NH_3 in IRC +10216

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ABSTRACT

Ammonia has been detected in the circumstellar envelope of IRC +10216 by means of 3 infrared absorption lines in the ν_2 band around 950 cm^{-1}. The lines are fully resolved at a resolution of 0.22 km/sec and indicate that most of the circumstellar gas is accelerated to expansion velocities around 14 km/sec within a few stellar radii. The NH_3 profiles indicate a rotational temperature between 400 and 700 K, an H_2 density between $10^8 cm^{-3}$ and $10^{10} cm^{-3}$, and an NH_3 column density of $10^{17} cm^{-2}$. The H_2 density indicates that the mass of the circumstellar envelope within a 1 arcsec radius is $\sim$0.1 solar masses.

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I. Introduction

Because IRC +10216 is a prime example of a carbon star undergoing extensive mass loss, a good deal of observational and theoretical study has been devoted toward understanding the structure and dynamics of its circumstellar envelope (Morris, 1975; Kwan and Hill, 1977). The importance of molecular spectroscopy in such a study is obvious in that the shapes of spectral lines are direct indicators of dynamical activity. Up to now the best velocity resolution has been at radio frequencies, and considerable evidence on mass loss has come from observations in this spectral region. However, the angular resolution of single radio telescopes is currently insufficient to resolve the structure within the $\sim$1 arcmin molecular envelope; and consequently, the line profiles are observed to be $\sim$30 km/sec wide, since they encompass molecules over the full range of projected expansion velocities. A more sensitive probe of molecular density and radial velocity variations in the expanding envelope would be expected from observations of infrared absorption lines against the relatively small $\sim$1 arcsec central continuum source. The absorption line profiles are influenced only by molecules along the line-of-sight toward the central source, and thus they greatly simplify the interpretation of the velocity structure.

The introduction of heterodyne spectroscopy to the infrared now allows these absorption lines to be studied at a velocity resolution previously obtainable only at radio frequencies. This Letter reports the initial application of this technique to stellar spectroscopy with the detection of ammonia in the circumstellar envelope of IRC +10216. Three transitions of $^{14}NH_3$ in the ν_2 rotation-vibration band around 950 cm^{-1} have been observed. Although ammonia has a well studied microwave inversion spectrum near 24 GHz and is frequently found in interstellar clouds, it has so far escaped detection in stellar sources. The significance of its detection in IRC +10216 lies not only in adding one more molecule to the list, but especially in that ammonia by itself can provide a unique probe for many parameters of interest in the study of mass loss effects.

II. Observations

The observations were made on a number of nights in 1978 June with the McMath Solar Telescope of Kitt Peak National Observatory*. The initial detections were obtained with a 81 cm auxiliary solar telescope and improved upon a week later with the main 1.5 m telescope. At frequencies around 950 cm^{-1}, the beam widths are only slightly larger than the diffraction-limited sizes of 3.2 arcsec for the smaller telescope and 1.7 arcsec for the larger. The heterodyne receiver employs a HgCdTe photodiode mixer and a CO_2 laser local oscillator and is much the same as described by Betz et al. (1977). However, a new 64 channel filter bank of 20 MHz filters now extends the velocity coverage to a width of $\sim$14 km/sec. The system sensitivity with chopping and telescope losses is measured in each channel to be 1.0×10^{-15}W for a signal-to-noise ratio of 1 after a 1 sec integration. Because the laser oscillates on only discrete rotation-vibration transitions of CO_2 and because only a limited intermediate frequency bandwidth of $\sim$1500 MHz is available from the mixer, only Doppler-shifted transitions of NH_3 in fairly close coincidence with available laser lines may be observed (Hillman et al. 1977).

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In IRC +10216, the particular lines which were searched for were the aR(1,1), aQ(2,2), aQ(6,6), and aQ(6,4) transitions of $^{14}NH_3$ in the ν_2 rotation-vibration band around 950 cm^{-1}. Figure 1 illustrates the observed profiles for the first three lines. The center velocity of each 0.22 km/sec channel is accurate to ±0.05 km/sec. The aQ(6,4) line at 932.6358 cm^{-1} was not detected to an equivalent width limit of $\sim10^{-5} cm^{-1}$ in a bandwidth equal to that of the observed lines. The hyperfine components of ammonia are not resolvable in these spectra and would not be discernible at higher resolution, since the Doppler widths of the individual components are very much larger than the hyperfine splittings.

To assure the correct identification of these lines, each feature was observed on several occasions over the course of 10 days. Changes in the orbital velocity of the Earth caused a frequency shift of $\sim$1 channel per day for the line position, which confirmed that the lines occurred in the correct sideband for ammonia. To insure that no parts of the wings of the NH_3 lines are folded over from the opposite infrared sideband after mixing, all the line centers were observed at high intermediate frequencies >900 MHz. It is important to emphasize that there are no baseline irregularities in these spectra of the type which commonly plague microwave line receivers. The technical explanation cannot be given here. The continuum contribution from the opposite infrared sideband is assumed to be uniform and has been carefully measured and removed in these single-sideband spectra. The conversion gains of the two sidebands are known to be equal to within <0.5% from laboratory measurements. Thus, apart from the noise level, the shapes of the resolved, but incomplete, features are real. Around the aQ(2,2) and aQ(6,6) line frequencies, which are both in coincidence with $^{13}C^{16}O_2$

laser lines, lunar spectra show only a flat continuum level with no spectral features from the terrestrial atmosphere. The aR(1,1) frequency, however, is 1440 MHz below the R(14) line of $^{12}C^{16}O_2$ (the laser line). Absorption from the wide pressure-broadened wings of terrestrial CO_2 in 2 airmasses produces a smooth 50% change in atmospheric transmission across the aR(1,1) spectrum. For this line only, a fully resolved calibration spectrum of the Moon was used to normalize the NH_3 data from IRC +10216. Because of increased atmospheric attenuation and a shorter integration time, the noise level on this line is higher. Finally, there is some evidence that the rather narrow features marked A, B, and C may all be real. However, any confirmations will require further observations.

III. Analysis

A) H_2 Density and Rotational Temperature.

The spectroscopy of ammonia is sufficiently complex that the population of rotational levels will probably not follow a simple thermal distribution in a circumstellar environment. Not only is gas closer to the central star likely to be hotter, denser, and in a stronger radiation field than that further away, but the effectiveness of collisions in thermalizing the energy levels diminishes rapidly at larger radial distances. Consequently, absorption lines from rotational levels requiring a high level of excitation may be formed at locations quite different from those where the low energy-level lines are produced. A thoroughly quantitative determination of temperature, density, and NH_3 abundance as a function of radial distance can only be obtained from a careful analysis of resolved line profiles in combination with a refined model of mass distribution in the circumstellar envelope. On the other hand, a reasonable start toward estimating these quantities can be made from the less ambitious approach taken there.

At low H_2 densities, $\rho_{H_2} < 10^8 cm^{-3}$, only the metastable rotational levels (J=K) will be populated as their radiative lifetimes are $\sim 10^9$ sec (Oka et al. 1971). The non-metastable levels (J>K) of ammonia can decay via allowed ($\Delta J=-1$, $\Delta K=0$) transitions in times of 100 sec or less. If radiative trapping is unimportant, the populations of metastable levels will then assume a non-Boltzmann distribution, and a unique rotational temperature will not be derivable. As the H_2 density is increased from this limit, more of the non-metastable levels can be populated via collisions; and at densities $>10^{10} cm^{-3}$ the populations of levels up to about J=6 will all assume a roughly thermal distribution. At intermediate densities, $10^8 cm^{-3} < \rho_{H_2} < 10^{10} cm^{-3}$, only some of the low energy non-metastable levels such as (2,1) and (3,2) will be collisionally populated, which will bring the population ratios between the metastable levels closer to the thermal limit.

For IRC +10216, a reasonable upper limit for the hydrogen density near the ammonia can be derived from the non-detection of the aQ(6,4) transition. The radiative lifetime of the (6,4) rotational level is about 1 sec, after which it decays via an 119 cm^{-1} photon to the (5,4) level. Since the aQ(6,6) transition was easily detected, and the excitation energy of the (6,4) level is only 25% higher, collisions must not be frequent enough to maintain any significant population in the (6,4) level. A collisional cross section of $\sim 10^{-15} cm^2$ for H_2 on NH_3 and a kinetic temperature of 500 K (justified later) then implies that $\rho_{H_2} < 10^{10} cm^{-3}$, if radiative trapping at 119 cm^{-1} can be ignored. A lower bound on the H_2 density may be computed indirectly from infrared measurements of the CO column density, if it may be assumed that the NH_3 lies at or within the radius of the CO distribution. A CO/H_2 abundance ratio of $\sim 10^{-3}$, a CO column density of $10^{20}cm^{-2}$, and a radial distribution over $\leq 10^{15}$cm then set a lower limit on the H_2 density of $\rho_{H_2} > 10^8 cm^{-3}$ (Barnes et al. 1977). Consequently, most of the NH_3 is expected to be observed at intermediate densities: $10^8 cm^{-3} < \rho_{H_2} < 10^{10} cm^{-3}$. Actually, a slightly better estimate of the H_2 density can be obtained by comparing the relative intensities of the 3 observed lines.

Of the 3 line profiles of Figure 1, the most notable difference is between the aQ(2,2) and aQ(6,6) lineshapes. Although the aQ(6,6) is stronger than the aQ(2,2) in both the low and high frequency wings, it is weaker at line center. The aR(1,1) and aQ(2,2) profiles are more comparable, but still their relative intensities differ between the wings and the line centers. Since the aQ(6,6) and perhaps even the aQ(2,2) line appears optically thick at line center, a better estimate of the rotational temperature can be deduced from the relative strengths of the optically-thin wings between LSR velocities of -34 and -38 km/sec. For H_2 densities between $10^8 cm^{-3}$ and $10^{10} cm^{-3}$, the aQ(2,2)/aR(1,1) ratio by itself requires only that the rotational temperature, T_{rot} is >200 K. The aQ(6,6)/aQ(2,2) intensity ratio sets a better limit: 400 K < T_{rot} < 700 K. Furthermore, in the limit $\rho_{H_2} < 10^8 cm^{-3}$, the increased non-thermal population of the (2,2) metastable level would not allow the aQ(6,6)/aQ(2,2) ratio to be as high as that observed, even at much higher temperatures. The high ratio requires that $\rho_{H_2} > 10^8 cm^{-3}$ and that the (3,2) and (2,1) rotational levels are also thermalized. Of course the above comparison makes the reasonable assumption that the abundances of the ortho- and para- species of ammonia are equal, and that both species can be characterized by the same rotational temperature.

B) Location

To date, all the molecules detected in the infrared have been associated with the inner 2 arcsec of the circumstellar envelope (Hall and Ridgway, 1978). Most of the ammonia can also be localized in this region because of both the high rotational temperature and the high H_2 density. However, a more definite assessment of the gas distribution can be made after first considering the spatial distribution of the continuum source. The first measurements to resolve the infrared continuum were the lunar occultation observations of Toombs et al.(1972). These results were interpreted with a simple two component model: an optically-thick inner shell of diameter 0.4 arcsec and temperature 600 K and an optically-thin shell ($\tau \sim 0.2$) of diameter 2 arcsec and temperature 375 K. Each of these discrete shells was estimated to produce about half of the total continuum radiation at 1000 cm^{-1}. Recent interferometric observations by Sutton (1978), however, indicate that about 10% of the 900 cm^{-1} flux from IRC +10216 actually comes from an unresolved (<0.2 arcsec) component and that the remaining 90% has a Gaussian intensity distribution with a 1/e diameter of $\sim$0.9 arcsec. These results imply a more continuous process of mass loss rather than discrete outbursts. A similar conclusion has been reached by McCarthy (1978) and Selby and Wade (1978), who have measured the continuum distribution at a number of infrared wavelengths. Furthermore, Crabtree and Martin (1979) have shown in a theoretical model that the R^{-2} density distribution expected from a constant rate of mass loss is also consistent with the original lunar occultation observations.

To estimate the ammonia distribution, a reasonable first approach might be to assume that the lines are seen in absorption against all of the 900 cm^{-1} continuum radiation. Unfortunately, this simple configuration leads to severe difficulties in interpreting the optically-thick appearance of the aQ(6,6) profile. The relatively weak saturation depth of this line would imply that the vibrational temperature of the ammonia is ~96% of the ≥400 K continuum brightness temperature. The upper level of the vibrational transition cannot be thermalized at this temperature by collisions, as this would require H_2 densities in excess of the limit imposed by the undetected aQ(6,4) line. The radiative lifetime of the upper level is only ~0.1 sec. Therefore, the population in the upper vibrational level would have to be maintained by the radiation field, which would approach the required intensity only in the immediate vicinity of the hot dust. However, if the ammonia were this close to the continuum source, then the observed line profiles would be many times broader than those observed. This is because outflowing gas over almost the entire 15 km/sec range of projected expansion velocities would be seen in absorption against the finite size of the continuum source. Thus, most of the ammonia cannot be outside of the major part of the continuum source, and the inclusion of some radiative trapping does not significantly alter this basic conclusion. This interpretation is strengthened by the observation that the ~0.9 fractional intensity at the center of the aQ(6,6) line is also the fraction of the total 900 cm^{-1} continuum radiation seen outside of 0.2 arcsec in the interferometer results of Sutton (1978). 90% of the observed continuum is therefore picked up from the 0.9 arcsec Gaussian continuum distribution while most of the detectable ammonia must be within this diameter. Now, if the vibrational temperature of the ammonia were even as hot as 600 K, any optically-thick absorption lines would be intrinsically more than 80% deep against the even hotter interior dust or the stellar photosphere at $\geq$1500 K. The intensity ratio between the spatially resolved and unresolved continuum components can also be used to fix the optical depth of the dust in the resolved part to be on the order of 1, if the unresolved source can be characterized at $\sim$1500 K and the resolved part at $\sim$500 K. Optical depths $\leq$1 are consistent with the observed Gaussian distribution for the resolved continuum intensity. (At 119 cm^{-1}, important for radiative excitation of the (6,4) level, the optical depth of the dust should be negligible.)

Although most of the ammonia is interior to a large part of the dust responsible for the 900 cm^{-1} continuum radiation, it is still probably associated with the region of dust formation. This is because radiation pressure on dust grains is expected to drive the gas to the observed expansion velocity, and no ammonia is seen at H_2 densities $>10^{10} cm^{-3}$. The narrowness of the profiles also requires that the molecules in the observed levels not be too close to the unresolved (<0.2 arcsec) component. To some extent, this happens naturally, as molecules closer to the star will be hotter and distributed over a larger number of energy levels. Preliminary calculations also indicate that, for such narrow lines, the ammonia abundance should at first increase with increasing distance from the central source, as would be the case if the relative NH_3 abundance were in equilibrium with the grain temperature and not fixed at the photospheric value.

Finally, because the (2,2) and (1,1) rotational levels will have larger populations at low temperatures <200 K, the additional absorption seen in these lines below the 0.9 intensity level can be attributed to optically-thin NH_3 far outside the warm dust producing the 900 cm^{-1} continuum. In this respect it is interesting to note the constancy of the expansion velocity in the asymmetric profile of the aQ(2,2) line. Most of the ammonia within the central 1 arcsec of IRC +10216 is observed at expansion velocities between 11 and 15 km/sec, the same range as other molecules found in the much larger "radio" envelope (Morris, 1975). Most of the acceleration in mass loss thus occurs within a few stellar radii. The remarkably low velocity dispersion seen in these lines (only a few times more than the thermal velocity of NH_3 at 600 K) is in good agreement with the turbulence estimate derived by Geballe et al. (1973) based on observations of infrared CO lines. A good measurement of this turbulence is important for accurate modeling of the radiative transfer and cooling effects of various microwave and infrared emission lines.

C) Column Density

After the uncertainties in rotational temperature, hydrogen density, and the possible saturation of the aQ(2,2) line are taken into account, the radial column density of ammonia can be estimated at $\sim 1 \times 10^{17} cm^{-2}$ from the equivalent widths of the aR(1,1) and aQ(2,2) lines, and the ν_2 band intensity given by Taylor (1974). This estimate is uncertain by a factor of 2, and it assumes that only 10% of the observed continuum radiation is emitted behind the ammonia.

The ammonia column density of $10^{17} cm^{-2}$ and the approximate H_2 volume density of $\sim 10^8 cm^{-3}$ at a radius of $\sim 10^{15}$ cm from the star can be used to get a rough estimate of the H_2 column density of $\sim 10^{24} cm^{-2}$ and a NH_3 fractional abundance of $\sim 10^{-7}$. This fraction is higher than the photospheric ratio calculated by Tsuji (1964) for a 1000 K supergiant, and may be further evidence that the ammonia abundance evolves after ejection from the photosphere. The H_2 column density implies that the mass of the circumstellar envelope within a 1 arcsec radius is about 0.1 solar masses, an estimate which is independent of any assumed abundance ratios. It would be useful to compare the relative abundances of NH_3 and CO, since the formation of both molecules is relatively insensitive to the amount of carbon lost to grains. However, any realistic comparison would require a better understanding of the radial distribution of CO, a study which may also be possible with infrared heterodyne techniques.

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Figure 1 Caption

Spectra of three $^{14}NH_3$ lines in the ν_2 band: aR(1,1) at 971.8822 cm^{-1}, aQ(2,2) at 931.3334 cm^{-1}, and aQ(6,6) at 927.3232 cm^{-1}. The Doppler shifts of these lines are plotted relative to the local standard of rest (LSR). LSR velocities may be converted to heliocentric values by the relation: $V_H = V_{LSR} + 7.12$ km/sec. The circumstellar expansion velocity is determined by taking the intrinsic stellar velocity as -26 ± 1 km/sec (Kuiper et al. 1976). The observed intensities are expressed relative to the continuum level, and error bars are illustrated for 2 standard deviations.

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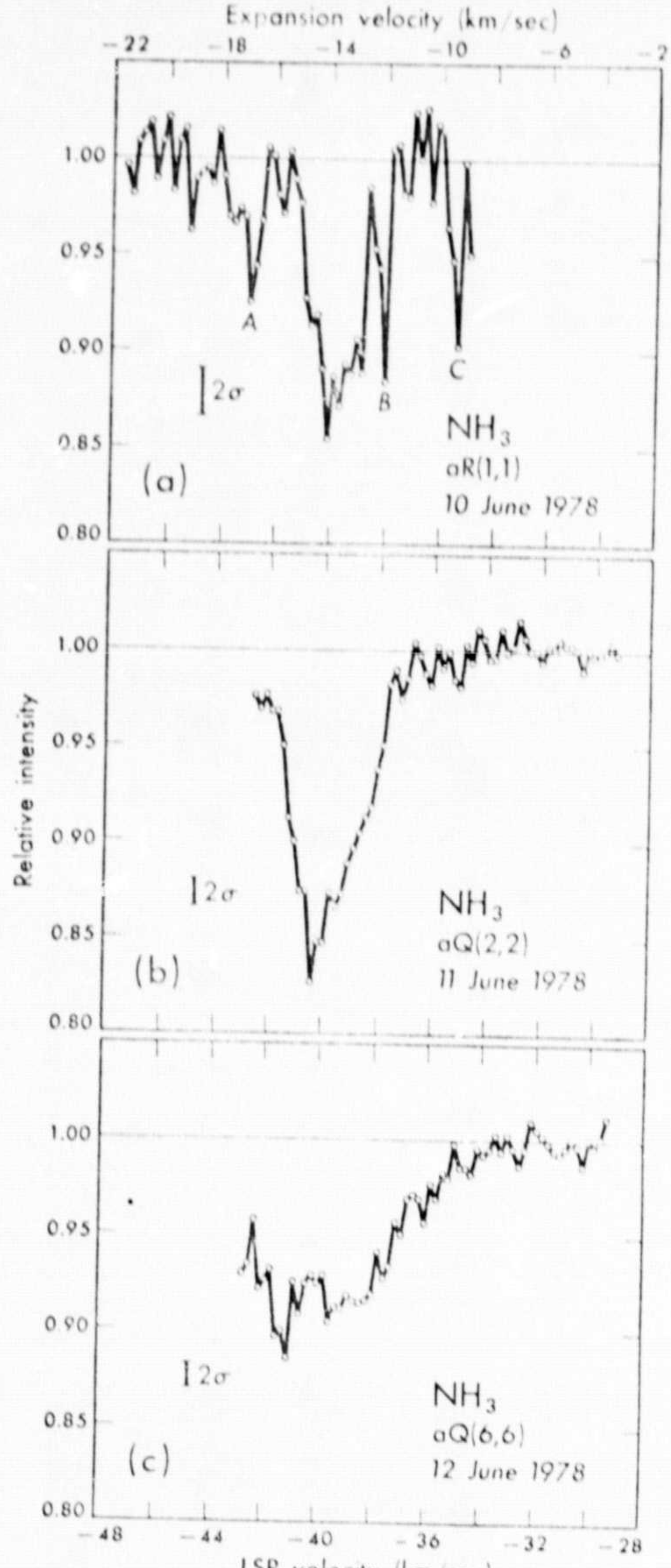

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