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CO OBSERVATIONS OF MASS OUTFLOW FROM THE INFRARED STAR CIT 6

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ABSTRACT

We present observations of CO emission from the molecular envelope surrounding the carbon star CIT 6 (IRC +30219) made at five epochs spanning 17 months. There is no evidence for any variation in the CO line intensity on this time scale, but the intensity is much lower than that reported by previous authors. In addition, we were unable to confirm an earlier report of ^{13}CO line emission, and we measure the carbon isotope ratio ^{12}C/^{13}C to be greater than 20. The shape of the CO emission line observed at all epochs can be fitted by a uniformly expanding cloud model in which the CO is optically thin except through the longest lines of sight.

Subject headings: stars: carbon — stars: circumstellar shells — stars: mass loss

I. INTRODUCTION

Thermal emission in millimeter-wave molecular lines has provided a powerful observational tool for the study of the expanding molecular envelopes around late-type red giant stars and long-period variables evolving toward the planetary nebula stage. The molecules of primary interest are CO (e.g., Zuckerman *et al.* 1978) and SiO (Morris *et al.* 1978), but others such as HCN, HC$_3$N, SiS, and CN have also been detected in several stars. Information about elemental and isotopic abundances, excitation, mass-loss rates, and evolutionary status of the circumstellar envelopes can be obtained from these observations.

The shapes of the lines observed from these stars are typically parabolic (for optically thick lines) or rectangular (for optically thin lines) as expected for a uniformly expanding sphere of gas (Morris 1975). An exception to this is provided by the observations of Mufson and Liszt (1975, hereafter ML) of double-peaked profiles in both the ^{12}CO (hereafter CO) and ^{13}CO lines from the infrared star CIT 6 (also known as GL 1403, IRC +30219), for which CO and HCN emission were discovered by Wilson, Schwartz, and Epstein (1973, hereafter WSE). ML concluded that these double-peaked profiles were most likely the result of mass ejected from the star in a rotating disk.

In the course of other investigations, we have made several observations of the CO emission from CIT 6 using the NRAO 11 m telescope. Our results show that the CO emission line is considerably weaker than reported both by ML and by WSE; further, we were unable to detect ^{13}CO emission from the star. In addition, our CO line profiles do not show double-peaked structure, but rather are flat-topped parabolas.

The purpose of this paper is to rediscuss the envelope of CIT 6 and to show that the mass-loss mechanism for this star is probably like that of similar late-type giant stars. In the following, we describe the observations (§ II), consider the shape of the CO line and the CO abundance in the molecular envelope (§ III), and discuss the possible variability of CIT 6 (§ IV). The summary and conclusions are presented in § V.

II. OBSERVATIONS

The observations were made in five periods between 1976 December and 1978 May with the 11 m telescope of the National Radio Astronomy Observatory[1] at Kitt Peak, Arizona, equipped with a cooled, single-polarization Cassegrain receiver, whose system temperature was ~700 K.

The telescope half-power beamwidth (HPBW) at the CO frequencies was ~65″, and the pointing was checked by observations of planets to be accurate to about 10″. The observations were all made in the position-switching mode, with the OFF position displaced from the source by typically 10′–30′. The CO and ^{13}CO lines at 115.3 and 110.2 GHz, respectively, were observed with filter banks giving resolutions of 0.1 MHz (~0.26 km s^{-1} per channel) and 0.5 MHz (~1.3 km s^{-1} per channel) (1976 December and 1977 March), and 0.5 MHz and 1 MHz (1977 June, 1978 April, and 1978 May).

The temperature scales for both the CO and ^{13}CO lines are expressed in units of T_A*, the Rayleigh-Jeans equivalent brightness temperature for a source observed above the atmosphere with a lossless antenna.

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[1] The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

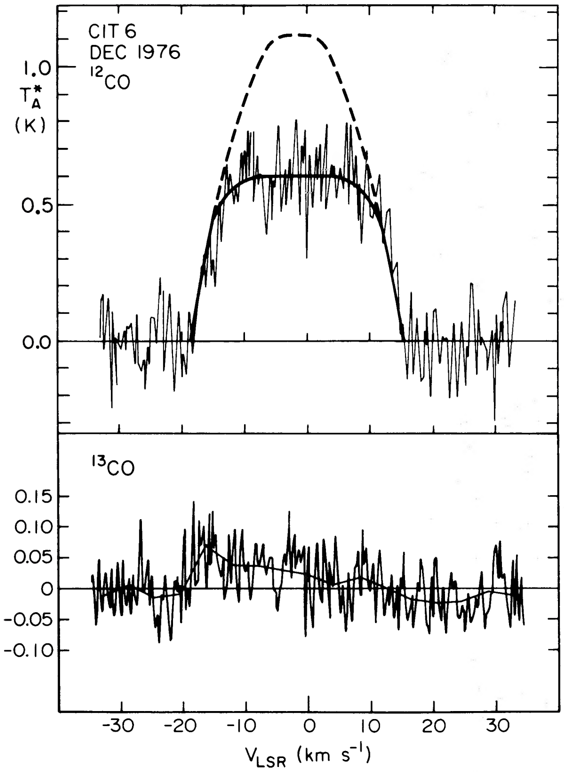

FIG. 1.—Observations of the ^{12}CO and ^{13}CO lines toward CIT 6, 1976 December. The spectral resolution is ~0.26 km s^{-1}. The CO profile is compared with a model partially optically thin profile (see text). The parabolic profile is that expected if the source is optically thick and of diameter 20″.

This temperature scale is appropriate for a source of emission which is very extended relative to the main beam of the antenna; thus it is not appropriate for CIT 6, whose size is smaller than the antenna beam (see below). However, the temperature is expressed in this scale (on which the peak temperatures of Ori A and IRC +10216 as measured by the 11 m antenna are 60 K [Ulich and Haas 1976] and 4.7 K [Ulich 1977], respectively, to facilitate intercomparison of observations taken at different times. Further corrections for the source size will be applied when the envelope parameters of CIT 6 are calculated (§ III).

The CO observations of CIT 6 are summarized in Figures 1 and 2 and Table 1. Figure 1 shows the CO and ^{13}CO profiles obtained in 1976 December; for the ^{13}CO observations we also indicate the profile obtained by averaging the data in ~4 km s^{-1} bins. The CO profile predicted from an expanding-spherical-cloud model is shown in Figure 1 and will be described in § III. In Figure 2 are shown the individual CO profiles from the five observing sessions. In Table 1 we list for each observing period the peak temperature observed in each line and the expansion velocity of the envelope V, which is half the width across the base of the profile. Also listed in Table 1 are these parameters from the observations of WSE and ML. We have adjusted their temperatures to the same scale as ours. In the case of the observations of WSE, the adjustment factor we have used was checked by applying it to their published observations of lines toward IRC +10216 and T Tau.

TABLE 1

OBSERVATIONS OF CO EMISSION FROM CIT 6

Date of Observation	T_A^*(CO) (K)	T_A^*(^{13}CO) (K)	V^a (km s^{-1})	Observers
1971 May....	2.6	< 0.8	21	WSE
1974 Apr.....	1.5	0.4	16	ML
1976 Dec.....	0.59 ± 0.08	< 0.05	17	Present paper
1977 Mar....	0.67 ± 0.1	< 0.08	17	Present paper
1977 Jun.....	0.62 ± 0.2	...	19	Present paper
1978 Apr.....	0.69 ± 0.1	< 0.2	18	Present paper
1978 May....	0.54 ± 0.12	...	17	Present paper

[a] Envelope expansion velocity.

The approximate size of the CO envelope around CIT 6 was determined in 1976 December from a nine-point map centered on the star, with spacings of 30″ and 60″. These observations are given in Table 2, and show that position and telescope pointing errors were not significantly different from zero, and that the half-power source diameter, after correction for telescope beam broadening, is 30″ ± 10″, consistent with the more carefully measured diameter of 20″ ± 10″ reported by ML.

Examination of Table 1, and comparison of the CO spectra from our figures and Figure 1 of ML, shows: (1) The CO line temperature appears to have dropped substantially between 1971 May and 1976 December, and to have stayed essentially constant thereafter. (2) Emission in the ^{13}CO line has not been detectable since at least 1976 December. (3) No evidence is found for the double-peaked structure seen by ML in any of our CO profiles. (4) The LSR radial velocity of CIT 6 is −1.5 ± 0.2 km s^{-1} and is unchanged throughout the observing sessions. (5) The expansion velocity $V = 17$ km s^{-1}.

Could the discrepancies (points 1, 2, and 3 above) between our observations and those of ML be produced by telescope pointing errors? For our CO observations this would have required an error of ~50″ (for a source size of 20″) and for the ^{13}CO observations an error greater than ~90″. While such errors can occur

TABLE 2

CO MAP OF CIT 6 (1976 December)

Point	T_A^* (K)	ΔV (km s^{-1})	Int. Temp. (K × km s^{-1})
C..............	0.59 ± 0.08	34	16.5 ± 1.1
30″ N...........	0.45 ± 0.3	30	9 ± 4
30″ S...........	0.45 ± 0.3	39	10 ± 4
30″ E...........	0.55 ± 0.3	39	12 ± 4
30″ W...........	0.55 ± 0.3	29	12 ± 4
Sum............	0.49 ± 0.2	35	11.2 ± 3
60″ N...........	< 0.3	...	...
60″ S...........	< 0.3	...	...
60″ E...........	< 0.3	...	...
60″ W..........	< 0.3	...	...
Sum............	0.2 ± 0.3	32	2.1 ± 3

1979ApJ...233..140K

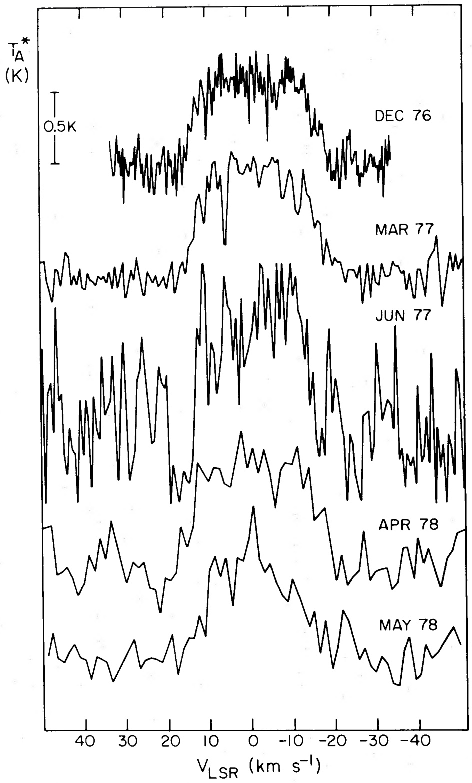

FIG. 2.—CO profiles of CIT 6 observed between 1976 December and 1978 May. The resolution for each profile is, respectively, 0.1, 0.25, 0.25, 0.5, and 0.5 MHz.

at the 11 m telescope, we think it highly unlikely to have been the case for our observations because (*a*) we checked the pointing by observations of planets, (*b*) the results of our nine-point map of CIT 6 showed that the pointing was not noticeably in error, (*c*) we obtained the same results for five different observing sessions, and (*d*) during three sessions we obtained the "correct" result for observations of the nearby object IRC +10216.

Also, pointing errors cannot account for the discrepancy in line shapes between our CO spectra and those of ML. In fact, however, within the noise the profile shapes are consistent since the dip in the CO profile of ML is of marginal statistical significance relative to our proposed expanding-cloud model (cf. Fig. 1).

Thus in summary the above observations show that the CO profile shape for CIT 6 is a flat-topped parabola (the line shape is further discussed in § III) and that there are real discrepancies among the various values of the CO temperature for this star. The possibility of time variations in this source will be discussed in § IV.

III. PHYSICAL PARAMETERS OF THE CIT 6 MOLECULAR CLOUD

The profile shapes observed for emission lines from most late-type stars have characteristic shapes: they are either parabolic (optically thick lines) or rectangular (optically thin). These characteristic shapes were shown by Morris (1975) to arise from a spherical cloud of gas expanding at a uniform velocity, unresolved by the antenna with which the cloud is observed. When such a cloud is resolved by the beam, optically thick lines become flat-topped while optically thin lines become double-peaked (Morris 1975; Kuiper *et al.* 1976).

This type of simple empirical model can be applied to CIT 6. The conclusions drawn in the following discussion are tentative since the ^{13}CO line has not been detected in the present work.

The CO profile observed for CIT 6 (Fig. 1) is flat-topped with parabolic sides and could be fitted by a partially resolved, optically thick expanding sphere. To reproduce the profile, however, would require that the source diameter be ~165″ (assuming the telescope HPBW = 65″), which is completely incompatible with the measured size of the source, less than ~30″. A second possibility is that the CO profile is partially optically thin—i.e., that the parabolic sides of the profile arise from the long, optically thick lines of sight through the center of the object—but that as the lines of sight become shorter (corresponding to smaller observed velocities with respect to the LSR velocity of the star), the source gradually becomes optically thin. A possible empirical model for the emission can then be constructed as follows. The antenna temperature at velocity v_z, the projected radial velocity of a gas element with respect to the systemic velocity of the star, is

$$T_A{}^*(v_z) = 2\pi G T_x \times \int_0^{p_m} \left\{1 - \exp\left[-\alpha n(r) \frac{p}{V}\left(1 - \frac{v_z{}^2}{V^2}\right)^{-3/2}\right]\right\} p dp \tag{1}$$

(see Kuiper *et al.* 1976), where G is the antenna response function, which we take as constant across the (fairly small) source;

$$T_x = \frac{h\nu}{k}\left\{\left[\exp\left(\frac{h\nu}{kT_e}\right) - 1\right]^{-1} - \left[\exp\left(\frac{h\nu}{kT_{\rm bb}}\right) - 1\right]^{-1}\right\} \tag{2}$$

(where T_e, the excitation temperature of the gas, is assumed to be constant through the source, and $T_{\rm bb}$, the background continuum, is taken as 2.7 K); p is the distance from the center of the source projected on the plane of the sky, and p_m its maximum value; R is the radius of the source; α is the CO absorption coefficient; and we assume the radial CO density dependence $n(r) = n_0/r^2$, corresponding to a constant mass-loss rate.

Equation (1) then integrates to

$$T_A{}^*(v_z) = 2\pi G T_x R^2\left(1 - \frac{v_z{}^2}{V^2}\right) \times \left\{0.5 - E_3\left[\alpha n_0 \Big/ VR\left(1 - \frac{v_z{}^2}{V^2}\right)\right]\right\}, \tag{3}$$

1979ApJ...233..140K

where E_3 is the exponential integral. This equation breaks into two parts; the resulting emission line is the optically thick parabola minus an increasing contribution as the optical depth decreases. Examination of Figure 1 suggests that the line begins to deviate significantly from optical thickness (i.e., to have about 90% of its optically thick intensity) at about $v_z = \pm 14$ km s^{-1}. Using this, we can calculate the expected line shape from equation (3). Figure 1 shows that the model agrees very well with the observations. Also shown is the model optically thick line for a source of diameter 20″ (ML) fitted to the sides of the observed line using the first half of equation (3). Because the source is of finite angular size, this line is slightly flat-topped.

We expect that the approximation T_e = constant does not greatly affect the profile shape. The empirical profile calculated with T_e = constant for IRC +10216 by Kuiper *et al.* (1976) agrees quite closely with that calculated from a model expanding cloud with T_e decreasing with radius (Kwan and Hill 1977).

The strength of the optically thick emission at $v_z = 0$ is

$$T_A{}^* = 4 \ln 2 \frac{R^2}{B^2} T_x \qquad (4)$$

if the antenna beam pattern is Gaussian with a full width at half-power of B. Taking $R = 10''$ and $B = 65''$, we find $T_x = 16$ K and $T_e = 19$ K.

The total CO mass of the envelope can be estimated as follows. The optical depth at v_z is

$$\langle\tau\rangle = \left[2\alpha n_0 \Big/ VR\left(1 - \frac{v_z{}^2}{V^2}\right)\right] \approx 2.3 \qquad (5)$$

at $v_z = 14$ km s^{-1}. For $T_e \approx 20$ K, α has the value 3.2×10^{-12}. The mass-loss rate for CIT 6 then becomes $4 \times 10^{50} R_p$ CO molecules per year, where R_p is the envelope radius in parsecs.

The similarity of the spectra of CIT 6 and IRC +10216 (Herbig and Zappala 1970), and the one-to-one correspondence between the spectral type and the bolometric luminosity for carbon stars (Gordon 1968), suggest that we might assume the mass-loss rates for the two stars to be the same. Taking the [CO]/[H_2] abundance ratio and the mean mass-loss rate for IRC +10216 to be 6×10^{-4} and 4×10^{-5} $M_\odot$ yr^{-1}, respectively (Kwan and Hill 1977), we find that the radius of CIT 6 is $R_p = 3.6 \times 10^{-2}$ pc, or about half that of IRC +10216. The total envelope mass is ~ 0.1 $M_\odot$.

Then, from the ratio of the observed source diameters ($\sim 20''$ and 120″), CIT 6 is roughly 3 times as distant as IRC +10216. This agrees with the ratio of CO temperatures (0.5:4.7, where we assume that the intensity of the CO $1 \rightarrow 0$ line, like that of the CO $2 \rightarrow 1$ line in IRC +10216, is strongly centrally peaked [cf. Kwan and Hill 1977; Wannier *et al.* 1979]) and also with the ratio of infrared fluxes (CIT 6 is about 9 times weaker than IRC +10216), all other things being equal (cf. Zuckerman *et al.* 1977).

The finding that the CO line from CIT 6 is partially optically thin is consistent with the failure to detect ^{13}CO emission from the star. From the present observations, we can only say that $N(^{13}\mathrm{C})/N(^{12}\mathrm{C}) \lesssim 1/20$.

Thus we find that the CO profile for CIT 6 can easily be fitted by a partially optically thin sphere expanding at constant velocity, and there is no need to invoke the rotational ejection of material as was done by ML.

IV. TIME DEPENDENCE OF THE CO EMISSION FROM CIT 6

Is the CO emission from CIT 6 time-variable? Table 1 suggests that it is; but during the time span over which these measurements have been taken, calibration procedures for millimeter-wave spectral line astronomy have undergone several changes so that the question should be examined a little more closely.

The variation, if any, is in the sense that some time between 1971 May and 1976 December the CO emission decreased by about a factor of 5 while the ^{13}CO emission decreased by at least a factor of 8, becoming too weak to detect. During 1977 and 1978 the CO line intensity remained the same while the ^{13}CO line remained undetectable.

Any variations in the CO emission from CIT 6 must be driven by variations in the radiative output of the central infrared object since the time scales for structural or chemical changes in the envelope are much too long. There are several possible ways of communicating changes in the output of the central star to the molecules, including (1) radiative heating of the dust and subsequent excitation of the molecules via gas-grain collisions (cf. Kwan and Hill 1977); (2) thermal population of the rotational levels in the $v = 0$ state via absorption of infrared radiation in the vibrational levels (cf. Morris 1975); and (3) possible nonthermal population of the rotational levels due to absorption of IR radiation in the vibrational levels.

The apparent variation in the optically thin ^{13}CO line can be produced by none of the above mechanisms. If $\tau \ll 1$, the line temperature is

$$T_L \propto \left\{\left[\exp\left(\frac{h\nu}{kT_e}\right) - 1\right]^{-1} - 0.15\right\} \times \left\{\left[1 - \exp\left(-\frac{h\nu}{kT_e}\right) \Big/ Q(T_e)\right]\right\}, \qquad (6)$$

where $Q(T_e)$ is the partition function. It is easy to see that the apparent at least eightfold decrease in the intensity of the ^{13}CO line cannot have occurred unless essentially all the gas in the envelope is currently at exactly 2.7 K.

The intensity of both the optically thick and optically thin CO lines could change if the size of the emitting volume changed. This could be accomplished by a change in the intensity of the radiation either at a wavelength of 5 μm (in the case of vibrational excitation) or over the whole spectrum (if the excitation of the CO molecule occurred via gas-grain collisions).

Observations of the infrared spectrum of CIT 6 which have been made over the past dozen years (Ulrich *et al.* 1966; Neugebauer and Leighton 1969; Strecker and Ney 1974; Price and Walker 1976; Merrill and Stein 1976; Alksnis and Eglitis 1976) are, with the exception of the 4.2 μm measurement in the Air Force Geophysical Laboratory (AFGL) survey, in agreement to within about a magnitude. There do appear to be genuine fluctuations of order 1–2 mag (cf. Ulrich *et al.* 1966), which, at least in the near-infrared, are semiregular with a period of ~640 days (Alksnis and Eglitis 1976). Fluctuations of this order cannot change the CO emission substantially by changing the gas temperature, but the size of the excited region could be changed (cf. Fig. 1 of Kwan and Hill 1977, which would have the same appearance if the luminosity varied instead of the gas-grain coupling constant).

It should be noted, however, that during the 500 day period over which our observations were made, no variation in the CO flux was seen. Also, the source mapping data obtained by ML and in the present paper show no significant difference in the apparent source size. Further, the above thermal excitation scheme cannot account for the fact that the ^{13}CO flux apparently varies more than the CO flux.

In modeling the emission from the molecular envelope of IRC +10216, Kwan and Hill (1977) found that under certain conditions (when the rate of absorption of 5 μm photons is high, i.e., close to the star, and when collisional quenching is low, i.e., at low mass-loss rates and a low CO abundance) maser action can occur in the $J = 1 \rightarrow 0$ transitions of both CO and ^{13}CO. Such a mechanism could lead to enhanced emission, particularly near $v_z = V$, and could produce a profile with the most intense emission at the extreme velocities such as that observed by ML. In this case, the apparent source size would be considerably smaller than that producing the thermal emission. Also, the smaller rate of photon trapping in the ^{13}CO transition (relative to that in the CO transition) could produce a greater inversion, and hence a greater variation, in the ^{13}CO line. If this mechanism was operating, it is surprising that we saw no variation during the 500 days covered by our observations. The possibility of such a mechanism operating in CIT 6 (and perhaps in other similar sources), however, warrants further (and more careful) observations.

V. CONCLUSIONS

We have made high-sensitivity observations of the CO emission from CIT 6 at several epochs. The ^{12}CO lines are all flat-topped and are considerably weaker than those reported by previous observers. Emission in the ^{13}CO line was not detectable. No variation in CO intensity has been apparent over the last year and a half. We conclude:

1. CIT 6, like many other late-type stars, is surrounded by a spherical cloud of gas apparently expanding at constant velocity. The CO emission is optically thin at velocities near the systemic velocity of the star and optically thick in the line wings.
2. There is a possibility that the CO emission from CIT 6 is time-variable: this should be investigated over longer time scales by observations of the CO and infrared emission. The variability, if it exists, is episodic rather than periodic.

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