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OBSERVATIONS OF CARBON MONOXIDE AT 4.7 MICRONS IN IRC+10216, VY CANIS MAJORIS, AND NML CYGNI*

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ABSTRACT

Individual vibration-rotation lines of $^{12}C^{16}O$ and $^{13}C^{16}O$ have been observed in IRC+10216, VY CMa, and NML Cyg, near 4.7 μ. The lines of CO seen in IRC+10216 are heavily saturated, yet quite narrow. Their widths, excitations, and radial velocity indicate physical association with the 2″ diameter component of IRC+10216 known from lunar occultation measurements. The CO lines seen in VY CMa and NML Cyg correspond well to the more blueshifted of the emission features seen in OH, and must be associated with expanding circumstellar clouds.

Subject headings: circumstellar shells — infrared sources — molecules — spectra, infrared

I. INTRODUCTION

Observations of selected lines of the fundamental vibration-rotation band of carbon monoxide at 4.7 μ have been made for the three bright infrared objects IRC+10216, VY Canis Majoris, and NML Cygni. The spectra were obtained at various times during 1972, using the coudé focus of the Lick Observatory 120-inch (305-cm) telescope and a tandem scanning Fabry-Perot interferometer. The infrared spectrometer has been described previously (Holtz 1971). For the present observations a beam size of 3″ and spectral resolution of 0.15 cm^{-1} were used. This is the first time that these infrared objects, which are the three brightest ones accessible to northern-hemisphere telescopes, have been examined in the 5-μ region with a resolution high enough to resolve typical molecular rotational structure.

Our observations of IRC+10216 are more complete and of better quality than those of the other two objects. Consequently, most of the discussion below is concerned with IRC+10216.

II. IRC+10216

The infrared object IRC+10216 (Becklin *et al.* 1969) is known from lunar occultation measurements (Toombs *et al.* 1972) to consist of two components: a 650° K optically thick object of characteristic diameter 0″.4 and an optically thin object of characteristic diameter 2″ whose color temperature is approximately 400° K in the 5–20 μ region. The smaller object is the source of about 80 percent of the continuum radiation near 5 μ. The central star is barely visible; Herbig and Zappala (1971) have classified it as a late-type carbon star. In addition, emission lines of CO, CN, CS, and HCN have been detected in the millimeter region by a number of observers (Wilson *et al.* 1971), (Morris *et al.* 1971). Wilson, Schwartz, and Epstein (1973) have measured

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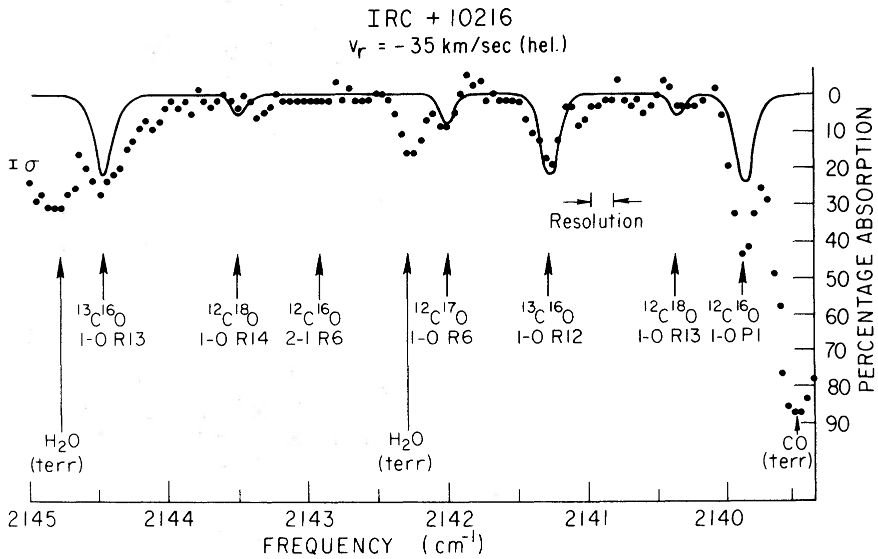

FIG. 1.—Infrared spectrum of IRC+10216 near 2142 cm^{-1}. *Dots*, observed spectra; σ is the probable error for a single data point. The solid line is a synthetic spectrum computed using the values for the parameters listed in table 1. The positions of terrestrial lines and possibly detectable lines in IRC+10216 are indicated by arrows.

the size of the $^{12}C^{16}O$ line-emitting region to be at least 2′ in diameter. The observed millimeter lines are 30 km s^{-1} broad, and indicate a cloud expanding about the star at 15 km s^{-1}. Both $^{12}C^{16}O$ and $^{13}C^{16}O$ have been detected; the antenna temperatures yield an isotopic ratio $^{12}C/^{13}C$ of no less than 8 (Wilson *et al.* 1971).

We have observed IRC+10216 in several frequency intervals near the vibration-rotation band center of $^{12}C^{16}O$. Figures 1 and 2 show spectra in intervals centered at 2142 cm^{-1} and 2174 cm^{-1}. An absorption scale, instrumental resolution, and rms noise for a single data point are given for each spectrum. Arrows indicate the positions

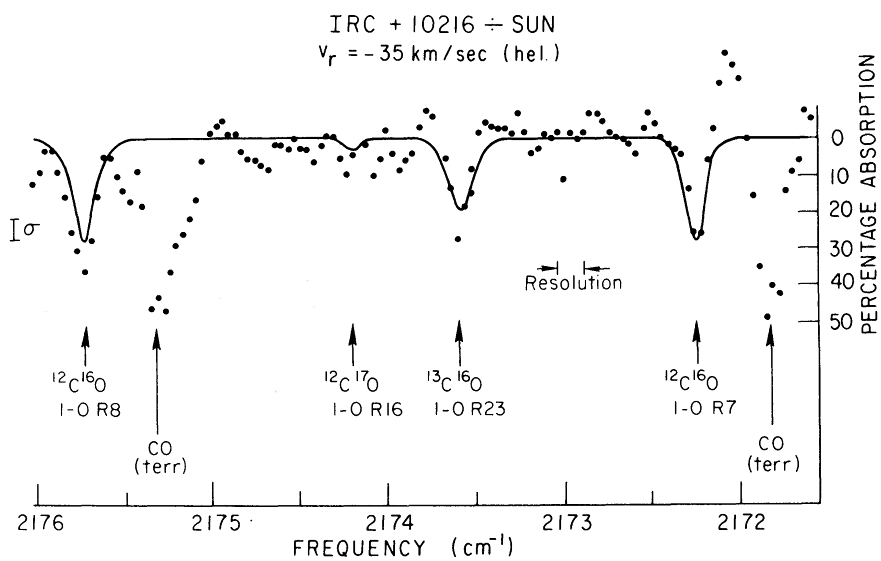

FIG. 2.—Infrared spectrum of IRC+10216 near 2174 cm^{-1}. The stellar spectrum is divided by a solar spectrum in order to remove a number of weak terrestrial lines.

of terrestrial lines and positions of CO lines in IRC+10216 for a heliocentric radial velocity of -35 km s^{-1}. The solid lines represent computer-generated synthetic spectra whose parameters, shown in table 1, have been chosen to fit the data.

In these two frequency intervals, every transition of $^{12}C^{16}O$ and $^{13}C^{16}O$ from the ground vibrational state is present in IRC+10216. No lines from excited vibrational states have been observed. The 1–0 *R*23 transition of $^{13}C^{16}O$ shown in figure 2 is the highest rotational transition of these two isotopic species for which we have searched. Lines of $^{12}C^{18}O$ have not been detected in the object. The 1–0 *R*6 line of $^{12}C^{17}O$ at 2142.0 cm^{-1} appears to be present in figure 1. However, we regard the detection of $^{12}C^{17}O$ in IRC+10216 as tentative, because the absorption in this line is only about three times the mean fluctuation and is located on the edge of a terrestrial H_2O absorption. No other lines of $^{12}C^{17}O$ have been detected, but this is consistent with the apparent strength of the 1–0 *R*6 line.

These spectra of IRC+10216 have several remarkable features. All detected lines appear no broader than the instrumental resolution of 0.15 cm^{-1} (20 km s^{-1}). Hence, the actual absorptions in the object must be less than half as broad and more than twice as deep as shown in our spectra. Also, all detected lines of $^{12}C^{16}O$ and $^{13}C^{16}O$ are the same strength to within observational error. In particular, the *R*23 line of $^{13}C^{16}O$ is as strong as the *R*7 line of $^{12}C^{16}O$. The isotopic ratio $^{12}C/^{13}C$ is probably 8 or greater, and at temperatures of 650° or less the $J = 7$ level is 3 or more times as populated as the $J = 23$ level. Thus the line-center optical depth of this $^{12}C^{16}O$ line must be at least 25 times that of the $^{13}C^{16}O$ line. Since the equivalent widths of both lines are the same, the $^{13}C^{16}O$ line itself must be heavily saturated.

A third interesting feature of the infrared CO absorption lines is their radial velocity. Figure 3 shows the radial velocity profile of the $^{12}C^{16}O$ 2.6-mm line (Wilson *et al.* 1971), with the positions of the stellar spectral features (Herbig and Zappala 1971) and the CO infrared absorptions indicated by arrows. The CO infrared absorption lines are blueshifted by 20 km s^{-1} with respect to the central star, and lie well outside of the half-power frequency of the millimeter emission line. We conclude that the carbon monoxide which we observe is in a small section of an expanding shell in front of the 0".4 diameter continuum source.

It is natural to attempt to associate the CO responsible for the 4.7-μ absorption lines with one of the observed physical components of IRC+10216. Because of the strength of the 1–0 *R*23 line of $^{13}C^{16}O$, it is unlikely that the CO observed at 4.7 μ is in the extended and presumably cold envelope producing the CO millimeter emission line. Also, it seems unlikely that the CO is associated with the 0".4 diameter continuum source, because geometric projection effects would produce an absorption line of width comparable to the expansion velocity, and appreciably broader than we observe. Hence, it appears that the CO is associated with the 2" diameter, 400° K component, which must be expanding about the central star at 20 km s^{-1}.

Synthetic spectra, such as shown in figures 1 and 2, were generated using the model

TABLE 1

PARAMETERS FOR SIMULATION OF OBSERVED IRC+10216 SPECTRA

Assumed T_{eff} (° K)....	650
T_R (° K).............	400
T_V (° K).............	< 300
$N(^{12}C^{16}O)$ (cm^{-2}).....	$10^{19.7}$
σ (cm^{-1})............	0.0063
$^{12}C/^{13}C$.............	8
$^{16}O/^{18}O$.............	> 1000
$^{16}O/^{17}O$.............	≥ 1000

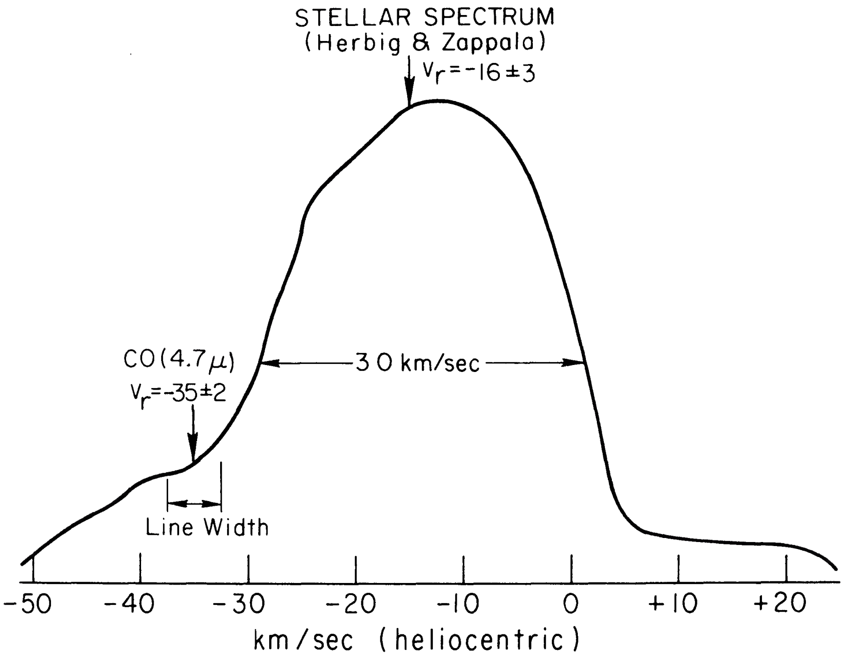

FIG. 3.—Profile of the 2.6-mm CO emission from IRC+10216 (Wilson *et al.* 1971). Arrows indicate positions in radial velocity of spectral features in the central star (Herbig and Zappala 1971) and of the CO absorbing at 4.7 μ. The width of a typical strongly saturated CO 4.7-μ absorption line is also shown.

of a 650° K background source, a spherically symmetric isothermal absorbing layer corresponding to the 2″ diameter shell, and a Doppler-broadened line profile convolved with the instrumental resolution (for a more complete discussion see Geballe, Wollman, and Rank 1972). A set of parameters which fit the data acceptably is shown in table 1. Note that the CO vibrational temperature, T_v, had to be set lower than 300° K, in order to suppress excited vibrational-state absorptions as well as P Cygni line profiles caused by redshifted emission from the large fraction of the 2″ shell which is not directly in front of the 0″.4 diameter continuum source. With T_v substantially lower than 650° K, the model produces lines of $^{12}C^{16}O$ and $^{13}C^{16}O$ out of the ground vibrational state which are totally opaque, and whose equivalent widths are sensitively dependent upon the value of the Doppler line-width parameter, σ. The value of σ deduced and listed in table 1 corresponds to a velocity half-width of only ± 1 km s^{-1} for an unsaturated line. It is somewhat unrealistic to use a pure Gaussian line shape for absorption in an expanding circumstellar shell; using it probably leads to an overestimate of the column density of $^{12}C^{16}O$. On the other hand, if the lower limit of 8 for the ratio $^{12}C/^{13}C$ (Wilson *et al.* 1971) is used, the value of $N(^{12}C^{16}O)$ in table 1 is the smallest one which produces a $^{13}C^{16}O$ 1–0 $R23$ line consistent with our observation. The column density and line-width parameter in table 1 produce line-center optical depths of ~ 1000 in the strongest 1–0 lines of $^{12}C^{16}O$. Yet, from the equal absorptions of the 1–0 lines of $^{12}C^{16}O$ and $^{13}C^{16}O$ all of the CO in the shell must be within a velocity range of only 5 km s^{-1}. In view of the velocity of expansion of 20 km s^{-1}, this uniformity of velocity is remarkable.

We adopt the distance estimate (Herbig and Zappala 1971) of 290 pc to IRC+10216. Our measured expansion velocity of 20 km s^{-1} for the 2″ shell implies that the age of that shell is ~ 20 years. The age of the extended envelope responsible for CO millimeter-line emission is about 1.5×10^3 years, if the envelope has a present diameter of 2′ and a constant expansion velocity of 15 km s^{-1}. It is unlikely that the central 0″.4 diameter object is expanding at such a high velocity. For it to do so implies an age of only ~5 years, which would be surprising since the only substantial variations in intensity from IRC+10216 which have been reported are periodic ones at 2.2 μ (Becklin *et al.* 1969).

Assuming [CO]/[H] is 10^{-4} in the 2″ shell, the column density in table 1 implies a shell mass of 5×10^{-3} $M_\odot$. If the thickness of the shell is one-tenth of its radius, we obtain $n_{H_2} = 2.5 \times 10^9$ cm^{-3}. Under these conditions the H_2 is in thermal equilibrium with the dust in the shell, which has a temperature of ~400° K. These temperatures and densities are sufficient to allow the CO to attain rotational thermal equilibrium, but not vibrational thermal equilibrium. Our upper limit for the vibrational temperature in table 1 is consistent with these physical conditions in the shell, and agrees with the absence of the P Cygni emission bump which we would observe if the vibrational temperature of the CO in the 2″ shell were greater than 300° K. One still might expect to observe P Cygni line profiles due to reemission from vibrationally excited CO molecules before they can be collisionally de-excited. However, the lunar occultation measurements (Toombs *et al.* 1971) yield a continuum optical depth in the 2″ diameter shell of ~0.2 at 4.8 μ. Resonant trapping of reemission from strong lines of CO increases the effective optical depth of the shell sufficiently to thermalize the scattered line radiation to the shell temperature, and hence to suppress line emission. This process may also significantly affect the shapes of CO absorption lines.

The extended envelope of CO millimeter emission will produce absorption in addition to that from the 2″ diameter shell for ground vibrational-state transitions of low rotational excitation (such as the $^{12}C^{16}O$ 1–0 *P*1 transition). We do not observe any effects of such an additional absorption. Our observation is consistent with the measured antenna temperature of the $^{12}C^{16}O$ 2.6-mm line (Wilson *et al.* 1971) if the CO millimeter-line emitting region has a characteristic diameter no smaller than 1′. This limit is in agreement with the estimated diameter for the region of at least 2′ (Wilson *et al.* 1973).

III. VY CANIS MAJORIS AND NML CYGNI

These two interesting objects are strikingly similar in all but their visible properties, NML Cyg being much more heavily obscured. In the infrared neither object can be described by a single temperature (Stein *et al.* 1969; Gillett, Stein, and Solomon 1970). Both objects exhibit several heads of the overtone vibration-rotation band of CO at 2.3 μ (Johnson 1968), (Hyland *et al.* 1969) which must originate in the atmosphere of the central star at a temperature of about 2500° K. The objects have similar OH radio emission profiles (Wilson, Barrett, and Moran 1970) with one component centered at the stellar radial velocity and the other component at a radial velocity 40 km s^{-1} to the blue.

The absence of absorption from highly excited states of CO, as well as the radial velocities of the detected low-excitation transitions, clearly indicate that the observed 4.7-μ absorption lines do not originate in the atmospheres of the central stars of these two objects. Spectra of VY CMa show no CO absorptions from higher than the first excited vibrational level, and imply a CO vibrational temperature of less than ~1000° K. Observations of NML Cyg reveal only ground vibrational-state $^{12}C^{16}O$ and $^{13}C^{16}O$ absorptions, and imply a vibrational temperature of less than ~800° K. More data are needed to determine the temperatures of the absorbing CO, line widths, and isotopic ratios in these objects.

The positions of the CO absorption lines correspond to heliocentric radial velocities of -43 ± 3 km s^{-1} in NML Cyg and $+20 \pm 2$ km s^{-1} in VY CMa. The former corresponds well to the more blueshifted component of OH; the latter value is on the low-frequency edge of the blueshifted component of OH. The radial velocities as well as the low excitation of the CO suggest physical association of the CO with the rapidly expanding clouds responsible for the blueshifted OH emission in these two objects.

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