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DETECTION OF A SECOND, STRONG SUBMILLIMETER HCN LASER LINE TOWARD CARBON STARS

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ABSTRACT

We have searched for and found strong laser action at a frequency near 891 GHz in the $J = 10$–9 transition between the (11^10) and (04^00) vibrationally excited states of HCN toward the mass-losing carbon stars IRC +10216, CIT6, and Y CVn. This line is part of a Coriolis-coupled system that has been well studied in the laboratory during the early years of molecular laser spectroscopy. This system also includes the 805 GHz $J = 9$–8 transition within the (04^00) state that was discovered toward IRC +10216 by Schilke, Mehringer, & Menten and that we also find to be lasing in CIT6. Toward both stars, the 891 GHz line is about an order of magnitude stronger than the 805 GHz line, and observations spaced about half a year apart provide clear evidence for temporal variability. As was concluded for the latter, given that the lines' lower energy levels are 4200 K over the ground state, they must arise from the innermost parts of the stars' circumstellar envelopes. Future high-resolution interferometric observations with the Atacama Large Millimeter Array of the HCN laser lines will yield important information on the dust formation zone of carbon stars.

Subject headings: circumstellar matter — masers — stars: AGB and post-AGB — stars: carbon — stars: mass loss

1. INTRODUCTION

Hydrogen cyanide (HCN) is one of the most abundant molecules in the atmospheres and envelopes of carbon stars (Tsuji 1964). In addition to thermal emission from various rotational transitions within different vibrationally excited states at millimeter, submillimeter, and far-infrared wavelengths (see, e.g., Cernicharo et al. 1996), a few lines have been found to be inverted toward several stars. Maser action in the $J = 1$–0 ground-state HCN transition was observed by Izumiura et al. (1987, 1995a) toward several optical or "blue" carbon stars, i.e., objects with relatively low mass-loss rates, $\dot{M}$, of order $10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. Millimeter-wavelength maser emission from vibrationally excited lines was detected toward the high mass-loss ($\gtrsim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$) objects CIT6 (RW LMi; Guilloteau, Omont, & Lucas 1987) and IRC +10216 (CW Leo; Lucas & Cernicharo 1989).

In 1998, we detected a surprisingly strong, narrow line near 805 GHz toward the carbon star IRC +10216 that was identified as the nonthermally excited $J = 9$–8 rotational transition within the (04^00) vibrationally excited state of HCN (Schilke, Mehringer, & Menten 2000, hereafter SMM00). SMM00 concluded that the line must originate from the innermost envelope of IRC +10216 within a radius of 0″.08 or $\approx 3.5r_*$, where the temperature is about 1000 K. Analyzing the excitation, they concluded that the pumping is related to the Coriolis coupling of two vibrational states [the (11^10) and (04^00) states]. These (11^10)/(04^00) lasers have been well studied in the laboratory (Gebbie, Stone, & Findlay 1964; Mathias, Crocker, & Wills 1965). We predicted that, analogous to the laboratory HCN laser lines, other transitions of this system also should be inverted. In particular, we pointed out the (11^10)–(04^00), $J = 10$–9 cross-ladder transition at 890.76 GHz and the 894.31 $J = 10$–9 line within the (04^00) state, because they were observable from terrestrial observatories (see Fig. 1 for a diagram of the relevant HCN energy levels). In this paper, we report the search for these transitions in IRC +10216 and the carbon stars CIT6 and Y CVn.

Both IRC +10216 and CIT6 have high mass-loss rates (2×10^{-5} and $6 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, respectively; Crosas & Menten 1997; Schöier & Olofsson 2001) and, consequently, dense circumstellar envelopes. Y CVn, on the other hand, is a blue carbon star with $\dot{M} = 1.2 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ (Olofsson et al. 1993).

2. OBSERVATIONS

We searched for the (11^10)–(04^00), $J = 10$–9 cross-ladder transition at 890.761 GHz in IRC +10216, CIT6, and Y CVn, the 894.31 $J = 10$–9 line within the (04^00) state in IRC +10216, reobserved the (04^00), $J = 9$–8 line in IRC +10216 and searched for it in CIT6 and Y CVn, and searched for the ground-state HCN(10–9) line in all three sources. In Y CVn, we additionally observed the ground-state HCN(4–3) line.

The observations were carried out in 2000 March (IRC +10216, CIT6, and Y CVn) and November (IRC +10216 and CIT6), and 2001 March and November (IRC +10216) with the 850 GHz receiver of the Caltech Submillimeter Observatory (CSO) 10.4 m telescope on Mauna Kea, Hawaii. Single sideband system temperatures during all observations were in the range 3000–10,000 K under good weather conditions, i.e., time periods when the precipitable water vapor content was around or below 1 mm.

Pointing was checked by observing the detected strong laser line at 891 GHz and the CO(7–6) line toward IRC +10216 itself, resulting in a pointing accuracy of $\approx$3″. However, in the 2000 March observations the intensities of the line varied widely from scan to scan, probably due to anomalous refraction effects. We have removed the spectra with weak lines from the analysis but our overall calibration accuracy is degraded, and we estimate it to be not better than $\approx$50%. We estimate the calibration accuracy of the other observations to be in the 30% range. At 805 and 891 GHz, the beam widths are 9″ and 8″ (FWHM), respectively, and the main beam efficiency was found to be 30% from

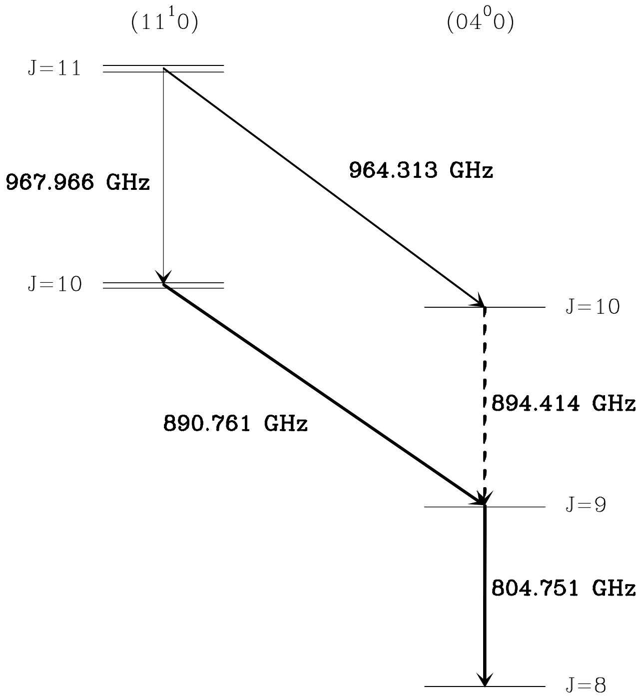

FIG. 1.—Excerpt from the level diagrams of the (11^10) and (04^00) vibrationally excited states of HCN near the Coriolis resonance involving the $J = 8$–12 rotational levels. *Arrows*: Frequencies of prominent laser transitions measured in the laboratory by Hocker & Javan (1967). *Bold arrows*: Lines observed toward IRC +10216. *Dashed arrow*: (04^00), $J = 10$–9 line not detected by us.

observations of the CO(7–6) line in IRC +10216 at 806 GHz.[1] The spectrometer and observing procedure are described by Menten & Young (1995). The ground-state HCN(4–3) line in Y CVn was observed in 2000 March with the facility 345 GHz receiver with a beamwidth of 25″ (FWHM) and a main -beam efficiency of 78%.

3. RESULTS AND DISCUSSION

Our results are summarized in Tables 1 and 2. We detected the (11^10)–(04^00), $J = 10$–9 line in all three sources, and the line intensity (which exceeds thermal values by more than 1 order of magnitude), variability, and narrow line widths prove that the line is indeed lasing. The (04^00), $J = 9$–8 line was found in IRC +10216, CIT6, and very tentatively in Y CVn and also appears to show laser action. The (04^00), $J = 10$–9 line, which SMM00 suggested might be a laser line, was not found in IRC +10216, the only source toward which we searched for it. In the following, we discuss the results for the individual sources.

[1] Information on http://www.cso.caltech.edu.

3.1. *IRC +10216*

The lines detected toward IRC +10216 are shown in Figure 2. The ground-state HCN(10–9) line shows a marked asymmetry with respect to the center velocity of the source, probably due to self-absorption at blueshifted velocities (i.e., toward the part of the envelope approaching us). The laser lines observed toward IRC +10216 are plotted again in Figure 3 with higher resolution, together with the (04^00), $J = 9$–8 laser line observed in 1998. The latter line appears to be weaker in 2000 that it was in 1998, but our calibration uncertainties are too large to say anything definite about this. The line shape, however, has changed considerably (Fig. 3): the line is much more symmetric in 2000 than it was in 1998, and the line center is redshifted instead of blueshifted. In 2000 March and November and in 2002 March [the latter observation being contemporaneous with an observation of the (04^00) line], the (11^10)–(04^00), $J = 10$–9 laser line is about a factor of 10 stronger than the (04^00), $J = 9$–8 line and appears to be almost symmetric, although blueshifted relative to the center velocity and with line wings. Apart from these wings, the blue flank of this line has exactly the same shape and velocity as the 1998 (04^00), $J = 9$–8 line (Fig. 3). This suggests that the blue side traces a physical limit of the expansion velocity in the gas in which these lines are generated: one finds a velocity of -29 km s^{-1}, corresponding to an expansion velocity of 3 km s^{-1}. The widest extent of the wings of the (11^10)–(04^00), $J = 10$–9 line and the 1998 (04^00), $J = 9$–8 line corresponds to an expansion velocity of 6 km s^{-1}, translating to stellar radii of $2.4R_*$and $3.8R_*$ for 3 and 6 km s^{-1}, respectively, using the continuous velocity field derived by Groenewegen (1997). On the basis of line intensity arguments for quasi-thermal highly vibrationally excited lines, SMM00 had estimated that these are emitted from a region inside of $3.5R_*$, which is in excellent agreement with the estimate obtained here. The dramatically lower line flux density of the (11^10)–(04^00), $J = 10$–9 line on 2001 November is obvious and established beyond calibration uncertainties. However, our time coverage is much too sparse to state anything about variations of the laser intensity with infrared phase. Such a correlation is firmly established in the case of silicon monoxide masers around O-rich red giants (Martínez, Bujarrabal, & Alcolea 1988).

We did not detect the (04^00), $J = 10$–9 line at 894 GHz, although we predicted it to be present because of

TABLE 1
RESULTS OF HCN OBSERVATIONS: THERMAL LINES

Source	Transition	Frequency (GHz)	T_R^* (K)	$v_{\rm LSR}$ (km s^{-1})	Δv (km s^{-1})
IRC + 10216	(000), $J = 10$–9	885.97	31.8 (0.5)	−24.8 (0.1)	17.0 (0.1)
	($01^{1c}0$), $J = 10$–9	885.86	6.5 (0.5)	−25.9 (0.1)	17.6 (0.1)
	(04^00), $J = 10$–9	894.41	<0.2	...	...
CIT6	(000), $J = 10$–9	885.97	1.7 (0.5)	-0.5 (1.8)	18.3 (0.7)
Y CVn.......................	(000), $J = 4$–3	354.51	0.9 (0.1)	22.4 (0.1)	8.3 (0.2)
	($01^{1c}0$), $J = 4$–3	354.46	0.2 (0.1)	21.5 (0.5)	8.5 (1.5)
	(000), $J = 10$–9	885.97	<0.3	...	...

TABLE 2

RESULTS OF HCN OBSERVATIONS: LASER LINES

Source	Transition	Frequency (GHz)	Epoch	S^{peak} (Jy)	v_{LSR}^{peak} (km s^{-1})	v_{LSR}^{range} (FWZM) (km s^{-1})
IRC + 10216.............	(04^00), $J = 9$–8	804.75	1998 May	1420	−27.3	[−31, −18]
	...	...	2000 Mar	840	−26.7	[−29, −21]
	(11^10)–(04^00), $J = 10$–9	890.76	2000 Mar	6120	−26.4	[−31, −20]
	...	...	2000 Nov	4430	−26.3	[−30, −20]
	...	...	2001 Mar	9230	−26.3	[−31, −20]
	...	...	2001 Nov	900	−23.0	[−31, −20]
CIT 6	(04^00), $J = 9$–8	804.75	2000 Mar	110	−6.5	[−9, −2]
	(11^10)–(04^00), $J = 10$–9	890.76	2000 Mar	1090	−5.1	[−11, 2]
	...	...	2000 Nov	1150	−5.4	[−12, 0]
Y CVn........................	(11^10)–(04^00), $J = 10$–9	890.76	2000 Mar	140	17.5	[11, 21]

laboratory laser analogies. In fact, it turns out that the listing of this line as a laboratory *laser* line by De Lucia & Helminger (1977) is probably erroneous. The original paper by Lide & Maki (1967) lists only four laser lines: the (11^10)–(04^00), $J = 10$–9 line at 891 GHz, the (04^00), $J = 9$–8 line near 805 GHz, both found by us, plus the (11^10), $J = 11$–10 line at 968 GHz and the (11^10)–(04^00), $J = 11$–10 line at 964 GHz, which are inaccessible from the ground. They also state that no laser action was observed in the 894 GHz line.

We were unable to locate exact transition strengths to perform quantitative calculations of the maser gains, but maximum resonance occurs at $J = 10$ (see Fig. 1). Lide & Maki (1967) state that the gain of the (11^10)–(04^00), $J = 10$–9 laser is 2.5 times that of the (11^10)–(04^00), $J = 11$–10 line. This means that population transfer from the (11^10) into the (04^00), $J = 9$ level is more efficient than to the (04^00), $J = 10$ level, which implies that the (04^00), $J = 10$ population will be *smaller* that the $J = 9$ population, and no laser action will occur in the (04^00), $J = 10$–9 line, which is what we observe. In the (11^10) level, this results in a more efficient draining of the $J = 10$ level than of the $J = 11$ level, which results in laser action in the (11^10), $J = 11$–10 line at 968 GHz.

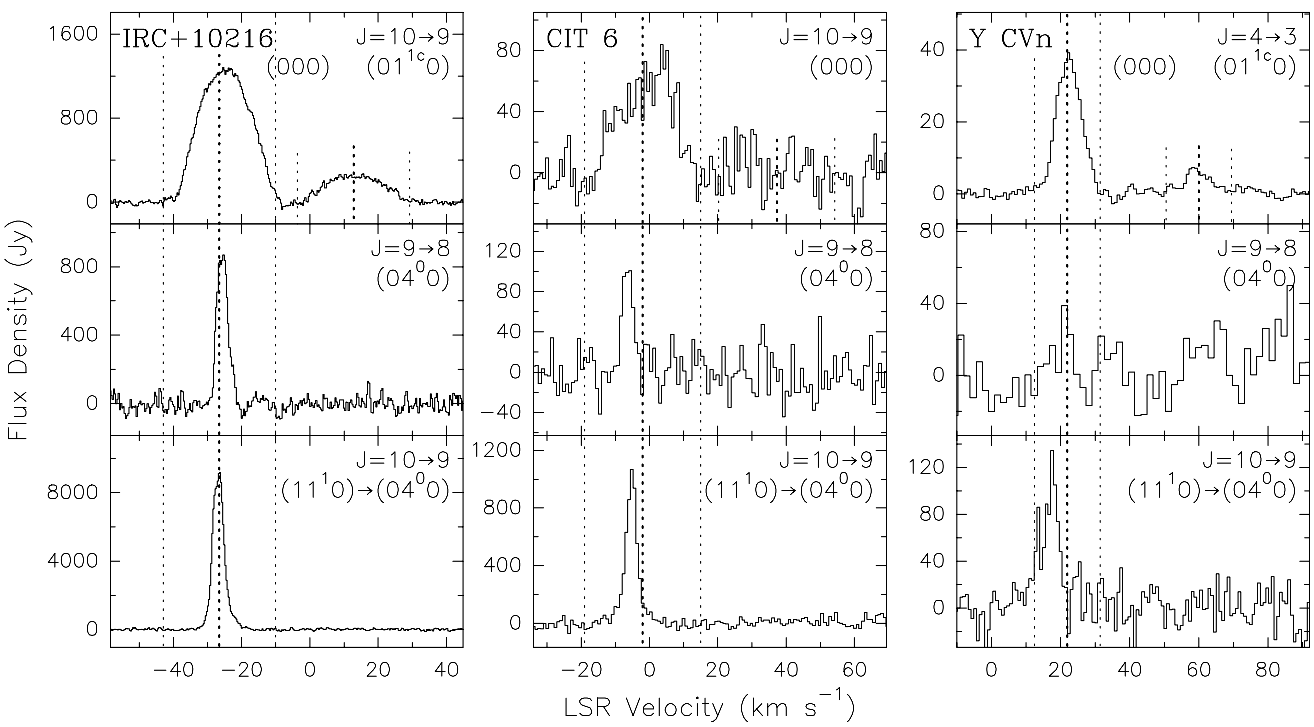

FIG. 2.—Spectra of various submillimeter HCN transitions observed toward the carbon stars IRC + 10216 (*left*), CIT 6 (*center*), and Y CVn (*right*), respectively. *Bottom panel*: Spectrum of the strong (11^10)–(04^00), $J = 10$–9 laser transition. *Middle panel*: Spectrum of the (04^00), $J = 9$–8 laser line. *Top panel*: Quasi-thermally excited HCN emission spectra. In the case of IRC + 10216, the stronger and the weaker lines are the $J = 10$–9 rotational lines from within the (000) and the $(01^{1c}0)$ vibrational states, respectively. *Vertical dotted lines centered near the velocity centroid of the lines in question*: Stellar velocity. *Dotted lines to the left and right*: Terminal expansion velocities of the respective stellar outflows from Loup et al. (1993). For CIT 6, the (000) $J = 10$–9 is clearly evident in the top panel, while the corresponding $(01^{1c}0)$ line is not detected. For Y CVn, the top panel shows the $J = 4$–3 rotational lines from the (000) and $(01^{1c}0)$ states. All spectra were taken in 2000 March.

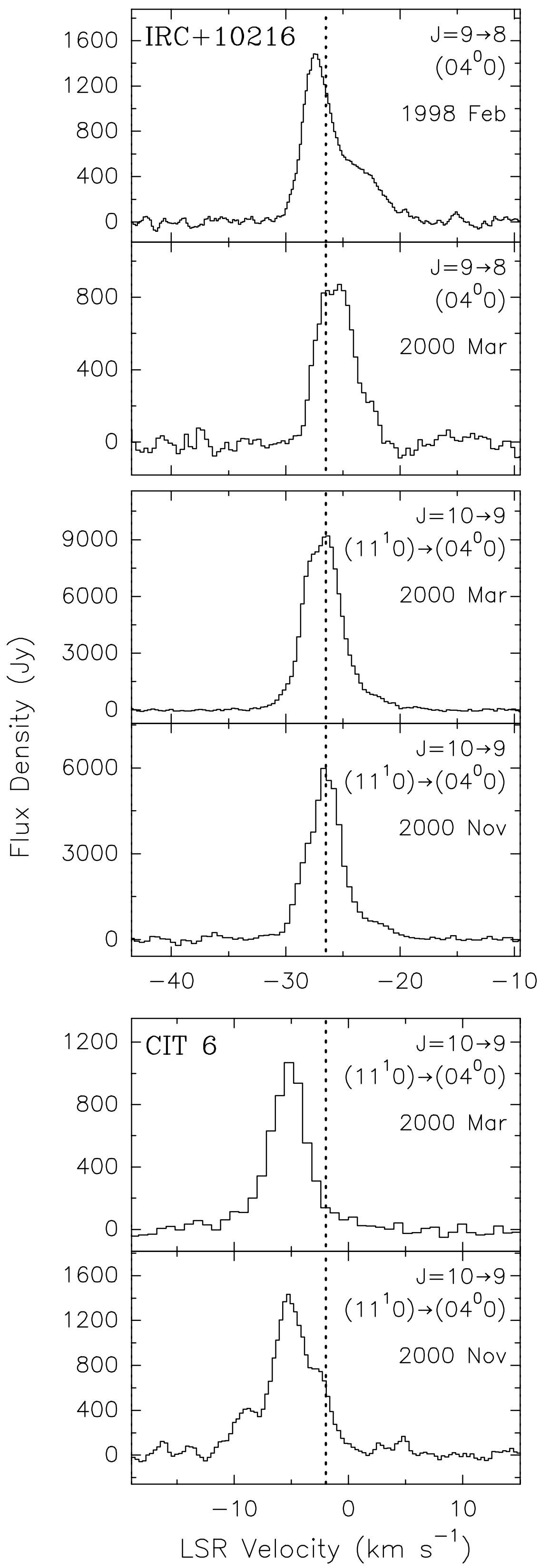

FIG. 3.—*Top two panels*: Spectra of the 805 GHz (04^00), $J = 9$–8 laser line observed toward IRC +10216 in 1998 February and 2000 March. *Lower four panels*: Spectra of the 891 GHz (11^10)–(04^00), $J = 10$–9 laser line taken on 2000 March and November and 2001 March and November. In each panel, the dotted line marks the stellar velocity. Note that the velocity scale spans the whole velocity range in the outer circumstellar envelope (see Fig. 2).

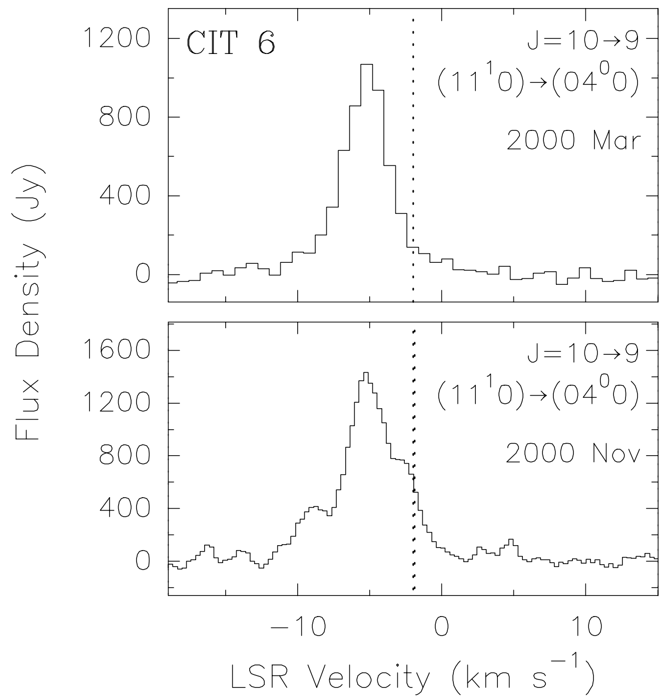

FIG. 4.—Spectra of the 891 GHz 11^10–(04^00), $J = 9$–8 laser line observed toward CIT6 in 2000 March and November. *Dotted line*: Stellar velocity. Note that the velocity scale spans the whole velocity range in the outer circumstellar envelope (see Fig. 2).

3.2. *CIT6*

CIT6 shows a very pronounced asymmetry in the ground-state $J = 10$–9 line. Both the (04^00), $J = 9$–8 and the (11^10)–(04^00), $J = 10$–9 laser lines are detected, the latter being an order of magnitude stronger than the former, just as in IRC +10216 (see Fig. 2). As shown in Figure 4, the line shape of the (11^10)–(04^00) line has changed markedly between 2000 March and November, particularly in the bluest portion of the line and just below the systemic velocity. Both laser lines are completely blueshifted with respect to the central velocity of the source. Possible reasons for this phenomenon are discussed in § 3.3.

3.3. *Y CVn*

In this source, the $J = 10$–9 ground-state transition is not detected, but the $J = 4$–3 line is observed. In order to remain undetected, the $J = 10$–9 line must be intrinsically weaker than the $J = 4$–3 line.

The (04^00), $J = 9$–8 line is very tentatively detected, but the (11^10)–(04^00), $J = 10$–9 is clearly present, showing that, again, the latter line is much stronger than the former. As in CIT6, the line is completely blueshifted with respect to the center velocity and appears to cover a significant fraction of the velocity width of the ground-state line. A possible reason for this blueshift could be blocking of the redshifted emission by the star (which would mean that the emission in these two sources comes from very far in and probably does not tie in with the velocity width) or that maybe the lasers amplify submillimeter continuum from the star. The HCN and $H^{13}CN$ $J = 1$–0 maser emission observed by Izumiura, Fujiyoshi, & Ukita (1995a) and Izumiura, Ukita, & Tsuji (1995b) between 1987 and 1994, accounting for emission from the three different hyperfine components each, seems to cover the whole $\pm v_\infty$ velocity interval, where v_∞ is the terminal expansion velocity (8 km s^{-1}; Loup et al. 1993). Interestingly, in 1993 the bulk of the 1–0 maser emission appears to be *redshifted* relative to the stellar velocity. If, as one might expect from the $J = 1$ level's low energy above the ground state, the 1–0 maser emission arose from the outer envelope of Y CVn, one might, analogously to the case of the 1612 MHz OH line in the shells around OH/IR stars, expect to observe a double-peaked line with "horns" at $\pm v_\infty$. We note that in order for the hyperfine components to be observable, the gain of the 1–0 maser must be modest and should, in principle, be determinable from the hyperfine component ratios. This is consistent with the relatively low intensity of the maser emission.

4. EXCITATION CONSIDERATIONS

Based on a rough estimate of the HCN formation rate, considering that the newly formed HCN molecules are formed in different vibrationally excited states, and taking into account the different decay rates of these states, SMM00 concluded that chemical pumping was a viable inversion mechanism for the 805 GHz laser line, and the same arguments may be used to explain the laser discussed here. Skatrud & De Lucia (1985) give an alternative mechanism that is supported by their laboratory evidence and theoretical calculations; in their scheme, vibrational energy transfer from excited N_2 to the HCN(100) state is followed by thermal excitation to the (110) state, while lower laser levels are rapidly depopulated down the (040) stack. Given the vastly different excitation conditions in a laboratory discharge and a stellar atmosphere, where most probably entirely different partial pressures of the constituents pertain, it is highly questionable whether this mechanism also works in the stellar case.

5. OUTLOOK

Future observations with the *Stratospheric Observatory for Infrared Astronomy* (*SOFIA*; Becklin 1997) will allow searches for the 964 and 968 GHz transitions and thus help establish a more complete picture of circumstellar HCN laser excitation. Observations of the 805 and 891 GHz lasers and the millimeter-wavelength HCN maser lines with the Atacama Large Millimeter Array (ALMA; see Wootten 2001) with $\lesssim 0\farcs1$ resolution will allow imaging of the laser emission. Moreover, as outlined by Menten (1996), the strong laser lines may serve as phase references: self-calibration of the laser line emission and transfer of the thus determined phase and amplitude correction factors to neighboring frequency intervals containing (nonlaser) lines and/or continuum emission will allow near-perfect imaging that might otherwise be difficult to attain at such high frequencies at these resolutions and thus allow fascinating studies of the structure, dynamics, and chemistry of the acceleration zone of circumstellar outflows. For example, it will be possible to observe the 806.65 GHz CO 7–6 line simultaneously with the 805 GHz HCN laser line with ALMA 8 GHz wide correlator bandwidth.

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