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AMMONIA IN IRC +10°216: THE INVERSION LINES AS A PROBE OF ENVELOPE THERMAL STRUCTURE

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ABSTRACT

The ammonia molecule is shown to be an effective probe of gas temperature in circumstellar envelopes of late-type stars. The inversion lines of ammonia, being narrowly separated in frequency but arising from states with widely different excitation requirements, are found to be capable of yielding the detailed thermal structure of circumstellar envelopes. Observations of IRC +10°216 have been made with possible detections of the (1, 1) and (2, 2) lines. Calculations performed for this star show that the (1, 1) line is expected to be emitted over an extended region, whereas the (2, 2) state is excited only in the inner part of the envelope. The observational results are compared to the model.
Subject headings: infrared: sources — interstellar: molecules — stars: carbon

I. INTRODUCTION

The importance of mass loss in the late stages of stellar evolution is now generally recognized. Continuous mass loss in the red-giant phase results in an extended circumstellar envelope which was first studied by infrared photometry (Woolf and Ney 1969; Gehrz and Woolf 1971), and this has led to the realization that dust grains play a major role in the mass-loss process (Gilman 1972; Kwok 1975; Lucy 1976). Molecules in the envelope give rise to both maser and thermal radio-line emission which provides useful tests of dynamical models (Kwok 1976; Elitzur, Goldreich, and Scoville 1976; Olnon 1977; Kuiper *et al.* 1976). Recently developed infrared spectroscopic techniques (cf. Merrill and Ridgeway 1979) also show promise as a probe of the warmer and denser regions of the envelope.

The carbon star IRC +10°216 (CW Leo) is particularly suitable for detailed study of the mass-loss process. It has a strong infrared continuum detectable as far as 1 mm (Campbell *et al.* 1976) and an extensive envelope rich in molecules. Detection of new molecules provides information about not only the chemistry of the envelope but also the physical conditions required to excite the molecules. Recently, rotation-vibration transitions of NH_3 have been detected in IRC +10°216 against the infrared continuum (Betz, McLaren, and Spears 1979). In this paper, we show that the inversion lines of ammonia can be used as an effective probe of the thermal structure of circumstellar envelopes. Radio observations of the (1, 1) and (2, 2) lines of NH_3 in IRC +10°216 are also reported and the results are discussed briefly.

II. OBSERVATIONS

The observations were made in 1979 April and May and 1980 February with the 46 m telescope of the Algonquin Radio Observatory,[1] which has a beamwidth of 1'.4 and an estimated beam efficiency $\eta_B \approx 0.28$ at 23.7 GHz. A cooled parametric-amplifier receiver with $T_s \sim 230$ K was used with a very wide band, 100 channel filter spectrometer (McLeish 1973). The center frequency was adjusted to include both the (1, 1) and (2, 2) transitions of NH_3 within the 90 MHz observing window and was shifted by 1–2 channels on different occasions during the observing session as a check againt possible instrumental effects.

All observations were made using a new technique designed to provide a stable baseline for the wide observing window. This technique has been used successfully at Algonquin Radio Observatory (cf. Bell 1980, and references therein) and is a simple adaptation, to spectral-line observations, of the common "wagging" technique used at most observatories to measure weak continuum sources. In practice it is similar to the conventional Dicke-switched mode of operation, with the exception that the off-source spectrum is obtained with the source in the reference beam instead of returning the telescope to the on-source starting hour angle. The amplitude of a spectral feature in the resulting difference spectrum (on-source minus off-source) is thereby increased by a factor of 2 over that obtained using the conventional Dicke-switched mode of operation. This new technique thus combines the stability of Dicke switching with the sensitivity of total-power operation. The fact that the off-source spectrum is not obtained over exactly the same hour-angle range was not found to affect the cancellation of non–source-related baseline components when a difference spectrum was taken. And since the continuum flux of IRC +10°216 is nondetectable at 1.4 cm, source-produced baseline components were not a problem.

In processing the data an appropriate factor was applied to each scan to correct for the variations in antenna gain and atmospheric attenuation with zenith angle. The data were then averaged separately for each observing session. The final spectrum was obtained by averaging together the spectra of the three observing sessions, smoothing over 1 channel, and removing a

[1] The Algonquin Radio Observatory is operated by the National Research Council of Canada, Ottawa, as a national radio astronomy facility.

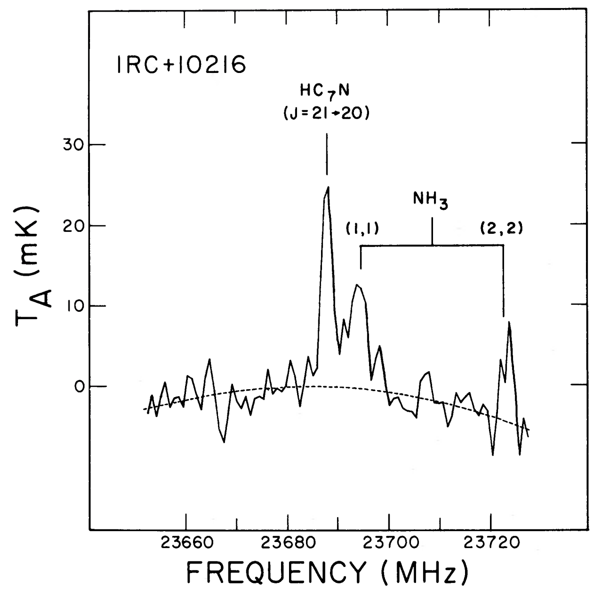

FIG. 1.—Spectrum of IRC +10°216 showing the (1, 1) and (2, 2) transitions of NH_3 observed with the 46 m telescope of the Algonquin Radio Observatory. Also shown in the spectrum is the $J = 21$–20 transition of HC_7N previously detected by Winnewisser and Walmsley (1978). The velocity resolution is 11.4 km s^{-1} per channel.

low-level sinusoid with a period of 8.1 MHz from the baseline. The 8.1 MHz frequency is that of the fundamental baseline component produced by a reflection between the telescope surface and the feed.

III. RESULTS

The final averaged spectrum of IRC + 10°216 is shown in Figure 1. Preliminary results of these observations have been reported by Bell, Kwok, and Feldman (1980). The spectrum contains ~ 2500 minutes of on-source integration time. In addition to the $J = 21 \rightarrow 20$ rotational transition of HC_7N, which was previously reported by Winnewisser and Walmsley (1978), we also find evidence for the (1, 1) and possibly the (2, 2) inversion lines of NH_3. Table 1 gives the values of (i) T_A, the measured peak antenna temperature corrected for the zenith-angle variations in both antenna gain and atmospheric attenuation; and (ii) T_A*, the antenna temperature corrected to outside the atmosphere (estimated transmission coefficient $\alpha \approx 0.94$ for unit air mass) and for the estimated beam efficiency $\eta_B \approx 0.28$ at 23.7 GHz. T_A* is equivalent to a main-beam brightness temperature. Quoted uncertainties are $\pm 1\ \sigma$ formal errors. The velocity and width of the (1, 1) line are found to agree with the values observed for other molecules in this source. However, the velocity of the (2, 2) line, if real, is -17 ± 4 km s^{-1} from the expected position. This discrepancy may be due to systematic instrumental errors or accidental blending with an unknown feature. There are a number of other weak spectral features which have recurred in each of the three observing sessions, and the possibility of line confusion (Thaddeus 1979) cannot be excluded. For example, Winnewisser and Walmsley (1978) and Winnewisser, Walmsley, and Toelle (1980) have found HC_5N and HC_7N to be relatively abundant molecular species in IRC + 10°216; hence, line confusion from even longer cyanopolyyne chains could be present in our spectrum (Oka 1978; Avery 1980). Further observations on more sensitive instruments are clearly necessary.

IV. ANALYSIS

For an expanding circumstellar envelope (see Fig. 2) the antenna temperature at each line-of-sight velocity (v_z) is given by

$$T_A^*(v_z) = \int_0^{p_{\max}} \frac{4 \ln 2}{\pi B^2} \exp\left(-4 \ln 2 \frac{p^2}{B^2}\right) \times T_B(p, v_z) 2\pi p dp\ , \quad (1)$$

where B is the half-power beamwidth of the telescope. The brightness temperatures (T_B) of the spectral line is given in terms of the corrected excitation temperature (T_x) and the optical depth (Kuiper *et al.* 1976):

$$T_B(p, v_z) = T_x\{1 - \exp[-\tau(p, v_z)]\}\ . \quad (2)$$

The optical depth along the line of sight $[\tau(p, v_z)]$ can be expressed as

$$\tau(p, v_z) = \int_{z_1}^{z_2} \frac{\alpha(r)}{\Delta v} n_m(r) dz\ , \quad (3)$$

where $\alpha(r)$ is the absorption coefficient, n_m the number

TABLE 1

OBSERVED AND CALCULATED MAIN-BEAM BRIGHTNESS TEMPERATURES OF THE (1, 1) AND (2, 2) LINES OF NH_3[a]

	OBSERVED				CALCULATED T_A* (mK)			
					$\beta = 0.7$		$\beta = 0.6$	
MOLECULE (1)	T_A (mK) (2)	T_A* (mK) (3)	V_{LSR} (km s^{-1}) (4)	Δv (km s^{-1}) (5)	$T_0 = 350$ K (6)	$T_0 = 400$ K (7)	$T_0 = 350$ K (8)	$T_0 = 400$ K (9)
$NH_3(1, 1)$	9 ± 2	34 ± 8	-27 ± 4	26 ± 5	42	41	39	37
$NH_3(2, 2)$	6 ± 2	23 ± 8	-43 ± 4	33 ± 8	18	20	25	27
$HC_7N(J = 21 \rightarrow 20)$	16 ± 2	62 ± 8	-24 ± 3	27 ± 3	...	...	...	...

[a] All quoted errors are 1σ formal errors derived from the processed spectrum.

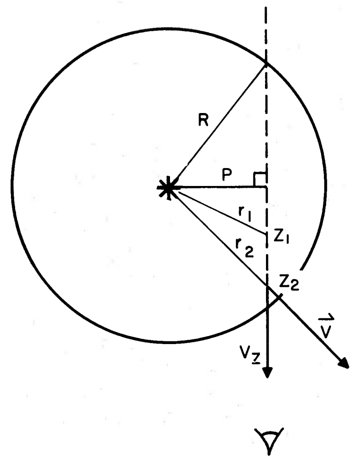

FIG. 2.—A schematic diagram of an expanding circumstellar envelope. The notation $z_1 z_2$ represents a column of molecules whose line-of-sight velocities (v_{z_1} and v_{z_2}) lie within the thermal line width (Δv).

density of molecules, and $|v_{z_1} - v_{z_2}| \leq \Delta v$ the thermal line width.

Assuming the envelope is expanding at a uniform velocity v, the integration variable can be transformed from z to r, giving

$$\tau(p, v_z) = \int_{r_1}^{r_2} \frac{\alpha(r)}{\Delta v} n_m r(r^2 - p^2)^{-1/2} dr \,, \qquad (4)$$

where r_1 and r_2 can be found by the expression

$$r_{1,2} = p\{1 - [(v_z \mp \Delta v/2)/v]^2\}^{-1/2} \,. \qquad (5)$$

The upper limit of integral (1) becomes $R[1 - (v_z/v)^2]^{1/2}$.

Since the non-metastable states decay rapidly via far-infrared transitions, their population densities are expected to be small. If we further assume that the metastable states are in thermal equilibrium at the kinetic temperature of the gas owing to $\Delta K = 3$ collision-induced transitions (Cheung *et al.* 1969) and that the star is undergoing steady mass loss, the number density of each metastable state is given by

$$n_i = \frac{g_i \exp(-E_i/kT)}{Z} \frac{A}{r^2} \,, \qquad (6)$$

where $A = y\dot{M}/4\pi\mu m_{H_2} v$, Z is the partition function, $\dot{M}$ is the mass-loss rate, and y the relative molecular abundance of NH_3(para)/H_2. Since the relaxation between ortho- and para-ammonia is extremely slow, the two states can be treated as separate species and their differences in nuclear spins ignored. For the para-ladder, the only change in statistical weight is $g_J = 2J + 1$; therefore

$$Z_{\text{para}} = \sum_{\substack{K \neq 3n \\ J=K}} g_J \exp\left(\frac{-E_{JK}}{kT}\right) . \qquad (7)$$

Substituting equation (6) into equation (2) and assuming optically thin conditions, we have

$$T_B(p, v_z) = T_x \int_{r_1}^{r_2} \frac{\alpha(r)}{\Delta v} \frac{A}{r^2} \frac{g_J \exp(-E_{JK}/kT)}{Z(T(r))} \frac{rdr}{(r^2 - p^2)^{1/2}} \qquad (8)$$

The kinetic temperature of the gas is mostly determined by heating due to grain-gas collisions and cooling due to adiabatic expansion and radiative losses (Goldreich and Scoville 1976; Kwan and Hill 1977). We find the calculated temperature distribution can be represented by a power law ($T \propto r^{-\beta}$); and the temperature distribution of IRC + 10°216 used by Kwan and Hill to fit the line profiles of CO can be approximated by $350(r/2 \times 10^{15}\ \text{cm})^{-0.7}$ K.

Table 1 shows the brightness temperature of the (1, 1) and (2, 2) lines calculated using the above temperature parameters. Equations (1) and (8) have been integrated numerically and the results averaged over the width of the line. A distance of 200 pc and a mass-loss rate $\dot{M} = 2 \times 10^{-5}\ M_\odot\ \text{yr}^{-1}$ (both adopted from Kwan and Hill 1977) have been assumed.

In order to reproduce the measured value of corrected antenna temperature T_A^* (1, 1) we require an abundance ratio $n_{NH_3(\text{para})}/H_2 = 3 \times 10^{-8}$, which agrees with the total NH_3 relative abundance of 10^{-7} reported by Betz, McLaren, and Spears (1979). To compare with other molecules in IRC +10°216, we note that the abundances of CO/H_2 and HCN/H_2 are 8×10^{-3} and 10^{-5}, respectively (cf. Kwan and Hill 1977).

Figure 3 shows the calculated fractional abundances of the (1, 1) and (2, 2) states as a function of distance from

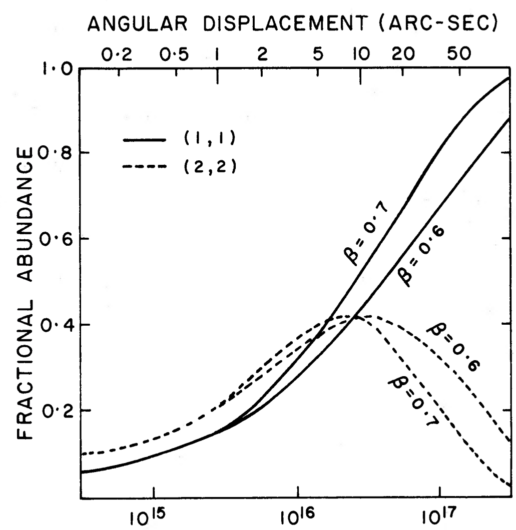

FIG. 3.—Fractional abundances of the (1, 1) and (2, 2) states as a function of distance from the star. The gas temperature distribution in the circumstellar envelope is assumed to be $T = 350\ (r/2 \times 10^{15}\ \text{cm})^{-\beta}$ K. Both the $\beta = 0.6$ and $\beta = 0.7$ cases are shown in the diagram.

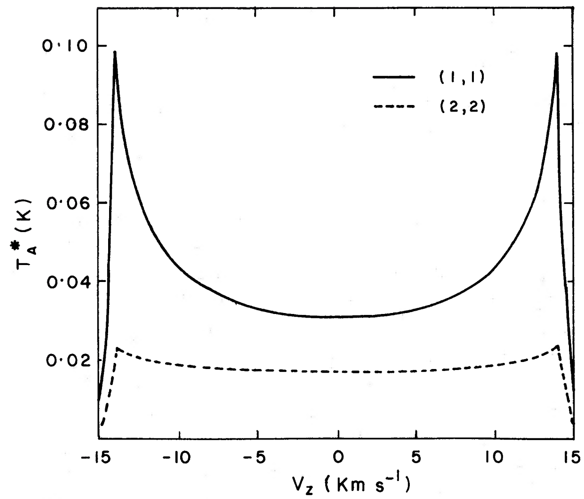

FIG. 4.—The profiles of the (1, 1) and (2, 2) lines predicted by the model. The parameters adopted are: $\dot{M} = 2 \times 10^{-5}$ $M_\odot$ yr^{-1}, $D = 200$ pc, $\beta = 0.7$, $T_0 = 350$ K, $y = 3 \times 10^{-8}$, $R = 240''$ and $B = 84''$. The actual spectrum may be further complicated by the presence of the hyperfine lines.

the star. We can see that the (2, 2) state is only significantly populated within 30″ of the star, and the expected (2, 2) line intensity is weak when observed with a large telescope beam. For our beamwidth of 84″ we find the observed (2, 2)/(1, 1) ratio to be in agreement with predictions of the model (see cols. [6]–[9], Table 1), given the uncertainties of the data. Line strengths calculated with variations of β and T_0 are also presented in Table 1 to show the dependence of the ammonia line ratio on the thermal structure of circumstellar envelopes.

Since the (1, 1) and (2, 2) lines originate from different parts of the circumstellar envelope, there exist interesting possibilities for future observations. Figure 4 shows the theoretical profiles of the two lines for the parameters $\beta = 0.7$ and $T_0 = 350$ K, and observed with a telescope having a beamwidth of 84″. The (1, 1) region, being resolved by the telescope, shows a double-peaked structure similar to lines of ^{13}CO and HC_5N, whereas the unresolved (2, 2) line has a "flattop" profile. Because of the wide filters used in our observations, we did not have the required frequency resolution or sensitivity to test this prediction. However this would be an interesting experiment to perform. Along the same line of reasoning, an increase in spatial resolution will lead to a strengthening of the (2, 2) line relative to the (1, 1) line.

V. DISCUSSION

The study of circumstellar envelopes consists mainly of the determination of six functions: $v(r)$, $n(r)$, and $T(r)$, for both gas and dust. Since radiation pressure on grains is almost certainly the dominant force at the outer parts of the envelope, the velocity fields of both gas and dust are unlikely to deviate from their respective constant terminal velocities. Models based on a constant velocity law are found to be consistent with both the ^{13}CO profiles in carbon-rich stars (Kuiper *et al.* 1976) and OH profiles in oxygen-rich stars (Kwok 1976; Elitzur, Goldreich, and Scoville 1976; Olnon 1977). Steady mass loss implies a $1/r^2$ density distribution; however, a time-dependent mass-loss rate cannot be completely ruled out. Far-infrared observations of IRC +10°216 show a steep decline in flux at long wavelengths which can be shown to be consistent with a $1/r^2$ dust density distribution (Campbell *et al.* 1976). The least understood of all is the thermal structure. Up to this time, most of our knowledge has been theoretical since no molecule has yet been found which can be used to sample the widely different temperature regions of the envelope. Infrared observations, when analyzed with proper radiative-transfer techniques (cf. Jones and Merrill 1976), can provide information on the dust temperature distribution. But since the gas and dust are likely to be thermally decoupled beyond several stellar radii, a separate tool must be used to measure the gas temperature.

In order to better determine the thermal structure of circumstellar envelopes it would be desirable to observe more than one transition of the same molecule and use the different excitation requirements of the transitions to sample different parts of the envelope. However, rotational transitions from molecules either have the rotational states too close to each other (e.g., HC_3N) to be able to reflect different excitation conditions, or have the transitions so far apart in frequency (e.g., CO) that inaccuracies may arise from different calibration procedures. The inversion transitions of ammonia, which have a very small frequency spread and can be observed simultaneously using wide-band spectrometers, do not suffer from such calibration problems. Also, the metastable states (from which the inversion transitions arise) have widely different rotational energies and therefore are quite sensitive to the thermal structure of the envelope. Furthermore, the ammonia lines are optically thin and can provide information deeper into the envelope. We hope this paper will stimulate interest in the ammonia molecule as an effective probe of the thermal structure of the envelopes of late-type stars.

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Note added in proof.—The observations reported here have recently been confirmed by observations at the Haystack Radio Observatory. These will be reported elsewhere.

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