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LINEAR POLARIZATION OF HCN MASER EMISSION IN CIT 6

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ABSTRACT

We have measured the linear polarization of the intense emission from vibrationally excited HCN in the circumstellar envelope of the carbon star CIT 6, detected by Guilloteau, Omont, and Lucas. On several days in 1987 March and April, the $J = 1$–0 transition of the (0, 2°, 0) state was observed with the FCRAO 14 m telescope and 3 mm wavelength polarimeter system. We found the emission to have a fractional linear polarization of 20% at a position angle of $-18°$, with no significant variation in percentage or angle across the line profile. The ground vibrational state line was found to be unpolarized, with a 1 σ upper limit of 3%. The strong polarization of the vibrationally excited line confirms that maser amplification, previously suggested by its narrow width and relatively high intensity, is present. The observed polarization could be produced either by anisotropic pumping or by the magnetic field in the envelope of CIT 6. The latter model correctly predicts the position angle of the observed linear polarization if reasonable assumptions about the source geometry are made.

Subject headings: line formation — masers — polarization — stars: carbon — stars: circumstellar shells

I. INTRODUCTION

Maser emission from OH, H_2O, and SiO molecules (see Reid and Moran 1981) is common in the envelopes of evolved oxygen-rich stars. SiS (Nguyen-Q-Rieu *et al.* 1984) is weakly masing in at least one object. While the study of masing emission should in principle be a very powerful diagnostic for the conditions in these regions, the complexity of the process of maser amplification has impeded drawing many definitive conclusions. The detection of polarized emission in a masing transition can give information about the magnetic field as well as other parameters in the region with gain (see Goldreich, Keeley, and Kwan 1973; Western and Watson 1984; Deguchi, Watson, and Western 1986).

A new intense spectral line with many of the characteristics of maser radiation was recently observed from $J = 1$–0 HCN emission from the (0, 2°, 0) vibrationally excited state in the envelope of the carbon star CIT 6 (Guilloteau, Omont, and Lucas 1987), and subsequently in six other carbon-rich envelopes (Lucas, Guilloteau, and Omont 1987). In this paper we report measurements of the linear polarization of the intense line from CIT 6. While there is no theory available specifically for this transition, the high degree of linear polarization detected confirms the presence of maser amplification. The observations are presented in the following section, and the results are discussed in § III.

II. OBSERVATIONS

The observations were carried out between 1987 March 20 and April 24 using the 14 m FCRAO radome-enclosed telescope. A Schottky mixer receiver with a quasi-optical single sideband filter and cooled image load provided SSB system temperatures typically 400 K referred to above the Earth's atmosphere. Pointing and focus were checked by continuum observations of 3C 84 or of HCN $J = 1$–0 emission from IRC +10216. The beamwidth and aperture efficiency were not measured during this program, but were found to be 55″ FWHM and 0.45, respectively, in a study of HCO^+ polarization at a very close frequency (Lis *et al.* 1987). The resulting conversion factor from antenna temperature T_A^* (corrected for warm telescope loss and atmospheric absorption) to unpolarized flux density is 41.6 Jy K^{-1}.

The linear polarization was measured using a rotating half wave plate made of slotted low-loss dielectric material. The instrumentation and data taking procedures are described by Wannier, Scoville, and Barvainis (1983) and by Barvainis and Predmore (1985). We have measured a residual instrumental (including antenna) polarization on the order of 0.5% at 89 GHz (Lis *et al.* 1987). The Stokes parameters I, Q, U are obtained by observations of the source with different half wave plate orientations. A reference position offset by 0°.5 in azimuth was used to determine the total intensity line profiles.

Spectral resolution was obtained with a 256 kHz filterbank consisting of contiguous 100 kHz filters with corresponding velocity width 0.34 km s^{-1} per channel. A spectrum expander operating at a factor of 4 times expansion and thus providing 25 kHz (0.084 km s^{-1}) resolution was employed for additional observations of the vibrationally excited line.

The basic parameters of the lines observed are given in Table 1. The ground vibrational state line in CIT 6 was observed on April 4, while the vibrationally excited line was observed on March 20 and 26 with 100 kHz resolution and on April 14 with 25 kHz resolution. The data for IRC +10216 were obtained as part of the system tests carried out throughout this project. The data from the spectrum expander suffered from problems with absolute calibration due to system nonlinearities, so they were not included in Table 1. Spectra of the ground and vibrationally excited lines are shown in Figure 1. The polarimetric data taken with 100 kHz filters and processed to 1 km s^{-1} resolution, together with the 25 kHz data for fractional polarization and position angle are given in

TABLE 1

OBSERVATIONS OF HCN $J = 1\text{–}0$ EMISSION IN CIRCUMSTELLAR ENVELOPES

Source[a]	Vibrational State[b]	T_A^* (K)[c]	δV_{FWHM} (km s^{-1})	V_{max}[d] (km s^{-1})	V_{mean}[e] (km s^{-1})	$\int T_A^* dV$ (K km s^{-1})
IRC +10216	(0, 0, 0)	5.15	22	−29.9	−27.8	98.2
CIT 6	(0, 0, 0)	0.42	25	−0.5	−4.6	8.75
	(0, 2°, 0)	0.92	1.1	−3.9	−3.8	1.02

[a] 1950 coordinates are IRC +10216: R.A. = $09^h45^m14^s.8$; decl. = +13°30′40″; CIT 6: R.A. = $10^h13^m11^s.0$; decl. = +30°49′17″.

[b] Frequencies from Maki 1974; for $J = 1\text{–}0$ transition in ground vibrational state: $F = 1\text{–}1$ component, $f_0 = 88.630416$ GHz; $F = 2\text{–}1$ component $f_0 = 88.631847$ GHz; and $F = 0\text{–}1$ component $f_0 = 88.633936$ GHz. For (0, 2°, 0) state, $F = 2\text{–}1$ component $f_0 = 89.08792$ GHz. The hyperfine structure is blended in the ground vibrational state emission from both sources. For the vibrationally excited emission from CIT 6, the data refer to the $F = 2\text{–}1$ component which is the only hyperfine component detected.

[c] Average of two linear polarizations for CIT 6; single linear polarization for IRC +10216 (which we assume to be unpolarized). Data taken with 100 kHz (0.34 km s^{-1}) resolution spectrometer. Antenna temperatures T_A^* are corrected only for atmospheric absorption and warm telescope losses.

[d] VLSR velocity of maximum emission. The uncertainty is ±4 km s^{-1} for the (0, 0, 0) line and ±0.15 km s^{-1} for the (0, 2°, 0) line.

[e] Mean VLSR velocity of emission = $\int T_A^* V\, dV / \int T_A^* dV$.

Table 2; the latter are shown in Figure 2. The fractional polarization at the center of the line is slightly higher than obtained from the 100 kHz data, but when processed to 1 km s^{-1} resolution is consistent (19.1% ± 2.4%) with the lower resolution data given in Table 2.

III. DISCUSSION

a) Characteristics of the Emission

The line width of the vibrationally excited emission is less than that of the ground state line by a factor of ∼25. The observed line width corresponds to a temperature of 700 K, assuming that thermal dispersion is the only source of line broadening. While the possible contributions of other mechanisms such as velocity gradients make this an upper limit, line narrowing due to maser gain could result in the observed profile being considerably narrower than the true line shape. Since we have little information on the maser gain, the upper limit on the temperature cannot be considered to be a very strong one.

The vibrationally excited HCN emission from CIT 6 is intense, given that the lower level is over 2000 K above the ground state. The total intensity given in Table 1 corresponds to a peak flux density of 38 Jy. This is approximately a factor of 2 weaker than that measured by Guilloteau, Omont, and Lucas (1987) 4 months earlier. The intensity measured at FCRAO was constant within the signal-to-noise ratio over a period of 1 month, and the pointing (Saturn and IRC +10216) and calibration (Saturn) measurements were made immediately preceding and following the CIT 6 observations. It seems unlikely that the present observations have a calibration uncertainty exceeding 25%. It is possible that the intensity of the emission has varied by a factor of 2 over this time interval. However, new measurements at the 30 m telescope in 1987 March and June (Lucas, Guilloteau, and Omont 1987) have shown that while the profile of the emission from CIT 6 has varied significantly, the intensity has not changed by more than 30%. As a result of the significant polarization of the source, the intensity observed at the 30 m telescope depends on the elevation of the source. The 75 Jy flux reported by Guilloteau, Lucas, and Omont (1987) should as a result be decreased by 10%–20% to represent the average of the two polarizations. We have no satisfactory explanation at present for the remain-

TABLE 2

POLARIMETRY OF HCN $J = 1\text{–}0$ EMISSION IN CIT 6

Vibrational State	I[a] (K)	Q (K)	U (K)	Linear Polarization	Position Angle[b]
(0, 0, 0)	0.83 ± 0.06			<3%[c]	
(0, 2°, 0)[d]	1.55 ± 0.05	0.19 ± 0.02	−0.13 ± 0.02	15.1% ± 1.1%	−17° ± 3°
(0, 2°, 0)[e]				20.1% ± 1.8%	−18° ± 2°.5

[a] Total intensity obtained by adding two orthogonal linear polarizations.

[b] Measured eastward of north.

[c] Data taken with 100 kHz (0.34 km s^{-1}) resolution. The limit on the polarization given is the standard deviation in a 1 km s^{-1} interval, of which there are 25 within the FWHM of the line profile.

[d] Average of data taken using 100 kHz (0.34 km s^{-1}) filters. The values given refer to a 1 km s^{-1} wide interval centered on the line peak velocity of −3.9 km s^{-1}. The error given is 1 standard deviation in the mean percentage polarization and position angle. The peak intensity is 1.84 K in 100 kHz channel width as indicated in Table 1.

[e] Data obtained with spectrum expander operating at 25 kHz (0.084 km s^{-1}) resolution. Although the intensities are not reliable in this measurement due to system nonlinearities, the fractional polarization and position angle should be correct. The results for fractional polarization and position angle are an average of the eight channels for which the measured fractional polarization is greater than 3 times the rms uncertainty. These cover a velocity interval 0.6 km s^{-1} wide centered at −3.9 km s^{-1}.

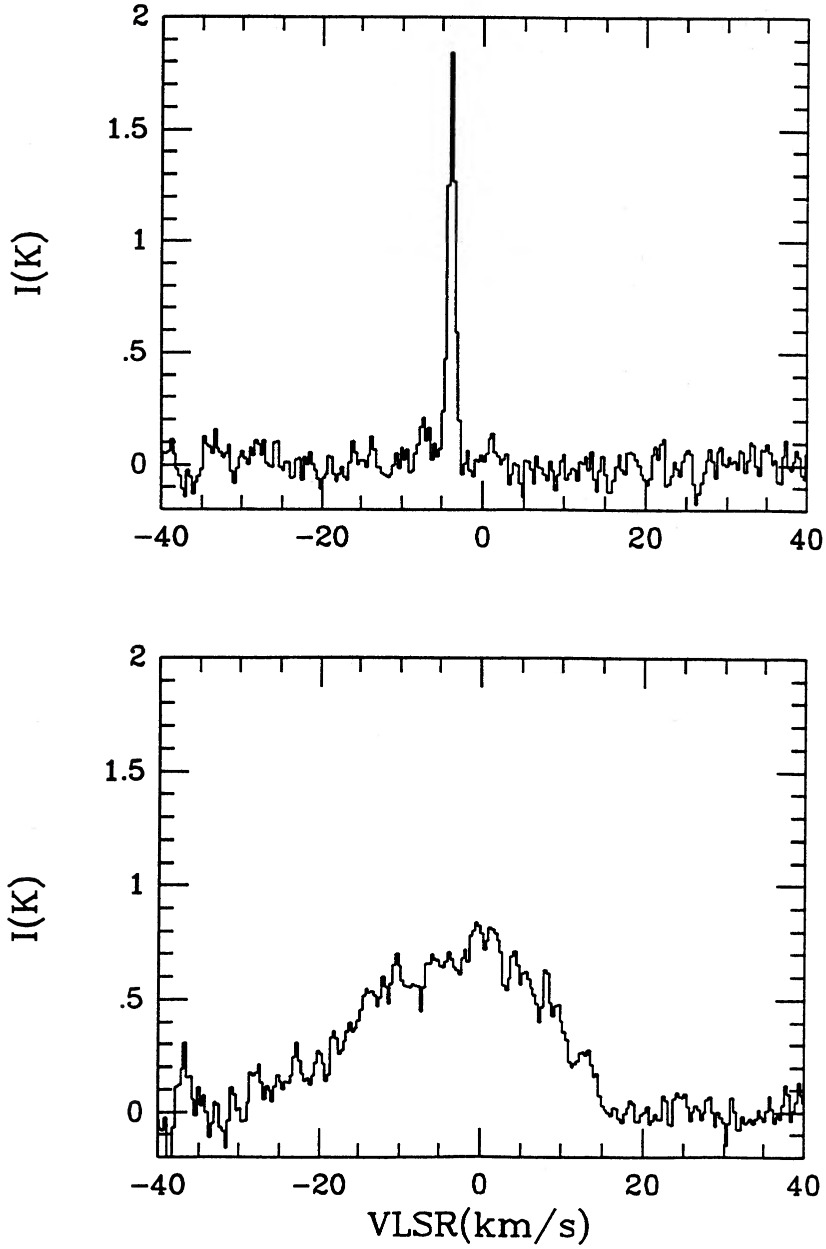

FIG. 1.—Spectra of HCN $J = 1\text{–}0$ emission from CIT 6 obtained with FCRAO 14 m telescope using 100 kHz (0.34 km s^{-1}) resolution spectrometer. The upper panel shows the line from the (0, 2°, 0) vibrationally excited state, and the lower shows the ground vibrational state emission. The intensity scale has been corrected only for atmospheric and antenna absorptive losses and is the average of that measured in two orthogonal linear polarizations. The velocity scale refers to the $F = 2\text{–}1$ hyperfine component in each case. The weaker $F = 1\text{–}1$ and $F = 0\text{–}1$ components with relative intensities 0.6 and 0.2 in LTE, and rest frequencies corresponding to velocity offsets of +4.7 and −7.1 km s^{-1} with respect to the 2–1 component, respectively, are not detected in the (0, 2°, 0) state.

ing disagreement, which is somewhat larger than the combined uncertainty of the two sets of observations (assuming the source intensity to have remained constant).

The line width of the vibrationally excited emission is, as shown in Figure 1, drastically narrower than that of the ground vibrational state line. The higher signal to noise profile of Omont, Guilloteau, and Lucas (1987) allowed detection of the $F = 1\text{–}1$ hyperfine component as well as the $F = 2\text{–}1$ component which is the only one clearly detected in Figure 1. The relatively large width and limited signal to noise ratio of thermal emission lines from CIT 6 makes determination of the central velocity problematic, and this difficulty is compounded by the hyperfine structure of HCN. Knapp and Morris (1985) obtain a stellar velocity of -1.78 ± 0.06 km s^{-1} by fitting the profile of CO $J = 1\text{–}0$ emission, while less accurate values of between 2.1 and 4.7 km s^{-1} are determined by Henkel *et al.* (1985) using CS and SiS emission lines. Sopka *et al.* (1987) report −1.9, 1.5, and 0 km s^{-1} for the central velocities of CO, HC_3N, and HNC emission, respectively. Guilloteau, Omont, and Lucas (1987) report 1.0 ± 0.2 km s^{-1} from a number of lines. It appears clear that the velocity of -3.9 ± 0.15 km s^{-1} for the vibrationally excited HCN line

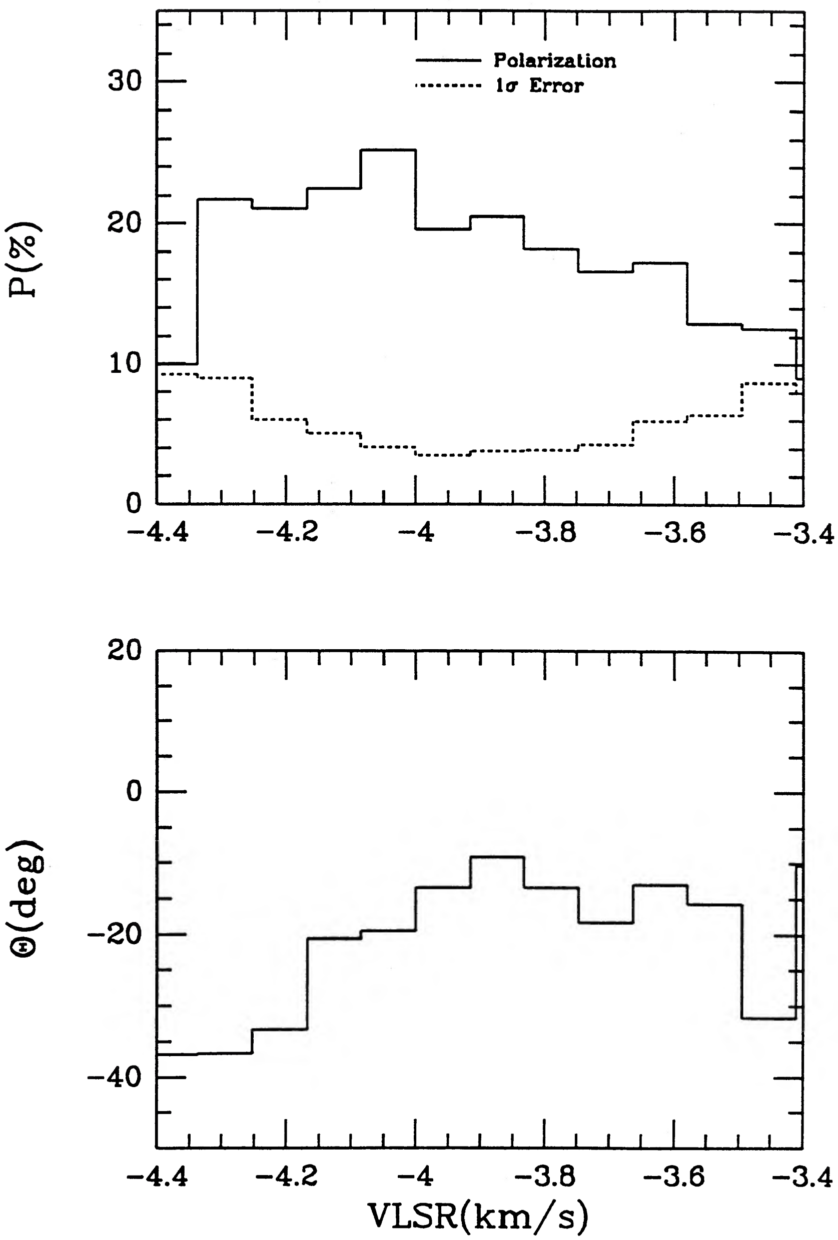

FIG. 2.—Results of linear polarization measurements of the HCN $J = 1$–0 (0, 2°, 0) line in CIT 6 using 25 kHz (0.084 km s^{-1}) resolution spectrum expander. Upper panel shows the fractional linear polarization and the one standard deviation error. The mean linear polarization, averaged over 1 km s^{-1}, which is approximately the FWHM line width, is 20% for these data. This is statistically consistent with the 15% measured for the lower spectral resolution data given in Table 2. Lower panel shows the position angle of the linearly polarized component (measured eastward from north) across the line. The mean angle for these data is −18°, again consistent with the −17° obtained from the lower resolution data.

(Table 1) is blueshifted with respect to the general centroid of the molecular emission. The implications for the maser location and gain path are discussed further in § III*b* below.

The linear polarization of the vibrationally excited $J = 1$–0 emission is clearly detected. The average fractional linear polarization measured in the eight 25 kHz channels covering the 0.6 km s^{-1} interval centered at −3.9 km s^{-1} is 20%, which is typical of the SiO masers observed by Troland *et al.* (1979) and by Barvainis and Predmore (1985). The rms statistical uncertainty in the fractional polarization is 5.2% in a 0.084 km s^{-1} velocity interval yielding a rms uncertainty of 1.8% for the mean polarization. The position angle (measured eastward from north) has a mean value of −18°, with a rms uncertainty of 2°.5 for the mean polarization. Within the measurement uncertainties, the fractional polarization and the position angle are constant across the (0, 2°, 0) $J = 1$–0 line profile.

b) HCN *Maser Location and Pumping*

While the data available are very limited, there do appear to be some general constraints on the possible models for the HCN maser in a stellar envelope. The extremely narrow maser line is probably a result of the selection of a very well defined region with narrow velocity dispersion, rather than line narrowing due to the maser gain. The narrow linewidth is in contrast to SiO masers which typically exhibit emission over a velocity width 10–15 km s^{-1} in atmospheres of evolved stars (see Nyman and Olofsson 1986). The blueshift of the maser line, ~2–4 km s^{-1}, indicates that it is in the region undergoing expansion, but which is not fully accelerated. The mass loss from CIT 6 has a terminal velocity of 16.9 km s^{-1} (Knapp and Morris 1985). Taking the form of the velocity field to be $v(r) = v_T(1 - r_0/r)^{0.5}$ (Kwan and Hill 1977), where r_0 is the inner radius of the acceleration region, we find r/r_0 between 1.01 and 1.06. Given the uncertainty in the dependence of the velocity on the distance from the stellar photosphere, this result can best be interpreted as indicating that the maser is located very close to the inner boundary of the expanding envelope surrounding the star. In this picture the gain path of the maser would be primarily radial.

An important question is whether there is a sufficient quantity of HCN in the atmosphere to provide reasonable maser gain in the relatively small scale indicated by the small maser line width. If we assume a fractional population inversion of 15% and a vibrational excitation temperature of 1000 K (which is reasonable for a maser located close to the stellar photosphere), the total column density of HCN molecules required in a 1 km s^{-1} velocity interval to obtain an optical depth equal to -10 is 2×10^{17} cm^{-2}. Detailed modeling of the IRC +10216 envelope yields $X(\mathrm{HCN}) = 2 \times 10^{-6}$ (Bieging, Chapman, and Welch 1984), and, adopting this value, although it may well be too small (e.g. Sopka *et al.* 1987), the required molecular hydrogen column density is 10^{23} cm^{-2}. The local hydrogen density depends on the mass-loss rate and hence the distance to CIT 6; scaling the result of Knapp and Morris (1985) to our adopted distance of 400 pc yields $dM/dt = 1.3 \times 10^{-5}$ $M_\odot$ yr^{-1}. For a given mass-loss rate and fixed velocity shift compared to the terminal velocity, the hydrogen density varies as r_0^{-2}. Adopting a value of 3×10^{13} cm for r_0 and $r = 1.06 r_0$ as derived above from the velocity shift taken to be 4 km s^{-1}, we find $n(H_2) = 4 \times 10^{10}$ cm^{-3}. The required size of the maser region is then 2.5×10^{12} cm.

The velocity gradient is large in the inner region of the envelope; with the above parameters $dv/dr = 1.2 \times 10^{-12}$ km s^{-1} cm^{-1}. The upper limit to the size of the maser region to produce the observed 1 km s^{-1} line width is thus just under 10^{12} cm. While this is a few times less than the size derived above, it appears, considering the uncertainties involved, that there is not a major problem with having a sufficient number of HCN molecules in a region close to the inner edge of the accelerating envelope to produce the maser emission observed.

For a velocity field of the form $v(r) = v_T(1 - r_0/r)^{0.5}$ adopted here, together with the relatively small value of v/v_T and hence r/r_0 found, the quantity $(r/v)dv/dr$ is much greater than unity, so that direction of maximum optical depth and hence maser gain will be tangential. There thus would be, in fact, no significant offset between the velocity of the maser and that of thermal emission lines. Since we do see such an offset, we conclude that this velocity law cannot be an adequate description of the velocity field in the region. This might be a result of a significant nonspherically symmetric component produced by the disk in the model of Cohen and Schmidt (1982), or the presence of appreciable clumpiness in the maser region (discussed further in the analysis of pumping below).

Pumping the HCN maser is an obvious question to be addressed. Collisional pumping is a possible mechanism. The calculations of Green and Thaddeus (1974) indicate that the cross sections for collisions (with He simulating H_2 molecules) for the rotational quantum number changing by 2 units are ~5 times larger than those for which J changes by 1 unit. This will have the effect of overpopulating the $J = 1$ level when the collision rate is somewhat below that required for thermalization, or ~5×10^5 cm^{-3} (Goldsmith 1972). However, this density is at least a factor of 10^4 less than required for reasonable excitation of the vibrationally excited state. In addition, it is difficult to see how thermalization of the rotational transitions could be avoided if the excited vibrational state population were maintained by collisions, and there is also no apparent reason why this mechanism should operate preferentially in that state. While collisional pumping of a different type (see Elitzur 1980; Kylafis and Norman 1986) cannot be ruled out, it appears more reasonable to investigate radiative pump mechanisms either alone, or combined with collisional pumping similar to those developed for SiO by, e.g., Kwan and Scoville (1974), Robinson and Van Blerkom (1981), and Langer and Watson (1984).

The radiative pumping mechanisms are based on absorption of the infrared photons at the wavelengths of the vibration-rotation bands of the molecule in question. The (0, 2°, 0) state lies 2050 K above the ground state and can be directly excited by absorption of a photon of wavelength 7 μm; it can also be reached from the (0, 1, 0) state which lies 1025 K above the ground state by absorption of a photon of wavelength 14 μm (see Ziurys and Turner 1986 and references therein). We can at least verify the plausibility of a radiative pump mechanism by calculating the number of available infrared photons and comparing this to the number of millimeter wavelength photons emitted in the one masing line identified to date.

Calculation of the number of photons emitted by the maser is made difficult by the issue of the isotropy of the maser emission and the large uncertainty in the distance to CIT 6. Cohen (1979) derives a distance of 190 pc, but indicates that this is to be regarded as a lower limit. Rowan-Robinson and Harris (1983) derive a distance of 400 pc, based on their model for the circumstellar IR emission, with a stellar photospheric temperature of 2000 K. Clausen *et al.* (1987) utilize data from the 2 μm sky survey, and with the assumption that all stars have M(K) = -8.1 mag, obtain a distance of 710 pc, but which they indicate is probably an overestimate. Accordingly, we favor a distance of 400 pc, which corresponds to a source luminosity of ~10^4 $L_\odot$ (Sopka *et al.* 1985). If we assume that the emission is isotropic and that the distance is 400 pc, the total number of (0, 2°, 0) $J = 1$–0 photons emitted per second is 3.3×10^{42}. Note that this is at the low end of the SiO maser photon emission rate, 10^{42}–10^{45} s^{-1} (Clemens and Lane 1983).

We first consider pumping at 7 μm wavelength, since $\delta v = 2$ transitions seem required to pump SiO masers. We model the radiation emitted by CIT 6 as that of a 2800 K blackbody with a radius of 3×10^{13} cm ($L = 10^4$ $L_\odot$), and find that the total number of photons available in a 1 km s^{-1} interval is 2×10^{43} s^{-1}. Since this exceeds the number of millimeter-wave photons by a factor of ~6, we conclude that the 7 μm radiative pump is capable of providing the observed number of photons from an isotropic maser.

Radiative pumping via the 14 μm transitions with $\delta v = 1$ could be considered as a mechanism for producing the inversion in the (0, 2°, 0) state. These transitions are believed not to be efficient for pumping SiO, but the situation could be different for HCN as a result of the structural complexity introduced by the l-doubling. The number of photons available based on the same stellar parameters as given above is just sufficient, but the implication is that essentially every available pump photon must be used. While it is true that photons in a number of vibrational-rotational transitions may contribute to the pumping, this will probably not change these results appreciably. We conclude that although the radiative pump in a symmetric circumstellar envelope is energetically possible, detailed calculations are required to answer the question of the nature of the maser pump mechanism.

A critical aspect of the pump mechanism (e.g., Kwan and Scoville 1974) is that the $\delta v = 1$ vibration-rotation transitions be optically thick. From the spontaneous decay rates for the infrared transitions (Ziurys and Turner 1986, and references therein) we can calculate the absorption coefficients. We assume that population of the rotational levels in the lower vibrational states as well as the relative population of vibrational levels is characterized by an excitation temperature of 1000 K, and take the total column density of HCN to be 2×10^{17} cm^{-2}, as derived above. We find that the optical depth of the 7 μm transition out of the ground state is only 0.1, and that the optical depth of the analogous 14 μm transition is 0.7. The optical depth for the 14 μm transition connecting the (0, 1, 0) and (0, 2, 0) states will be comparable since the increased line strength largely offsets the reduced lower level population. Accordingly, this pumping seems possible, but the moderate optical depth suggests that there is considerable clumpiness, which would increase the optical depth in the pumping transitions. IR absorption by HCN in CIT 6 has been reported by Ridgway, Carbon, and Hall (1978) and by Ridgway and Hall (1980), but no quantitative results are given, preventing assessment of the line opacities. A clumpy model is also consistent with VLBI results for SiO masers by Lane (1982) and McIntosh (1987), and has been developed by Alcock and Ross (1986).

c) *Maser Polarization and Source Structure*

Linear polarization of maser emission lines can be produced by magnetic fields (Goldreich, Keeley, and Kwan 1973; Western and Watson 1984) and by anisotropic pumping (Western and Watson 1984). Neither of these treatments is exactly appropriate to HCN (i.e., with hyperfine structure), but the general conclusions should nevertheless be applicable to the present data.

i) *Polarization due to Magnetic Field*

We must first establish in which regime of magnetic splitting relative to maser line width and stimulated emission rate the HCN maser is operating. HCN in the ground vibrational state has a magnetic g factor of -0.1, but in the (0, 1^1, 0) state has different factors for magnetic field parallel and perpendicular to the molecular symmetry axis, -0.1 and $+0.38$, respectively (Maki 1974). Data for the (0, 2°, 0) state are not available, but assuming a g factor of 0.2 yields a magnetic splitting of 152 Hz G^{-1}. For a representative magnetic field of 50 G in circumstellar envelopes found from circular polarization of SiO masers by McIntosh (1987), we find a magnetic splitting of 7.6 kHz. This is clearly much less than the maser line width, which (as discussed above) should be close to the observed line width of 325 kHz. Determination of the stimulated emission rate is highly uncertain since little is known about the radiation field in the masing region. Following the reasoning of Alcock and Ross (1986), the stimulated emission rate must exceed the collision rate, for maser saturation. With the H_2 density of 4×10^{10} cm^{-3} determined above, the (rotational) collision rate is 2 s^{-1}, but if the material is clumped and the density is on the order of 10^{12} cm^{-3}, it could be as high as 50 s^{-1}. The relative weakness of HCN masers compared to SiO masers, and the large relative intensity of the main compared to weaker hyperfine components in CIT 6 suggest that the HCN maser is not heavily saturated. The effective line width R from the stimulated emission probably does not exceed a few hundred Hz, and we are thus in case 2 of Goldreich, Keeley, and Kwan (1973; hereafter GKK), with $R <$ magnetic splitting $<$ maser line width.

The linear polarization of maser emission has been treated by GKK in the limiting cases of completely unsaturated (stimulated emission rate much less than pump rate) and highly saturated emission. This analysis has been extended by Western and Watson (1984), and Deguchi, Watson, and Western (1986), who calculated the polarization as a function of emergent intensity; their results in the appropriate limiting conditions agree with those found previously by GKK. A very crude summary of the results of both of these treatments is that a fractional linear polarization of 20% can be achieved if the angle θ between the magnetic field direction and the direction of propagation of the radiation is less than 30° or more than 70°. In the Western and Watson (1984) calculation, this requires that the emergent intensity be at least 10 times the saturation intensity (i.e., the stimulated emission rate be at least 10 times greater than the pump rate). The sign of the fractional polarization is opposite for the two regimes of θ; for large θ the polarization of the electric field of the emitted radiation is parallel to the projection of the magnetic field on the sky. The fractional polarization increases as the degree of saturation increases, and as θ approaches either 0° or 90°. The dependence of the polarization upon stimulated emission rate obtained by Deguchi, Watson, and Western (1986) is the same, but occurs at a factor 10–100 lower intensity, due to the different radiative transfer model employed. The issue of the magnetic field direction in the source and its relationship to the polarization angle measured will be discussed further below.

ii) *Anisotropic Pumping*

Anisotropic pumping can also produce polarization of emitted spectral line radiation. This effect has been analyzed for circumstellar envelopes by Morris, Lucas, and Omont (1985), and for masers by Western and Watson (1984). The basic mechanism depends on having different pumping rates into the various substates of the upper level of the maser transition. This can result simply from the angular momentum of a photon coming from a central pump source. For plausible conditions, its effect can be very significant, but the wide variety of possible pumping asymmetries and maser locations make a definitive assessment of anisotropic pumping for the CIT 6 HCN maser impossible at the present time.

iii) *Source Structure and Observed Polarization*

Cohen and Schmidt (1982) studied the optical polarization of CIT 6, and as a result of the peculiar variation of fractional polarization and position angle with wavelength, were led to construct a model which comprised a moderately optically thick disk seen nearly edge-on, together with two lobes of material oriented perpendicular to the plane of the disk. The light scattered from the lobes would be polarized essentially parallel to the plane of the disk, while at longer wavelengths the radiation detected would be primarily that emerging through the disk, and would be polarized perpendicular to the plane of the disk. In this picture, the outflow axis is nearly perpendicular to the line of sight and has an orientation parallel to the position angle of the short-wavelength radiation, 176°.

A number of studies indicate that the outflow axis is parallel to the direction of the magnetic field (see Strom and Strom 1987). If this relationship holds for CIT 6, we can, using the Cohen and Schmidt (1982) source model, determine the magnetic field position angle to be 176°; the magnetic field direction must also be essentially perpendicular to the line of sight. The maser polarization produced by the magnetic field for $\theta = 90°$ has $P < 1$, so that the polarization angle is parallel to the magnetic field direction. The observed position angle of $-18°$ is the same as $+162°$ and thus agrees with that expected from the source model with outflow axis parallel to the magnetic field, with the linear polarization observed being produced by the Zeeman effect.

IV. SUMMARY

We have detected strong linear polarization in the HCN $J = 1$–0 transition from the (0, 2°, 0) vibrationally excited state, in the envelope of the carbon star CIT 6. The large fractional polarization of 20% confirms that maser amplification is present. The vibrationally excited emission is blueshifted with respect to the velocity centroid of the thermal emission lines by 2–4 km s^{-1}, suggesting that the maser, with upper level 2000 K above the ground state, is relatively close to the photosphere of the star. Analysis of the pumping requirements for the maser suggests that a spherically symmetric geometry is marginally possible, but that significant clumpiness is likely to be present. The observed fractional polarization can be produced by anistotropic pumping, but due to the uncertainties in the source geometry, little quantitative information can be obtained. Polarization due to the magnetic field appears consistent with what is known about the rates for different processes affecting the maser levels. The optical polarization data of Cohen and Schmidt (1982) led these authors to suggest a bipolar geometry for the source, with the axis perpendicular to the line of sight at a position angle of 176°. If the axis of symmetry of the bipolar structure coincides with the direction of the magnetic field, the observed position angle of the HCN polarization, $-18°$ (equivalent to 162°) agrees well with the theoretical prediction that the observed electric field orientation should be parallel to the magnetic field in the maser region.

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