INFRARED HETERODYNE SPECTROSCOPY OF CIRCUMSTELLAR MOLECULES

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ABSTRACT

Ammonia has been detected in the circumstellar envelopes of IRC+10216, VY CMa, VX Sgr, and IRC+10420. A number of absorption lines of $^{14}NH_3$ in the ν_2 vibration-rotation band around 28 THz (950 cm^{-1}) have been observed at a velocity resolution of 0.2 km/s. Typical linewidths are 1 to 4 km/s, and the details of the line profiles provide additional insights on the process of mass loss in these stars.

1. INTRODUCTION

The extension of heterodyne techniques to infrared spectroscopy now permits the vibrational transitions of interstellar and circumstellar molecules to be studied at the high velocity resolution commonly used in microwave line observations. Well-resolved line profiles are especially necessary in characterizing the dynamics of mass loss in circumstellar environments. The interpretation of these profiles is considerably simplified for infrared absorption lines in that only the radial velocity component of circumstellar expansion is seen against a small (<1 arcsec) continuum source. Typical linewidths are 1 to 4 km/s. This is in contrast to microwave emission line observations with ∿1 arcmin beamwidths, where line emission over the full range of projected expansion velocities is seen, and wide (∿30 km/s) profiles are observed centered about the stellar velocity.

The usefulness of heterodyne techniques in infrared spectroscopy has been demonstrated by the detection of ammonia in the circumstellar envelope of IRC+10216 (Betz et al. 1979). Subsequent observations on this source and several supergiant maser stars show that ammonia is relatively abundant and is an excellent indicator of dynamics throughout the circumstellar cloud. Also, for the maser stars, the velocities of the ammonia absorption lines can be correlated with those of OH-maser emission features determined from VLBI measurements to fix

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the location of the central star relative to the extended cloud of maser components.

2. INSTRUMENTATION

Figure 1 shows a simplified schematic of the receiver which is used at the 1.5 m McMath Solar Telescope of Kitt Peak National Observatory. At a wavelength of 10.6μm, the diffraction-limited beam-size is ∿1.5 arcsec. The local oscillator is a CO_2 laser capable of oscillating on any one of a number of discrete vibration-rotation transitions of CO_2 in the 10μm band. Centering of the laser to the peak of the power output curve controls the LO frequency to a fractional accuracy better than 10^{-7}. The mixer is a HgCdTe infrared photodiode with an output current response extending from DC to 1800 MHz. The output of the photomixer is processed by a second mixer and directed into a filterbank of sixty-four 20 MHz filters. Each channel corresponds to a velocity width of ∿0.2 km/s.

A number of close frequency coincidences have been measured between CO_2 laser lines and fundamental transitions of NH_3 in the ν_2 vibration-rotation band. Laboratory measurements have been accomplished with a variety of laser-related techniques, principally laser-Stark spectroscopy (Ueda and Shimoda 1975), laser-microwave double-resonance spectroscopy (Freund and Oka 1976), and laser heterodyne spectroscopy (Hillman et al. 1977). As in microwave astronomy, good rest frequencies must also be known in the infrared before attempting observations. This is especially apparent when the total IF velocity coverage is only ∿14 km/s.

Since the local oscillator frequencies are fixed, stellar sources are fine-tuned into frequency coincidence using the orbital motion of the earth. At a particular time, only a few molecular lines may fall within the 14 km/s "window", and observing times must be selected with this in mind. The orbital motion of the earth shifts the spectra

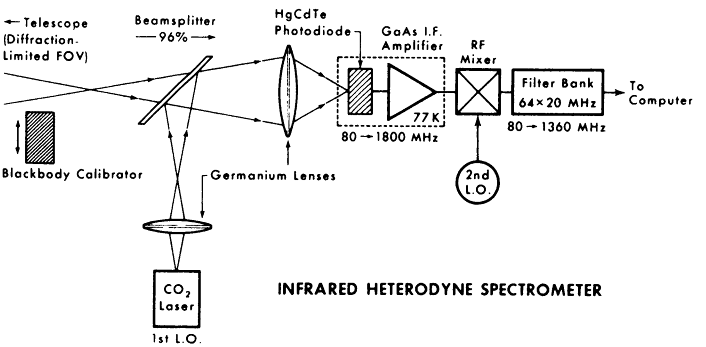

Figure 1

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~1 channel/day, and repeated observations over a few days are generally needed to unambiguously identify the infrared sideband into which an isolated line may fall. Although this technique is not as convenient as having direct frequency control of the local oscillator, it is still practical in that many of the strongest NH_3 lines are accessible for most supergiant stars. It is particularly fortunate that ammonia has such a rich spectrum overlapping the 10μm CO_2 laser bands. The non-metastable energy levels of NH_3 are especially important in that the collisionally-excited population of these levels is sensitive to H_2 densities of 10^6 to 10^{10} cm^{-3}, which are characteristic of the densities expected in circumstellar clouds.

3. OBSERVATIONS

A) IRC+10216

The identification of NH_3 in IRC+10216 was based on the detection of 3 lines in the ν_2 band: aR(1,1), aQ(2,2) and aQ(6,6) (Betz et al. 1979). These observations were completed in early June 1978, close to the time of maximum infrared brightness. Additional observations were done in May 1979, near minimum infrared brightness, when the continuum intensity was about 2.5 times weaker than at previous maximum. In these latter observations, the aR(0,0) transition illustrated in Figure 2 was also detected. The rotational level of the lower state of this vibrational transition has no 24 GHz inversion transition and hence cannot be detected in microwave observations.

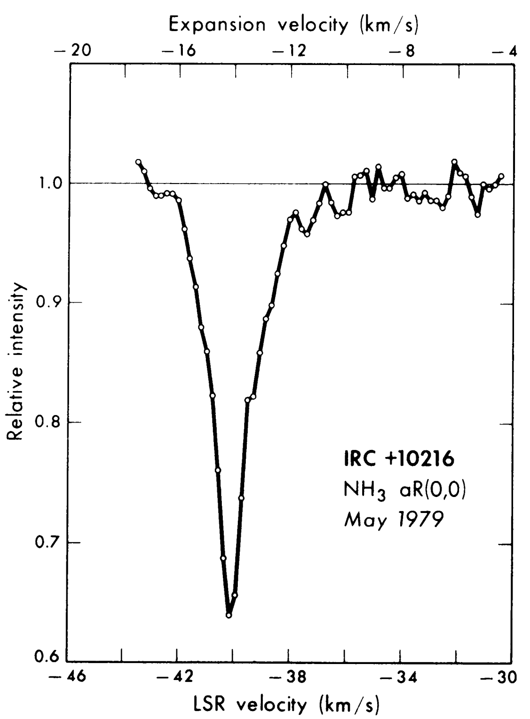

Figure 2: The aR(0,0) line of NH_3 in IRC+10216. The rest frequency of this transition is 28.533534 THz. The expansion velocity for circumstellar gas assumes an intrinsic stellar velocity of -26 km/s.

Both the old and new results indicate that ammonia is relatively abundant, with a column density around 10^{17} cm^{-2} and a fractional abundance of 10^{-7} relative to H_2. Ammonia can be seen both close to the star such that continuum emission from intervening dust partially obscures the lines, and also at large

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radial distances where the molecular population collects into the lowest rotational levels. The appearances of lines of different rotational excitation are consequently to some extent indicative of gas at different radial distances and in environments of differing temperature and density. Close to the star, within the region of 10μm continuum radiation from dust, a rotational temperature of 400 to 700 K and an H_2 density around 10^9 cm^{-3} are indicated. The central intensities of lines such as (J,K) = (0,0) also reveal that ammonia is detectable in the cooler, <200 K, regions of the circumstellar cloud, well outside the area of 10μm continuum emission. In all the lines, the circumstellar expansion velocity is seen to be remarkably constant. By the time NH_3 is abundant enough to be detectable, the expansion velocity is already close to the terminal velocity of ∿14 km/s. If radiation pressure on grains drives the gas expansion and the hottest grains form about 5 stellar radii (0.2 arcsec) from the central star (Sutton et al. 1979), then the ammonia extends outward from this radius. The relatively large column density of NH_3 and the sharpness of the line profiles suggest that the relative NH_3 abundance is rather more in equilibrium with the dust grain temperature than frozen at the photospheric value. Modeling of the observed line profiles by D. Crabtree at Toronto also indicates that turbulence in the circumstellar gas is small but measureable at about 1 km/s. Future observations should clarify the radial dependence of the NH_3 abundance close to the star and establish more quantitative estimates of the H_2 density throughout the region of NH_3 absorption.

B) OH/IR Supergiants

Ammonia was searched for and detected in 3 OH-maser stars: VY CMa, VX Sgr, and IRC+10420 (McLaren and Betz 1979). In these sources the absorption lines are all on the order of 20 to 30% deep, and the linewidths range from 1 to 4 km/s. In VY CMa the NH_3 is seen at -4.5 km/s (LSR). If the stellar velocity may be taken at +18 km/s from the midpoint of the two OH maser peaks, then the NH_3 is observed at a uniform expansion velocity of about -23 km/s. It is interesting to associate the NH_3 absorption-line velocity with the -4.5 km/s OH maser component seen near the physical center of the masing region in VLBI observations (Reid and Muhleman, 1978; Moran et al. 1977). Presumably, this -4.5 km/s component indicates the gas in direct line-of-sight expansion from the central star. This interpretation is strengthened by similar associations between NH_3 absorption-line velocities in VX Sgr and IRC+10420 and OH maser components seen near the apparant centers of maser groupings in these sources (Moran et al. 1977, Benson et al. 1979). In VX Sgr, NH_3 absorption and OH emission are both seen at -14.3 km/s, while in IRC+10420, NH_3 and OH are found at +45.9 km/s. It thus seems reasonable that the central stars are located directly behind these velocity components. These velocity correlations do not necessarily imply that the NH_3 absorption and OH emission occur at the same radial distance from the star. Gas is already accelerated near the terminal velocity by the time the hottest

NH_3 is seen, and it continues outward at this velocity toward the cooler region where OH emission occurs. However, NH_3 in the low energy rotational states such as (0,0) certainly extends into the OH emission region. Additional observations of NH_3 in a larger number of maser stars will allow more quantitative estimates to be made.

4. FUTURE PROSPECTS

Within the next year or two, expected system improvements in both sensitivity and frequency coverage will greatly expand the applications of heterodyne spectroscopy. Under good seeing conditions, a 3-m class telescope will give a 4-fold increase in sensitivity over the 1.5 m telescope currently in use; and, together with modest receiver improvements, will permit good absorption line spectroscopy at 10μm on well over 100 sources. With recently improved photomixers and more IF filter channels, the simultaneous velocity coverage can now be extended to ∿28 km/s. This will not only provide a decent baseline for continuum estimates but also double the efficiency of telescope usage. Laser technology, principally with CO_2, N_2O, and CO gas lasers, is well enough advanced to give thousands of LO frequencies over the 5 to 12μm region, and thus encourage observations of other important circumstellar molecules such as CO and SiO.

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DISCUSSION FOLLOWING BETZ

Snyder: Could you comment on the agreement between your radial velocities and the radial velocities found for radio molecules, for example CO, in IRC+10216.

Betz: We observe NH_3 in absorption at $\sim$ -40 km/s V_{LSR}. The broad radio emission lines of CO and other molecules are centered at -26 km/s and extend from $\sim$ -40 to -12 km/s. Consequently, if we interpret the intrinsic stellar velocity as -26 km/s and the circumstellar expansion velocity as 14 km/s, all the observations are in agreement.

Feldman: Bell, Kwok and I have recently detected both the (1,1) and (2,2) transitions of NH_3 in the radio spectrum of IRC+10216 (this volume). Preliminary results are that the velocity widths are similar to those of other molecules previously found in the circumstellar envelope of IRC+10216, and that the relative abundance of ammonia is $\sim 10^{-7}$ compared to H_2.

McCabe: At what distance in stellar radii from the star are you observing the NH_3 in IRC+10216?

Betz: The ammonia absorption lines are sharp, and indicate that the gas has already been accelerated close to the terminal velocity of $\sim$14 km/s before much of the NH_3 in these lines is formed. Most of the mass-loss acceleration must occur within a few stellar radii, and most of the observable ammonia is outside of this region. NH_3 lines requiring higher excitation, such as the (6,6), are predominantly formed closer to this few-stellar-radii limit than "cold" lines such the (0,0) which extends out into the larger "radio" envelope.