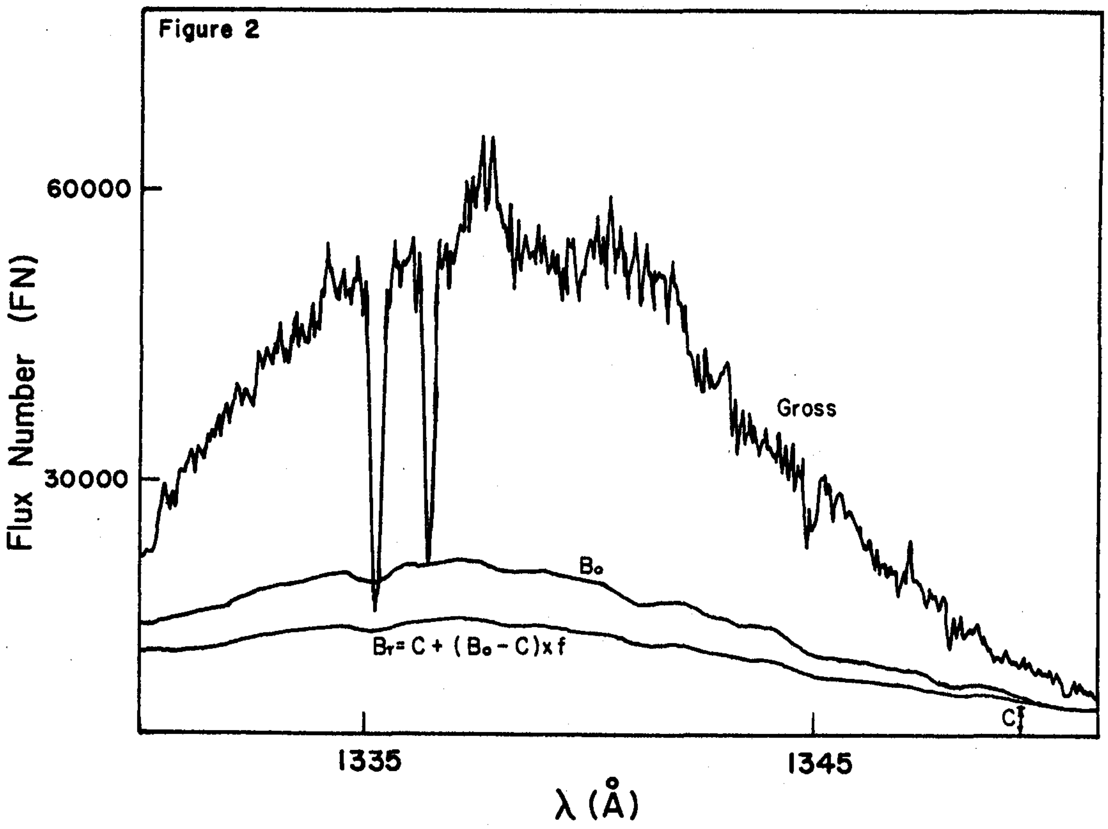


Figure 4

2. An example of the gross spectrum and the background subtraction technique used; B_0 is the IUE extracted spectrum, and B_T is the "true" background, as indicated by the equation. After the computation of B_T, it is smoothed by a median smoothing routine.



3. Radio and optical observations of CO. The radio observations are of the 1-0 rotational transition, and the UV CO are due to the 2-0 vibrational band of the Fourth Positive electronic system.



4. The $F^1\Pi_u - X^1\Sigma_g^+$ system of C_2, showing the 0-0 vibrational band at 1341.63Å (band origin). The strong feature at the left is the 1335Å line of CII which originates from the excited fine structure level of the ion.