

## ETHYLENE IN IRC +10216

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### ABSTRACT

Ethylene has been detected in the circumstellar gas surrounding the supergiant star IRC +10216. Two lines of the  $\nu_7$  vibration-rotation band near 28 THz ( $949\text{ cm}^{-1}$ ) have been seen in absorption at an expansion velocity of  $14\text{ km s}^{-1}$  relative to the central star. The line intensities indicate a rotational temperature of  $T > 400\text{ K}$  and a radial  $\text{C}_2\text{H}_4$  column density of  $10^{16}$  to  $10^{17}\text{ cm}^{-2}$ .

*Subject headings:* stars: circumstellar shells — interstellar: molecules

### I. INTRODUCTION

Ethylene,  $\text{C}_2\text{H}_4$ , is a planar asymmetric-top molecule with a carbon-carbon double bond and is the simplest member of the alkene family of hydrocarbons. Like the other basic hydrocarbons previously detected in IRC +10216—methane,  $\text{CH}_4$  (Hall and Ridgway 1978), and acetylene,  $\text{C}_2\text{H}_2$  (Ridgway *et al.* 1976)—ethylene has no permanent dipole moment and consequently lacks a strong rotational spectrum open to investigation by microwave observations. The intense  $\nu_7$  vibration-rotation band, on the other hand, falls in the infrared around 28 THz ( $949\text{ cm}^{-1}$ ) and is accessible to spectroscopy with  $\text{CO}_2$  and  $\text{N}_2\text{O}$  lasers. (The  $\nu_7$  band is the fundamental out-of-plane bending mode of the molecule about the center of symmetry.) Recently, laboratory spectroscopy with various high-resolution laser techniques has been combined with existing spectroscopic data on ethylene to generate a complete set of molecular constants for the  $\nu_7$  band (Lambeau *et al.* 1980), so that an astronomical search for individual lines of ethylene is at last possible. This *Letter* reports the initial detection of two of these lines in the circumstellar envelope of IRC +10216. Heretofore, the only nonlinear molecules seen in this source were the saturated-bond species: methane (Hall and Ridgway 1978) and ammonia (Betz, McLaren, and Spears 1979).

### II. OBSERVATIONS

The observations were conducted in 1980 June with the 1.5 m McMath Solar Telescope of Kitt Peak National Observatory.<sup>1</sup> At a frequency of 28 THz, the diffraction-limited beamwidth of this telescope is  $\sim 1.7''$ . The heterodyne receiver uses a HgCdTe photodiode mixer, laser local oscillator, and a bank of sixty-four 20 MHz filters to achieve  $\sim 0.2\text{ km s}^{-1}$  velocity resolution over a  $14\text{ km s}^{-1}$  interval (Betz 1980).

Because the laser oscillates on only discrete rotation-vibration transitions and because only a limited intermediate frequency bandwidth of 2000 MHz is available from the photomixer, only Doppler-shifted transitions

of ethylene in fairly close coincidence with available  $\text{CO}_2$  and  $\text{N}_2\text{O}$  laser lines may be observed. For this initial search, only those transitions in coincidence with  $^{14}\text{N}_2\text{O}$  (rather than  $^{12}\text{CO}_2$ ) laser lines were chosen because of the more favorable atmospheric transmission around the  $\text{N}_2\text{O}$  laser frequencies. (In mid-June, IRC +10216 was already approaching two air masses in the western sky at sunset.) Table 1 lists the three lines selected for observation. Original identifications for the  $5_{15} \leftarrow 5_{05}$  and  $8_{08} \leftarrow 8_{18}$  rest frequencies came from the listing of Lambeau *et al.* (1980), while the  $1_{10} \leftarrow 0_{00}$  line was given by Johansen (1973). The  $1_{10} \leftarrow 0_{00}$  and  $8_{08} \leftarrow 8_{18}$  line frequencies were subsequently remeasured with the heterodyne spectrometer to 5 MHz absolute accuracy so as to achieve  $0.05\text{ km s}^{-1}$  accuracy on the LSR velocity scale. The  $5_{15} \leftarrow 5_{05}$  line, on the other hand, lies so close to the  $\text{N}_2\text{O-R}(15)$  laser frequency that its laboratory absorption profile falls into both infrared sidebands of the double-sideband receiver, and difficulties are encountered in locating the true center of the line. Fortunately, this particular transition was measured by the direct laser absorption technique of Lambeau *et al.* (1980) to about 9 MHz accuracy, and so their line frequency is used in Table 1.

Figure 1 shows the observed spectra for the  $1_{10} \leftarrow 0_{00}$  and  $5_{15} \leftarrow 5_{05}$  lines in IRC +10216. The two profiles show the outflowing gas to be in absorption in the line of sight to the central star. Unfortunately, at this time, observations of the  $8_{08} \leftarrow 8_{18}$  line were only possible over the nonoptimum LSR velocity range of  $-43$  to  $-29\text{ km s}^{-1}$ , but they did reveal a slope in the continuum similar to that seen in the  $5_{15} \leftarrow 5_{05}$  line over this same velocity range. However, since lunar observations over this frequency interval showed a similar, but reduced slope, about  $\frac{1}{3}$  as strong from terrestrial atmospheric absorption, a confident claim of detection for the  $8_{08} \leftarrow 8_{18}$  line is not possible, especially without an established continuum level at low (negative) velocities. On the other hand, for the  $1_{10} \leftarrow 0_{00}$  and  $5_{15} \leftarrow 5_{05}$  lines, lunar spectra taken immediately after the stellar observations and also at similar air masses showed less than  $\frac{1}{5}$  of 1% slope over the entire frequency interval, and no other terrestrial features to within the noise

<sup>1</sup> Kitt Peak National Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1  
ETHYLENE LINE FREQUENCIES

C <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> O	C <sub>2</sub> H <sub>4</sub> -N <sub>2</sub> O (MHz)	C <sub>2</sub> H <sub>4</sub> (MHz)
1 <sub>10</sub> ← 0 <sub>00</sub> . . . . .	R(19)	-1028 ± 5	28,623,918 ± 5
5 <sub>15</sub> ← 5 <sub>05</sub> . . . . .	R(15)	-45 ± 9	28,532,442 ± 9
8 <sub>08</sub> ← 8 <sub>18</sub> . . . . .	R(09)	+569 ± 5	28,391,253 ± 5

NOTE.—The 5<sub>15</sub> ← 5<sub>05</sub> line frequency is from Lambeau *et al.* 1980, whereas the 1<sub>10</sub> ← 0<sub>00</sub> and 8<sub>08</sub> ← 8<sub>18</sub> frequencies were measured in this work. Absolute frequencies of the N<sub>2</sub>O laser transitions are given by Whitford *et al.* 1975.

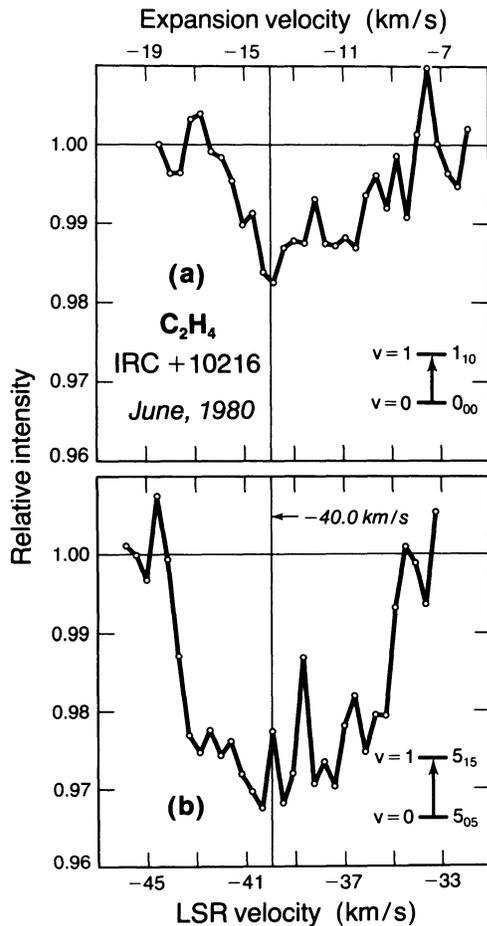


FIG. 1.—Observed profiles in IRC +10216 for the (a) 1<sub>10</sub> ← 0<sub>00</sub> and (b) 5<sub>15</sub> ← 5<sub>05</sub> transitions of C<sub>2</sub>H<sub>4</sub> in the ν<sub>7</sub> band. Adjacent filter bank channels have been averaged to yield 0.42 km s<sup>-1</sup> resolution in the plotted spectra. Intensities are expressed relative to the SSB continuum level. In each spectrum, statistical uncertainties of 2 standard deviations are equivalent to the peak-to-peak fluctuation seen in the five leftmost resolution elements. The integration time for the 1<sub>10</sub> ← 0<sub>00</sub> line was 176 minutes total over 2 nights, and for the 5<sub>15</sub> ← 5<sub>05</sub> line, 88 minutes total over 2 nights. The vertical line at -40 km s<sup>-1</sup> marks the velocity of peak absorption for NH<sub>3</sub> lines seen in this source (Betz and McLaren 1980). LSR velocities may be converted to heliocentric values by the relation  $V_H = V_{LSR} + 7.12 \text{ km s}^{-1}$ .

level. After the atmospherically induced slopes were removed from the stellar data, only residual linear slopes of  $< \frac{1}{4}$  of 1% remained, presumably because of slow intensity changes in the source continuum level. These small residual slopes have also been removed from the presented data. Other observational precautions necessary to confirm the reality of spectral features detected with this instrument are described in a previous publication (Betz, McLaren, and Spears 1979).

### III. ANALYSIS

Since the 1<sub>10</sub> ← 0<sub>00</sub> and 5<sub>15</sub> ← 5<sub>05</sub> transitions are likely to be optically thin, the observed intensity ratio sets a lower bound on the rotational temperature of  $T > 400$  K. A definite upper limit cannot be derived from the available data. Even at  $T = \infty$ , the limit of the 5<sub>15</sub> ← 5<sub>05</sub> to 1<sub>10</sub> ← 0<sub>00</sub> intensity ratio is only 2.6, as given by the ratio of the squares of the transition matrix elements and the total statistical weights for the two respective lower levels. [In addition to the normal degeneracy factor of  $(2J + 1)$  for each rotational level, ethylene has a nuclear spin degeneracy factor contributed by the four hydrogen nuclei, which gives an additional statistical weight of seven to rotational levels with both  $K_a$  and  $K_c$  even and a weight of three to all others.] For  $T = 400$  K, the intensity of the 8<sub>08</sub> ← 8<sub>18</sub> line should be 40% stronger than that of 5<sub>15</sub> ← 5<sub>05</sub>, which is qualitatively consistent with the strong slope seen near the 8<sub>08</sub> ← 8<sub>18</sub> frequency. Rotational temperatures of 400–700 K have been found in similar observations of infrared ammonia lines in this source (Betz and McLaren 1980). Ethylene is unlike ammonia, however, in that it has no permanent dipole moment and hence no permitted radiative transitions between rotational levels in the same vibrational state. Consequently, its rotational and kinetic temperatures are likely to remain in equilibrium throughout the entire circumstellar envelope. In addition, since ethylene is an asymmetric rotor and has a large number of nondegenerate energy levels available for excitation, it is less likely to be optically thick in a given line than any other molecule yet detected in the infrared. Therefore in future observations ethylene should be the best probe of the circumstellar temperature structure, especially in the inner envelope where the lines are more readily detected.

The high rotational temperature for ethylene, as well as for all other molecules detected in the infrared, indicates that most of the observed gas lies within the inner 2" of the circumstellar envelope. Similar to what is seen for ammonia, most of the observed ethylene is already accelerated to a terminal velocity of 14 km s<sup>-1</sup> relative to the central star. The broader profile for the higher excitation 5<sub>15</sub> ← 5<sub>05</sub> line suggests a possibly higher degree of turbulence in the inner part of the envelope. A similar condition is seen in ammonia, where absorption in the higher- $J$  lines extends from -44 to -35 km s<sup>-1</sup> (A. L. Betz *et al.*, unpublished).

The equivalent width of the 5<sub>15</sub> ← 5<sub>05</sub> line is  $6.9 \times 10^{-4} \text{ cm}^{-1}$ , and that of the 1<sub>10</sub> ← 0<sub>00</sub> line is  $2.5 \times 10^{-4}$

$\text{cm}^{-1}$ . With the  $\nu_7$  band strength of  $330 \text{ cm}^{-2} \text{ atm}^{-1}$ , taken from Komornicki and McIver (1979) based on the interpretation of Jalsovszky and Pulay (1975) of the original data of Golike *et al.* (1956), the column density of ethylene is calculated to be  $1.3 \times 10^{14} \text{ cm}^{-2}$  in just the observed lower levels. This lower bound can be compared with a reasonable total value based on the simplifying assumption that, on the average, all gas is in LTE at 500 K. Under such a condition, the total column density is  $\sim 10^{16} \text{ cm}^{-2}$ . This estimate can probably be increased by as much as an order of magnitude to  $\sim 10^{17} \text{ cm}^{-2}$  to allow for continuum radiation from intervening hot dust which obscures the true depths of the lines, as has been noted in the case of ammonia (Betz, McLaren, and Spears 1979). Since our recent observations (unpublished) of nonmetastable ammonia lines confirm that the  $\text{H}_2$  column density is  $\sim 10^{24} \text{ cm}^{-2}$ , the fractional abundance of ethylene is  $\sim 10^{-7}$ . This value is in good agreement with the theoretical estimate of Tsuji (1964) for the photospheric abundance of ethylene in a 1100 K carbon-rich supergiant. The theoretical prediction, however, is in agreement only if no

significant amount of carbon is lost to the formation of graphite grains. (Whether graphite is actually the dominant condensate in IRC +10216 has recently been discussed by Lewis and Ney 1979.) For the most part it appears that ethylene is like other simple hydrocarbons (Hall and Ridgway 1978), but unlike ammonia (Betz and McLaren 1980), in that its fractional circumstellar abundance is close to the predicted photospheric value. This fact is significant in evaluating "freeze-out" models which seek to explain the abundance of circumstellar molecules (McCabe, Smith, and Clegg 1979). Additional observations of a greater number of lines with a wider velocity coverage will no doubt provide more definitive insights into the conditions under which ethylene forms.

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