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A SENSITIVE LINE SEARCH IN CIRCUMSTELLAR ENVELOPES

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ABSTRACT

A molecular line search in the range between 85 and 89 GHz has been performed in the circumstellar envelope of 11 evolved stars using the 45 m telescope at Nobeyama Radio Observatory equipped with an acoustooptical spectrometer with a 2 GHz bandwidth. Emissions of ^{29}SiO $J = 2$–1, ^{28}SiO $J = 2$–1, HCN $J = 1$–0, $H^{13}CN$ $J = 1$–0, HCN $J = 1$–0 ($v = 2$), HC_5N $J = 33$–32, HCO^+ $J = 1$–0 transitions, and other transitions of C_2H, C_4H, and C_3N have been observed in 11 stars. We have detected the ground-state ^{29}SiO $J = 2$–1 maser in several stars. We have also detected HCN emission in VY CMa, an oxygen-rich star. The HCN profile in VY CMa shows a slight asymmetry with respect to the line center and can be interpreted in terms of an activity of the circumstellar envelope. A narrow $H^{13}CN$ spike feature near the central velocity has been found in the spectrum of CRL 2688. This narrow spike may be maser emission.

Subject headings: line identifications — radio sources: lines — stars: circumstellar shells

I. INTRODUCTION

An increasing number of molecular transitions have been detected in the circumstellar envelopes of evolved stellar objects through recent sensitive searches with large radio telescopes (e.g., Lucas *et al.* 1986). Some progress has been made toward the understanding of chemical processes at work in the circumstellar medium, based on both observational results and non–LTE chemical calculations and modeling (Huggins and Glassgold 1984; Truong-Bach, Graham, and Nguyen-Q-Rieu 1987; Glassgold *et al.* 1987). Detailed aperture synthesis mapping is valuable in this regard. Using the VLA and Hat Creek interferometers, Nguyen-Q-Rieu, Winnberg, and Bujarrabal (1986) and Bieging and Nguyen-Q-Rieu (1988) found that the NH_3 and HCN shells of CRL 2688 are toroids, while HC_7N is distributed in a spheroidal halo. The internal structures of the envelope also depends on the molecular species. In IRC +10216, radicals and molecules such as C_2H and HC_3N which are probably formed through photodissociation by interstellar UV or through ion-molecule reactions have been found to be concentrated in the outer layers, whereas SiS which might be ejected from the central star has its emission peaked in the inner part of the envelope (Bieging and Nguyen-Q-Rieu 1986). The molecule HCN which was believed to exist only in carbon-rich atmospheres has been found in oxygen-rich envelopes (Deguchi and Goldsmith 1985). Other long-chain cyanopolyynes and hydrocarbons, i.e., HC_7N and C_6H, have also been detected in the IRC +10216 and CRL 2688 (Nguyen-Q-Rieu, Graham, and Bujarrabal 1984; Guelin *et al.* 1987; Saito *et al.* 1987). Furthermore, several interesting kinematic features like anisotropic ejection of matter and rotation have also been revealed in the envelope of CRL 2688 by interferometric mapping (Nguyen-Q-Rieu, Winnberg, and Bujarrabel 1986; Bieging and Nguyen-Q-Rieu 1988). Vibrationally excited HCN maser emission has recently been detected in CIT 6 (Guilloteau, Omont, and Lucas 1987).

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The above considerations suggest that the envelopes of cool stars are rich in molecules and physical phenomena and prompt us to perform an unbiased sensitive search for molecular transitions in a sample of circumstellar shells, using the 45 m radio telescope at Nobeyama. Several new molecular transitions, both thermal and maser, have been detected. We present in this paper the result of our molecular line search for 11 stars.

The sources which we have observed are oxygen-rich supergiants, S and C stars, and protoplanetaries. They are in a late stage of stellar evolution and show a high mass-loss rate. A helium-burning core is developed in carbon stars, and carbon atoms are created in the core unless their masses are smaller than 1.5 $M_\odot$. The dredge-up processes change surface chemistry from oxygen-rich to carbon-rich (Iben and Renzini 1983). The rate of mass loss of these stars is between 10^{-6} and 10^{-4} $M_\odot$ yr^{-1}. Molecular line observations of these stars are useful for investigating stellar evolution as well as determining the chemical abundance, mass-loss rates, and bipolar structures of the envelope.

II. OBSERVATIONS

The observations were made in 1987 March and May using the 45 m radio telescope at Nobeyama. We searched for molecular transitions in the range between 85.00 and 89.25 GHz (excluding 87.00–87.25 GHz) in a sample of 11 envelopes known to be rich in carbon or oxygen. The sample also consists of visible and unidentified giants, supergiants, and protoplanetary objects. They all exhibit strong CO emission. The aperture and beam efficiencies at the observing frequencies were 0.35 and 0.67, respectively. The half-power beamwidth was ~23″. The receiver consists of a cooled Schottky diode mixer. The system noise temperature referred to above the atmosphere was 600 K (single sideband). An acoustooptical spectrometer (AOS) with eight arrays and 2048 channels each was used. The frequency resolution and channel separation were 250 and 125 KHz, respectively. The frequency coverage of each array was 250 MHz. A high-resolution eight-array AOS, achieving a resolution of 37 KHz, was used to detect lines or expected strong transitions. It is also used for pointing calibration purpose toward SiO maser sources. The pointing was checked every 2 hr. The pointing accuracy was about $\sim 5''$, on average, in moderate wind conditions (wind speed less than ~ 5 m s^{-1}).

III. RESULTS

The observed sources and their coordinates are listed in Table 1. The results of the line search are summarized in Table 2, and the spectra are displayed in Figures 1–12. The antenna temperature T_A^* quoted in the spectra and tables are corrected for atmospheric attenuation and gain loss of the telescope, but not for the beam efficiency. The frequency resolution in the figures is 250 KHz. A linear baseline removal has been made in most of the spectra. The line width, DV, in Table 2 is the width at zero intensity.

TABLE 1

Observed Sources

Sources	R.A. (1950)	Decl. (1950)	Comment
IK Tau	$03^h50^m43^s.7$	11°15′30″	OH/IR
CRL 618	04 39 33.8	36 01 15	Protoplanetary
VY CMa	07 20 54.7	−25 40 11	OH/IR
CIT 6	10 13 11.0	30 49 17	C-type star
V Hya	10 49 11.3	−20 59 05	C-type star
W Aql	19 12 41.7	−07 08 08	S-type star
χ Cyg	19 48 38.5	32 47 12	S-type star
V Cyg	20 39 41.3	47 57 44	C-type star
CRL 2688	21 00 19.9	36 29 45	Protoplanetary
CRL 3068	23 16 42.4	16 55 10	C-type star
IRC 40540	23 32 00.4	43 16 17	C-type star

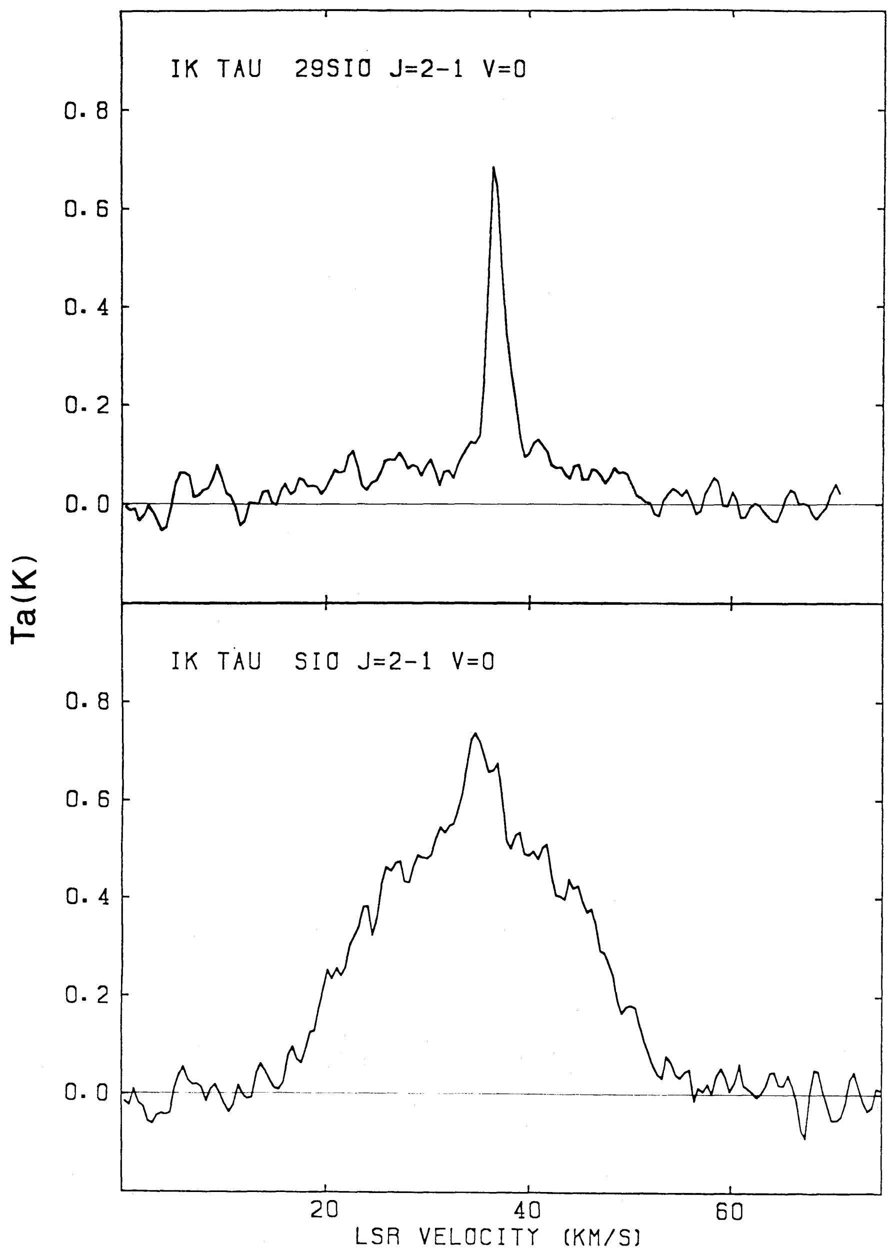

Fig. 1.—The SiO emission in IK Tau. The ^{29}SiO $J = 2$–1 transition (*upper panel*) and the ^{28}SiO $J = 2$–1, $v = 0$ transition (*lower panel*). Linear baseline removal has been made.

TABLE 2

OBSERVATIONAL RESULTS

	LINE INTENSITY (T_A^*)												VELOCITY	
Molecule:	HC_5N	C_4H	^{29}SiO	SiO	$H^{13}CN$	SiO	C_2H	HC_5N	HCN	C_3N	HCN	HCO^+		
Transition:	$J = 32–31$	9–8	2–1	2–1, $v = 1$	$J = 1–0$	2–1, $v = 0$	1–0	33–32	1–0	9–8	1–0, $v = 2$	1–0		
Freq. (GHz):	85.201	85.634 85.672	85.759	86.243	86.340	86.846	87.317 87.402	87.863	88.631	89.045 89.064	89.087	89.188		
SOURCE	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	V_{LSR} (km s^{-1})	DV (km s^{-1})
IK Tau	<0.15	<0.6	0.68	29.4	<0.04	0.72	...	...	...	...	...	...	35	42
CRL 618	<0.11	<0.09	<0.08	<0.09	0.07	<0.08	<0.15	<0.10	0.48	<0.15	<0.15	0.25	−24	22
VY CMA	...	...	...	...	...	...	<0.20	<0.22	0.20	<0.23	<0.20	<0.20	21	67
CIT 6	<0.12	<0.05	<0.04	<0.04	0.25	0.13	<0.06	0.04	0.95	<0.05	4.8	<0.05	−1	32
V Hya	<0.10	<0.06	<0.08	<0.06	<0.08	<0.08	<0.08	<0.07	0.16	<0.10	<0.15	<0.12	−13	34
W Aql	<0.08	<0.09	<0.07	11.5	0.05	0.28	...	...	...	...	...	...	−28	38
χ Cyg	<0.15	<0.08	0.07	25.5	<0.10	0.45	<0.09	<0.05	0.17	<0.06	<0.06	<0.06	12	16
V Cyg	...	...	...	...	...	...	<0.08	<0.05	0.35	<0.08	<0.08	<0.08	17	29
CRL 2688	<0.10	0.15	<0.04	<0.06	0.98	<0.07	0.35	0.20	3.2	0.20	<0.20	<0.20	−32	64
CRL 3068	<0.13	<0.09	<0.07	<0.08	0.25	<0.06	<0.12	<0.12	0.90	<0.13	<0.15	<0.20	−24	29
IRC 40540 ...	<0.08	<0.08	<0.07	<0.05	0.15	0.05	<0.08	<0.06	0.08	<0.09	<0.09	<0.09	−15	30

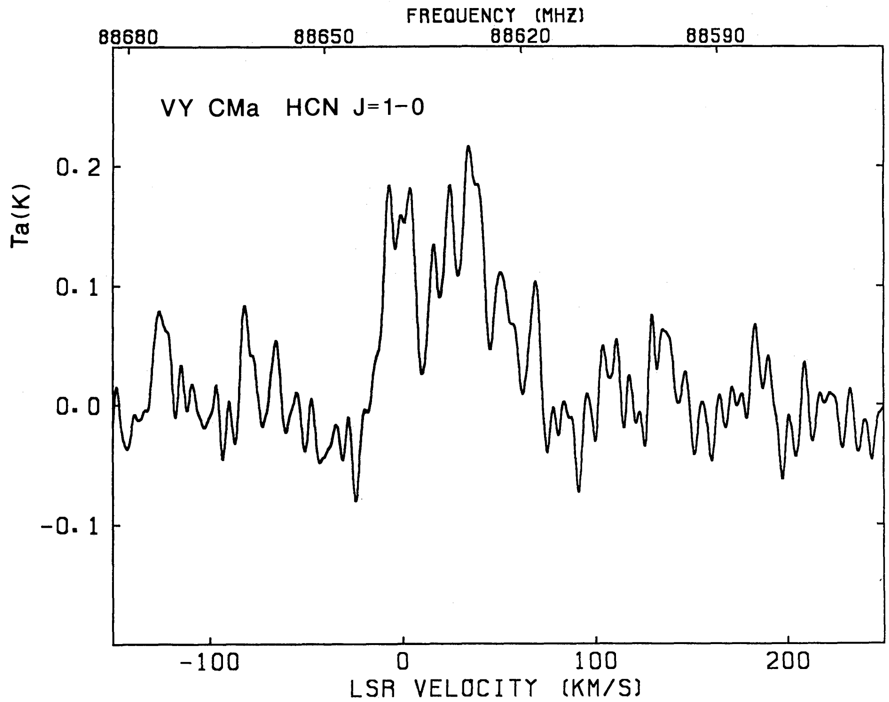

FIG. 2.—HCN $J = 1\text{–}0$ emission in VY CMa. Resolution is 250 KHz, and an eight-channel Hanning smooth was made.

We have detected many lines in the sample of 11 observed stars. HCN has been discovered in VY CMa, an oxygen-rich star. A high-J rotational transition of HC_5N ($J = 33\text{–}32$) has been observed in CRL 2688 and CIT 6. Thermal ^{28}SiO $v = 0$, $J = 2\text{–}1$ emission has been found in CIT 6 and IRC +40540. Two sources, IK Tau and χ Cyg exhibit narrow ^{29}SiO $v = 0$, $J = 2\text{–}1$ lines which are probably produced by a maser effect. A narrow $H^{13}CN$ peak superposed on a broad asymmetric line has been found in CRL 2688. This may be maser emission.

Detailed discussion on individual sources will be given below.

a) *IK Tau*

Figure 1 shows the spectra of the ^{29}SiO $v = 0$, $J = 2\text{–}1$ emission and the ^{28}SiO $v = 0$, $J = 2\text{–}1$ emission. The rare isotope emission is as strong as the main isotope emission in this star. The sharp-peaked ^{29}SiO feature at 35 km s^{-1} accompanied by the weak broad emission is likely to be maser emission, as has

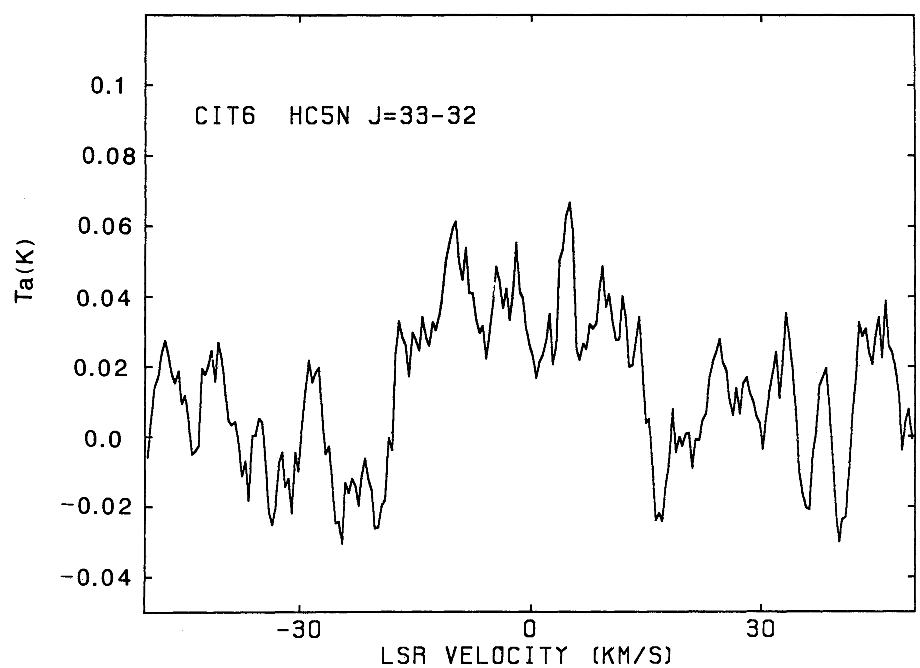

FIG. 3.—HC_5N $J = 33\text{–}32$ emission in CIT 6

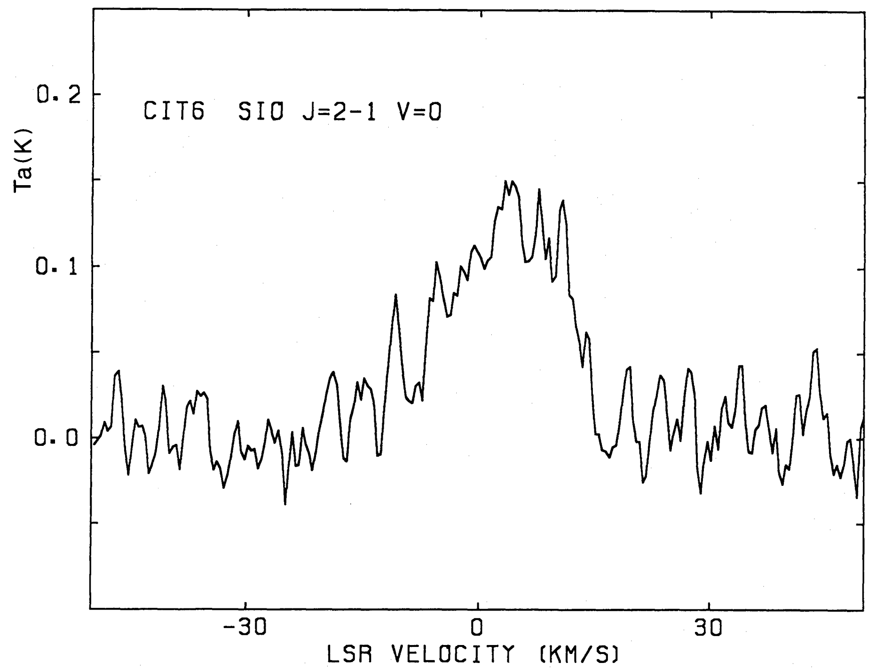

FIG. 4.—SiO $v = 0, J = 2$–1 emission in CIT 6

been found in other stars (Olofsson, Hjalmarson, Rydbeck 1981; Deguchi *et al.* 1983). The weak broad emission in the ^{29}SiO profile is $\sim$0.05 K above zero level, and the width of 40 km s^{-1} is comparable with the width of the ^{28}SiO line. The ^{28}SiO emission also has a weak narrow feature ($DV = 3.8$ km s^{-1}) superposed on the thermal parabolic-shaped emission. This narrow feature may also be a ground-state maser. The pedestal emission is either thermal or consists of a series of weak masers. The ^{28}SiO $J = 2$–1 emission in this star has been observed by Nyman and Oloffson (1986) and Deguchi, Claussen, and Goldsmith (1986), but the narrow feature was not recognized in these prior observations. The ^{29}SiO and ^{30}SiO $J = 2$–1 emission in this star has also been detected by Ukita and Kaifu (1988).

b) *VY CMa*

Figure 2 shows the spectrum of HCN emission in VY CMa. The emission seems to be composed of two narrow peaks and a weak broad emission extended to the high-velocity side up to $V_{LSR} = 60$ km s^{-1}. The center velocity and the full width of the

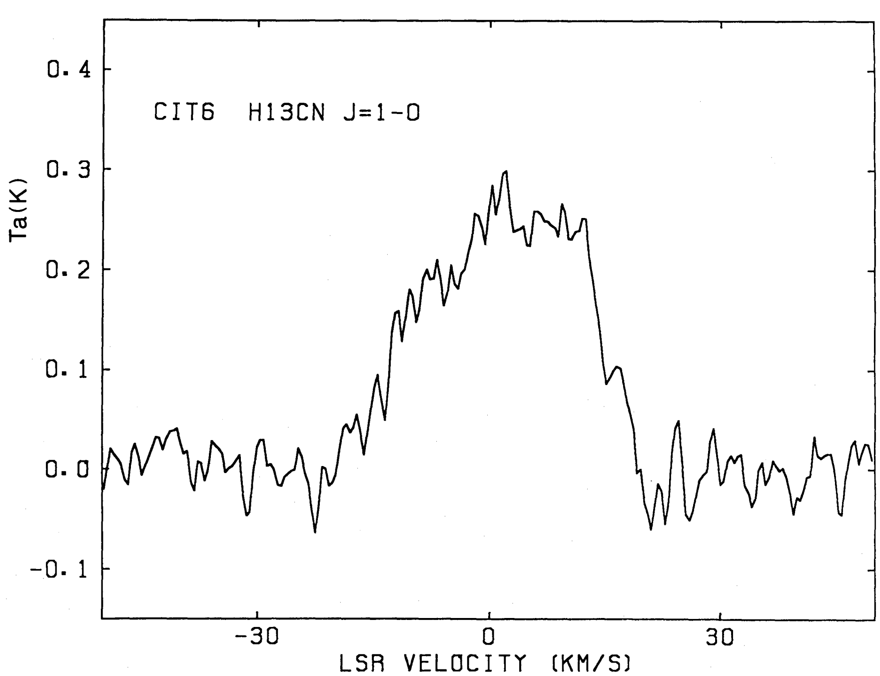

FIG. 5.—$H^{13}CN$ $J = 1$–0 emission in CIT 6

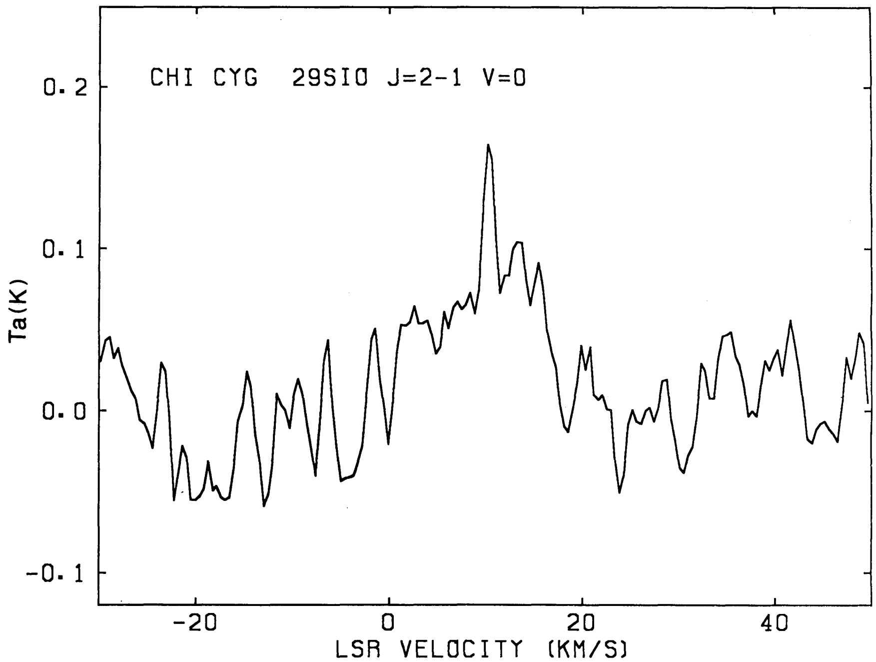

FIG. 6.—^{29}SiO $v = 0, J = 2$–1 emission in χ Cyg

emission line coincide well with those derived from OH 1612 MHz emission (e.g., Cohen *et al.* 1987). A curious fact is that the line is apparently not symmetric with respect to the velocity centroid. The spectrum can be compared with the SiO $J = 1$–0, $v = 0$ profile taken by Deguchi *et al.* (1983) and with the CO $J = 2$–1 profile taken by Zuckerman and Dyck (1986*a*). The central peak at $V_{LSR} = 21$ km s^{-1} is present in CO, SiO, and HCN spectra. However, the low-velocity narrow peak at $V_{LSR} = 0$ km s^{-1} seems to be present only in the HCN spectrum. We have also searched for the HCO^+ $J = 1$–0 transition but have detected no emission stronger than 0.1 K.

c) CIT 6

We have detected HC_5N $J = 33$–32 emission in CIT 6 (Fig. 3). The central velocity and the line width coincide well with those derived from the other molecular transitions (e.g., Lucas *et al.* 1986). The flat-top line shape indicates that the line is optically thin. In addition to the lines mentioned above, we

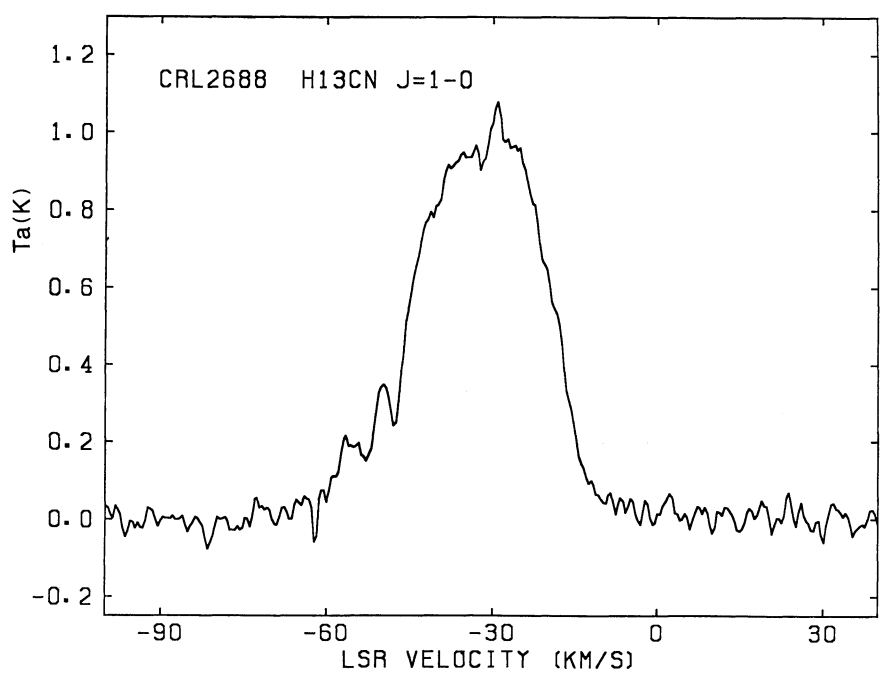

FIG. 7.—$H^{13}CN$ $J = 1$–0 emission in CRL 2268

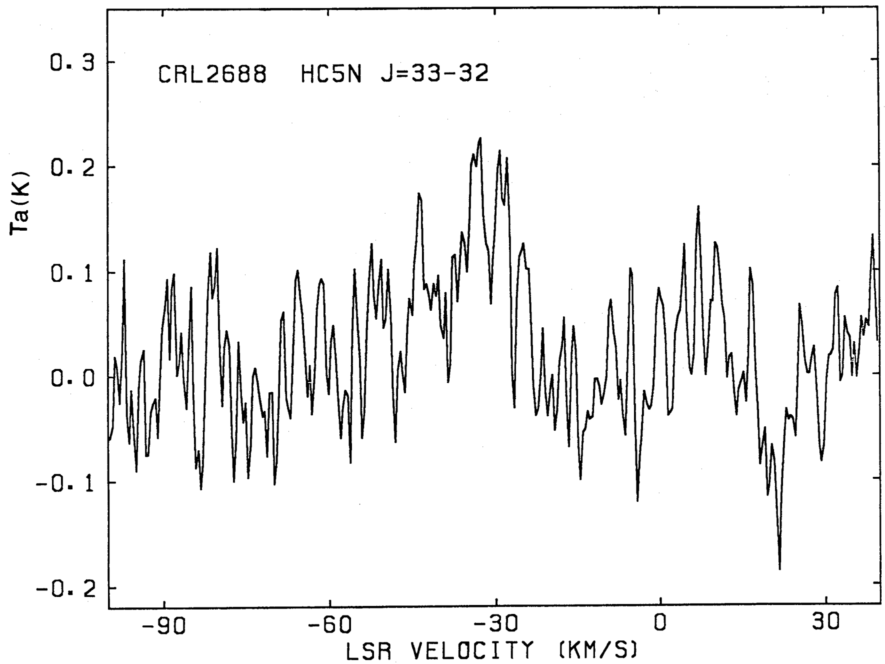

FIG. 8.—HC_5N $J = 33–32$ emission in CRL 2688

have observed vibrationally excited HCN at 89 GHz previously detected at IRAM by Guilloteau, Omont, and Lucas (1987). The peak antenna temperature T_A^* is ~4.8 K. The line intensity (main beam brightness temperature ~7.5 K) seems to be a factor of ~2 weaker than the intensity originally detected at IRAM. This might be due to a pointing error of the telescope in a windy condition or due to linear polarization of this maser line rather than due to a time variation. We have also detected the SiO $J = 2–1$, $v = 0$ thermal emission (Fig. 4). The profile seems to be a standard parabolic line shape which is expected for optically thick emission in a spherically expanding shell. (The $J = 3–2$ and $J = 5–4$ lines of SiO have been detected by Sahai 1987.) We have also found that the $H^{13}CN$ emission of this source shows an asymmetric parabolic profile (Fig. 5).

d) χ *Cyg*

We have detected a sharply peaked feature in the ^{29}SiO $J = 2–1$ profile in χ Cyg (probably maser emission), although the intensity of the isotope emission is less than that of the

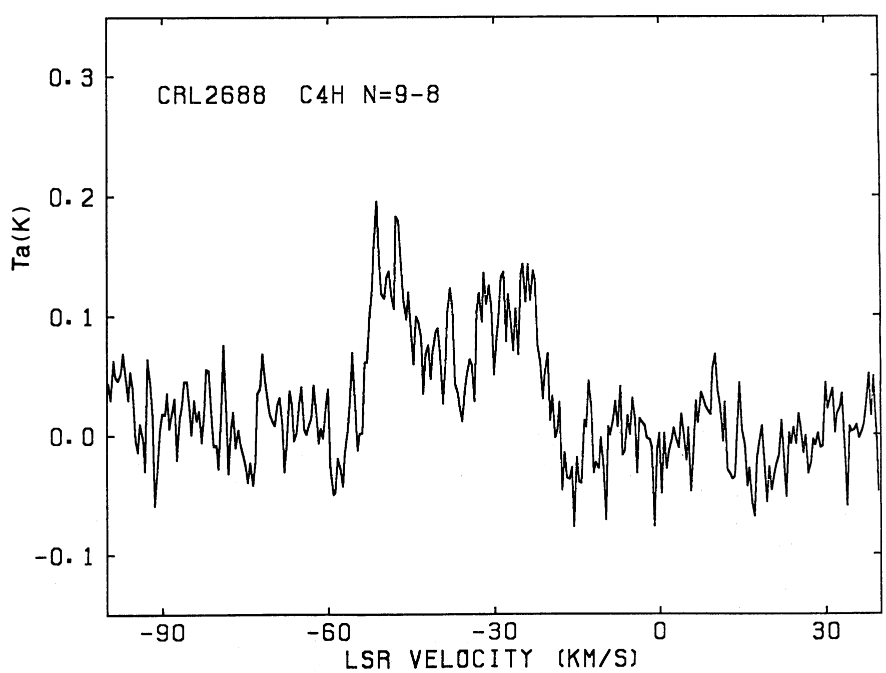

FIG. 9.—C_4H $N = 9–8$ emission in CRL 2268

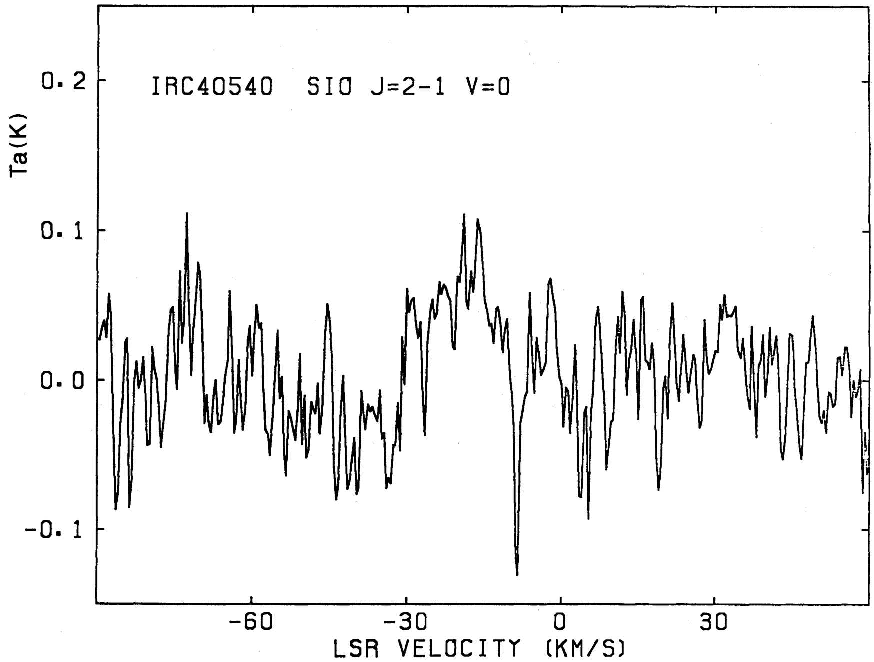

FIG. 10.—SiO $v = 0, J = 2$–1 emission in IRC 40540

main isotope (Fig. 6). The overall line width, 16 km s^{-1}, is consistent with those derived from other line profiles previously detected (i.e., Deguchi, Claussen, and Goldsmith 1986; Sopka *et al.* 1988).

e) *CRL 2688*

Figure 7 shows a peculiar feature of $H^{13}CN$ spectrum. The profile is composed of the central broad emission, the weak wing feature at the low-velocity side, and the spike emission feature near the line center at -29 km s^{-1}. Narrow absorption features appear in the low-velocity wing. We have also taken the HCN spectrum, but the HCN profile does not show any spike feature near the line center. (We also found strong absorption features in the high-velocity wing at $V_{LSR} = -60$, -53, and -47 km s^{-1}. The $H^{13}CN$ and HCN absorption features correspond to the hyperfine splittings of $H^{13}CN$ and HCN in the cool gas expanding at the terminal velocity.) We have tried to resolve the $H^{13}CN$ spike feature spatially by

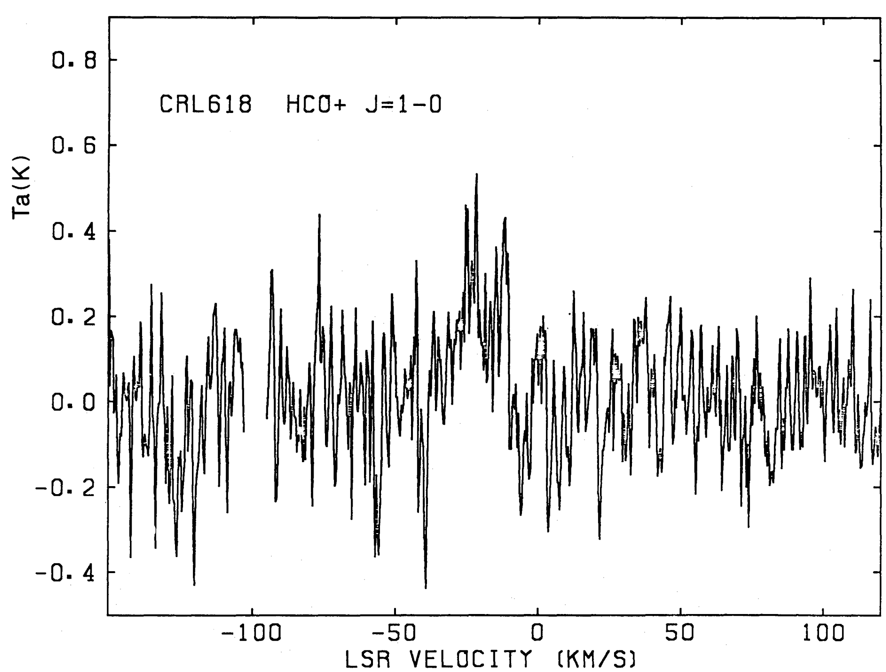

FIG. 11.—HCO^+ $J = 1$–0 emission in CRL 618

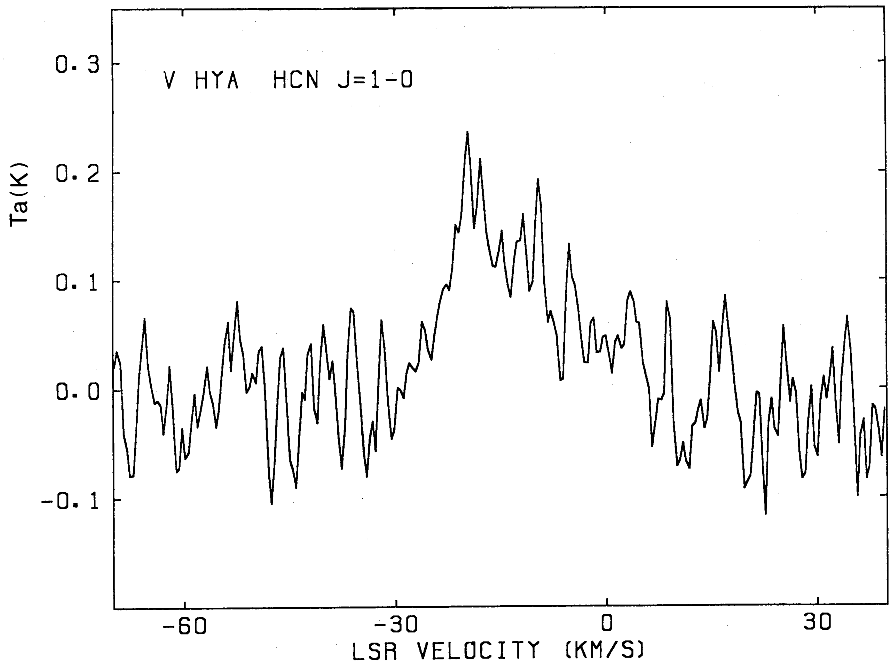

FIG. 12.—HCN $J = 1\text{–}0$ emission in V Hya

taking the spectra at positions of 10″ northwest (in the bipolar flow) and of 10″ northeast (perpendicular to the flow). This feature does not seem to be resolved.

We have also detected the $J = 33\text{–}32$ transition of HC_5N in CRL 2688 (Fig. 8). We have also detected emissions of C_4H $J = 9\text{–}8$ (Fig. 9), C_2H $J = 1\text{–}0$ and C_3N $J = 9\text{–}8$ transitions. The latter two transitions have been detected in this star previously by Lucas *et al.* (1986), and the other transition of C_3N by Sahai, Wootton, and Clegg (1984). These emissions show a typical double-peaked line shape, which is expected when the line is optically thin and the spherically expanding shell is resolved by the telescope beam, or when the flow is bipolar.

f) IRC 40540

We have detected weak thermal SiO $v = 0, J = 2\text{–}1$ emission (Fig. 10). The line width (~ 30 km s^{-1}) agrees well with those derived from CO and HCN spectra obtained at Onsala by Sopka *et al.* (1988). The main beam brightness temperature of $H^{13}CN$ $J = 1\text{–}0$ emission (~ 0.2 K) which we have detected is approximately the same as that observed at Onsala. The $H^{12}CN$ line has marginally been detected in our observation. The intensity of the $H^{12}CN$ line is weaker than that of the $H^{13}CN$ line. This is probably because of a bad weather condition at the time of observation.

g) Additional Sources

In addition to the results described above, we have detected many lines in various sources. A weak $H^{13}CN$ $J = 1\text{–}0$ emission has been detected in the S star, W Aql. Emission of HCO^+ $J = 1\text{–}0$ has also been observed in CRL 618 (Fig. 11). This has been previously detected by Guilloteau, Omont, and Lucas (1987). The three sources, CRL 618, V Cyg, and CRL 3068 show $H^{12}CN$ and $H^{13}CN$ $J = 1\text{–}0$ emissions which have also been detected by Sopka *et al.* (1988). The source V Hya is a carbon star in an initial phase of bipolar nebula formation and the CO $J = 1\text{–}0$ emission in this star shows weak maser features (Zuckerman and Dyck 1986*b*; Tsuji *et al.* 1988). We have detected HCN emission in this star (Fig. 12).

IV. DISCUSSION

a) HCN *in VY CMa*

Radio emission of HCN molecules has been found in four oxygen-rich stars: OH 231.8+4.2, IK Tau, IRC 10420 (Deguchi and Goldsmith 1985; Jewell, Snyder, and Schenewerk 1986), and VY CMa (present paper). In these objects, carbon atoms were supposed to be bound as CO, and no HCN emission was expected in these stars. However, the detection of HCN emission in these four stars indicates that CO molecules can be dissociated and complex chemical reactions can proceed in the outer circumstellar envelope of oxygen-rich stars. The abundance of HCN in the envelope of VY CMa is calculated to be 6.0×10^{-9} per H_2. We have assumed spherically symmetric mass loss of the rate of $3. \times 10^{-5}$ $M_\odot$ yr^{-1} with a constant velocity of 30 km s^{-1} and have performed a statistical equilibrium calculation. The telescope beam is assumed to be an ideal Gaussian, and integration of the outer envelope is taken to the radius of 2.4×10^{17} cm.

Recent discovery of HCO^+ emission in OH 231.8+4.2 (Morris *et al.* 1987) implies that ion-molecule reactions are responsible for producing HCN molecules in the outer circumstellar envelope. The presence of HCO^+ molecules in CRL 618, a carbon-rich star, indicates that the ion-molecular chemistry also plays an important role in the chemistry of the outer circumstellar envelope of carbon stars as well. Although we could not detect HCO^+ emission in VY CMa at the present level of sensitivity, the ion-molecule reactions might produce HCN in the outer envelope of VY CMa. The peculiar line shape of HCN may indicate that the HCN molecule is produced in an active region in the envelope.

b) Peculiar Profile of the $H^{13}CN$ *Spectrum in CRL 2688*

We have found a spike feature in the $H^{13}CN$ spectrum in CRL 2688. This source, a bipolar reflection nebula known as

Egg Nebula, has been extensively observed at infrared and radio frequencies (Ney *et al.* 1975; Nguyen-Q-Rieu, Graham, and Bujarrabal 1984; Kawabe *et al.* 1987). Interferometric observations (Bieging and Nguyen-Q-Rieu 1988) reveal a rotation of the disk with a velocity of ~ 0.5 km s^{-1}.

The origin of the spike feature at -29 km s^{-1} which we have found in the $H^{13}CN$ emission is not clear, and no counterpart appears in the $H^{12}CN$ spectrum. One of possible interpretations of this feature is that the spike emission is due to the presence of a (slowly expanding) extended coronal gas surrounding the expanding hot core which produces the main broad HCN emission. An absorption would appear in this model due to the cool $H^{13}CN$ in the coronal gas which is present in front of the core (P Cygni profile). The size of the core must be much smaller than a beam of the telescope. The $H^{13}CN$ molecule which lies outside of the beam of the core contributes as an emission. Because the coronal gas is slowly expanding (~ 1 km s^{-1}), the absorption would appear in the low-velocity side of the emission. The evidence of such absorption is weak in our on-source spectrum.

One of the difficulties of this interpretation of the spike profile is the absence of the similar feature in the $H^{12}CN$ spectrum. We have to consider that the kinetic temperature of the coronal gas is higher than that of the core and that the density of the gas is high enough to excite the HCN but not $H^{13}CN$ due to its low optical depth of the line. In this case, no absorption feature is expected in the HCN spectrum.

The other interpretation of the spike feature in the $H^{13}CN$ spectrum is, of course, that it is an anomalous excitation. This interpretation can be supported by the discovery of $H^{13}CN$ $J = 1$–0 maser in Y CVn (Izumiura *et al.* 1987). The hyperfine splittings of $H^{13}CN$ should appear at velocities -4.9, 0, 7.3 km s^{-1} with intensity ratios 1:5:3, respectively. The hyperfine features do not seem to be present in our spectrum. This fact strengthens the interpretation that the spike is produced by a weak unsaturated maser, where the weaker components do not appear due to the low optical depth.

For checking the above hypotheses, we have mapped the peculiar $H^{13}CN$ emission by taking spectra at the off-centered positions. The spike emission was not spatially resolved. This fact also supports the idea that the spike feature is a weak maser emission.

We have calculated the isotope abundance ratio ($^{12}C/^{13}C$) from the main broad component of the HCN line (excluding the peculiar feature in the $H^{13}CN$ spectrum). Statistical equilibrium calculations have been made by assuming a spherically symmetric mass loss with a rate of 10^{-4} $M_\odot$ yr^{-1}. A constant expansion velocity of 30 km s^{-1} and a kinetic temperature distribution of $30\,(R/5 \times 10^{15}\ \mathrm{cm})^{-0.25}$ K have been assumed. Of course, the assumption of spherical symmetry and constant mass-loss rate might be questionable in this source. However, bipolarity of the envelope may not influence the isotope ratio unless the density variation in the axial direction is irregular. The HCN abundance of 5.5×10^{-8} per H_2 and ($H^{12}CN/H^{13}CN$) = 4.6 are obtained. The molecular abundance and the isotopic ratio increases with decreasing the assumed kinetic temperature. It is well known that the isotope ratio ($^{12}C/^{13}C$) is much lower in carbon star atmospheres than in the normal interstellar medium (Wannier and Sahai 1977). This is due to dredge-up of materials formed by the nucleosynthesis of CNO cycle at the core of the star (Iben and Renzini 1983). It should be noted that the high isotopic ratio ($^{12}C/^{13}C$) of ~ 50 has been derived for IRC 10216 by Nguyen-Q-Rieu *et al.* (1984).

c) ^{29}SiO *Maser*

We have detected ^{29}SiO $v = 0$, $J = 2$–1 emission in χ Cyg and IK Tau. The profile shows a sharp spike and broad emission. Due to the sharpness of the feature, the spike may be maser emission. The velocity of the ^{29}SiO $J = 2$–1 maser is close to the stellar velocity determined from the thermal emission of CO and SiO. Similar ground-state masers have been found for the ^{29}SiO $J = 1$–0 transition (Kaifu *et al.* 1987). A pump mechanism for the ground-state ^{29}SiO maser proposed for Orion by Deguchi and Nguyen-Q-Rieu (1983) can be applied to χ Cyg and IK Tau.

d) High Rotational Transitions of HC_5N

High rotational transitions of HC_5N (J up to 35) have been detected in IRC +10216 (Bujarrabal *et al.* 1981). The present observation shows that the emission from these high rotational transitions are also present in CRL 2688 and CIT 6. Lower rotational transitions have been detected in CRL 2688 by Truong-Bach, Graham, and Nguyen-Q-Rieu (1987), and the velocity and width coincide well with those of our spectra.

Collisions with hydrogen molecules could excite these high rotational transitions if the kinetic temperature of the gas is high enough. However, infrared pumping through vibration-rotation bands would be more plausible for exciting these high rotational transitions (Deguchi and Uyemura 1984). The temperature of grains surrounding CRL 2688 has been found to be ~ 150 K, and the total luminosity $\sim 1.8 \times 10^4$ $L_\odot$ (Ney *et al.* 1975). The far-infrared radiation of grains is enough to excite the ν_{11} vibrational level from the ground vibrational state (~ 120 cm^{-1} higher from the ground state).

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