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FIRST DETECTION OF THE GROUND-STATE $J_K = 1_0 \rightarrow 0_0$ SUBMILLIMETER TRANSITION OF INTERSTELLAR AMMONIA

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ABSTRACT

The $J_K = 1_0 \rightarrow 0_0$ transition of ammonia at 572.5 GHz has been detected in OMC-1 from NASA's Kuiper Airborne Observatory. The central velocity of the line ($V_{\rm LSR} \approx 9$ km s^{-1}) indicates that it originates in the molecular cloud material, not in the hot core. The derived filling factor of $\gtrsim 0.09$ in a 2′ beam implies a source diameter of $\gtrsim 35''$ if it is a single clump. This clump area is much larger than that derived from observations of the 1_1 inversion transition. The larger optical depth in the $1_0 \rightarrow 0_0$ transition (75–350) can account for the increased source area and line width as compared with those seen in the 1_1 inversion transition.

Subject headings: infrared: sources — interstellar: matter — interstellar: molecules — nebulae: Orion Nebula — radio sources: lines

I. INTRODUCTION

Ammonia is one of the most useful molecules for studying the temperature and density structures of interstellar clouds. It was first detected (Cheung *et al.* 1969) through one of the many inversion transitions. These occur closely spaced near the wavelength of 1 cm, so that a single receiver-telescope combination can probe a range of excitation conditions. Only recently, however, has it become possible to observe the rotation-inversion transitions which fall in the far-infrared and submillimeter wavelength range. We report here the first detection of the ground-state rotation-inversion transition of interstellar ammonia ($J_K = 1_0 \rightarrow 0_0$) at a frequency of 572.49815 GHz (±0.1 MHz) (Helminger, DeLucia, and Gordy 1971) in OMC-1.

As shown in Figure 1, all the energy levels with $K \geq 1$ are split by inversion. The electric dipole allowed transitions between these inversion states within a given rotational level ($\Delta J = 0$) generally fall in the range 20–40 GHz. The most commonly observed inversion transitions are from splittings in the $J = K$ metastable levels, so named because radiative transitions to lower levels are forbidden by the dipole selection rule $\Delta K = 0$. The $K = 0$ ladder, however, has no inversion splittings because the exclusion principle eliminates half of the symmetry states. This means that, in the cool, dense interstellar medium, $K = 0$ ammonia is observable in emission only through $\Delta J = \pm 1$ transitions, and the true ground state is observable only through the $J_K = 1_0 \rightarrow 0_0$ transition.

Nuclear spin statistics of the three identical spin 1/2 particles in ammonia give rise to two different symmetry forms, just as in H_2. Ortho-ammonia occurs when $K = 3n$, where $n = 0, 1, 2\ldots$, while para-ammonia has $K = 3n \pm 1$. Ortho-ammonia and para-ammonia need not be in equilibrium, since generally neither radiative nor collisional transitions are allowed between the two forms. However, observations of the inversion splittings of the $J_K = 3_3$ level when compared to the 2_2 and 1_1 inversion splittings in Orion are consistent with only small departures from equilibrium (Morris *et al.* 1973; Barrett, Ho, and Myers 1977; Wilson, Downes, and Beiging 1979; Ho *et al.* 1979).

The observations reported here resulted in the first detection of a rotation-inversion transition in the $K = 0$ ladder of interstellar ammonia. Other far-infrared rotation-inversion transitions have been observed in Jupiter where the contributions from different K ladders cannot be resolved (Erickson *et al.* 1978). Far-infrared emission from ammonia has also been observed recently in OMC-1 from the $J_K = 4_3 \rightarrow 3_3$ transition (Townes *et al.* 1983).

II. OBSERVATIONS

At 524 μm, the wavelength of the ground-state rotational transition of NH_3, the Earth's atmosphere is quite opaque. For these observations on 1982 November 30 and December 2, we used an InSb hot-electron-bolometer heterodyne receiver similar to that described by Phillips and Jefferts (1974) on board NASA's Kuiper Airborne Observatory, flying at an altitude of 12.5 km. The bandwidth of the receiver was 1 MHz (0.52 km s^{-1}) which we stepped along the spectrum in units of 1 km s^{-1}, sweeping the klystron local oscillator under computer control. Our receiver noise temperature was ~ 500 K.

On our first flight, we observed the center of OMC-1. A four-point map consisting of positions separated by 1′

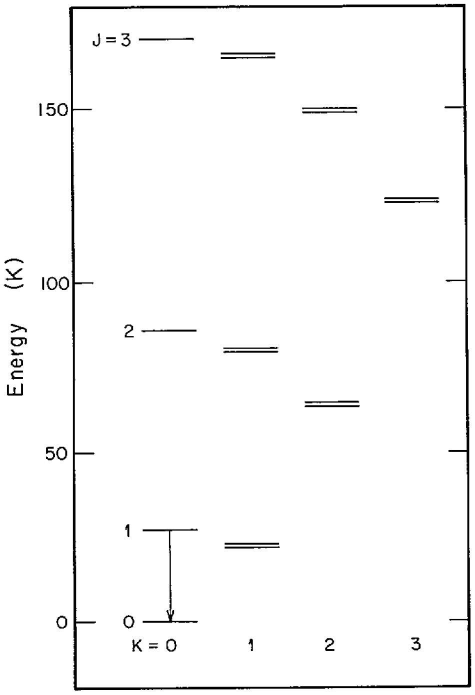

FIG. 1.—Energy diagram for the lowest few levels of NH_3 in its ground vibrational state. The observed $J_K = 1_0 \rightarrow 0_0$ transition is indicated by the arrow. Inversion splittings for $K \geqslant 1$ are shown approximately to scale.

from the center in the cardinal directions was completed during the second flight. We alternated integrations on the source positions with observations of two off-source positions located 15′ E and W of the center; integrations lasted about 2 minutes at each position. Total integration time for each of the spectra in Figure 1 was ~ 1.5 hr. We estimate that our absolute pointing accuracy was ±30″; relative pointing accuracy was ±10″. The beam size is determined by the diffraction of the 0.91 m telescope. At the wavelength of 524 μm, it is approximately 2′ FWHM.

We calibrated with observations of 290 K and 80 K loads to determine the receiver temperature and with observations of the moon to determine our beam efficiency. The moon was 95% fully illuminated. We assumed the temperature of the subsolar point to be 390 K and the submillimeter emissivity to be 97% (Linsky 1973). Our measured beam efficiency was 40%. We have not measured the correction for the decrease in efficiency for a point source, η_c (Kutner and Ulich 1981), but for a Gaussian beam the theoretical value for η_c is ~ 0.7.

III. RESULTS

The $J_K = 1_0 \rightarrow 0_0$ spectra of the peak of OMC-1 and of the average of the positions 1′ from the peak are shown in Figures 2*a* and 2*b* respectively. The data points are spaced by 1 km s^{-1}, but the spectra have been Hanning smoothed to an effective velocity resolution of 2 km s^{-1}.

The antenna temperature (T_A^*) at the center of OMC-1 is 3.5 K. The average temperature in the offset positions of 1.7 K indicates that the source is small compared with our beam, or less than 1′ since our beam size is ~ 2′.

The line central velocity with respect to the local standard of rest (V_{LSR}) is 9 ± 1 km s^{-1}, indicating that the emission originates in the molecular cloud material ("spike"), not in what is known as the "hot core" (Genzel *et al.* 1982) which is seen in some NH_3 inversion transitions at $V_{LSR} \approx 5$ km s^{-1}. The $J_K = 1_0 \rightarrow 0_0$ line width, Δv, is ~ 7 km s^{-1} (FWHM) and is affected very little by hyperfine splitting which has a maximum extent of 3 MHz or 1.5 km s^{-1}. There is possibly some underlying broad emission in the spectrum of the OMC-1 peak at a low level.

We have made preliminary searches for the $J_K = 1_0 \rightarrow 0_0$ line in NGC 1333, S140, DR 21 (OH), W3, and W3 (OH), without success.

IV. INTERPRETATION

In the following discussion we assume that the kinetic temperature (T_k) of the quiescent gas in OMC-1 and the

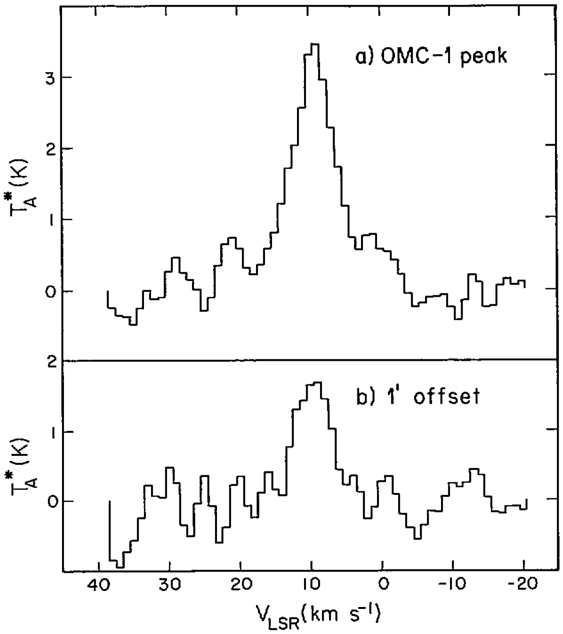

FIG. 2.—Observed NH_3 $J_K = 1_0 \rightarrow 0_0$ spectra of OMC-1: (*a*) peak of OMC-1, $\alpha(1950) = 5^h32^m46^s.7$, $\delta(1950) = -5°24'21''$; (*b*) average of four points offset from the peak by 1′ in the cardinal directions. The measurements were spaced by 1 km s^{-1}, but the spectra have been Hanning smoothed to a resolution of 2 km s^{-1}. There is some excess noise at the ends of the frequency scans, particularly at the low-frequency end of the 1′ offset position observations. This excess noise is not present near the scan centers.

excitation temperature (T_{ex}) of the metastable inversion levels are both 70 K (Liszt *et al.* 1974; Sweitzer 1978) and that the rotation temperature (T_{rot}) which is assumed to describe the populations of the various rotational states (J and K) is $\lesssim 70$ K. There is some evidence that the rotational levels of ammonia are subthermally excited and that T_{rot} may be closer to 30–40 K than to 70 K (Morris *et al.* 1973; Ho *et al.* 1979; Ziurys *et al.* 1981).

The $J_K = 1_0 \rightarrow 0_0$ T_A^* of 3.5 K, coupled with an efficiency factor $\eta_c = 0.7$ and a rotation temperature $T_{rot} \lesssim 70$ K implies a beam filling factor, Φ, of $\gtrsim 0.09$ for our 2′ beam. This corresponds to an emitting area with a diameter $\gtrsim 35''$. This area is compatible with our observations of points 1′ from the center, but is much larger than that inferred from observations of the 1_1 inversion transition. For a 1′.4 beam $\Phi \approx 0.04$ (Barrett, Ho, and Myers 1977; Sweitzer 1978) and for a 40″ beam $\Phi \approx 0.17$ (Wilson, Downes, and Bieging 1979), both implying a source diameter of $\sim 17''$. The emission from both the $J_K = 1_0 \rightarrow 0_0$ and the inversion line transition is probably due to multiple small clumps embedded in a lower opacity medium adding up to the total area measured in the two cases. Recent 40″ resolution maps by Ziurys *et al.* (1981) of the 1_1 and 2_2 inversion transitions indicate that the diameter of the total region containing spike emission is $\sim 40''$. We believe that the larger effective emitting area of the $J_K = 1_0 \rightarrow 0_0$ transition is due to the very much greater line opacity.

By turning the filling factor argument around we may derive a reasonable lower limit to the rotation temperature. If the diameter of the $J_K = 1_0 \rightarrow 0_0$ emitting region is less than 1′, as indicated by our observations, then $\Phi < 0.25$ and $T_{rot} > 32$ K.

Simple assumptions allow the ratios of the peak optical depths in the $J_K = 1_0 \rightarrow 0_0$ transition to the metastable inversion transitions to be calculated. We compare our data on the $J_K = 1_0 \rightarrow 0_0$ transition to the 1_1 rather than the 3_3 inversion transition, even though the $K = 0$ and 3 ladders are both ortho-ammonia and are thus more directly related. We do this because the hyperfine lines which provide a mechanism for determining optical depth are much stronger for the 1_1 transition than for the 3_3, and because the spectrum of the 3_3 line is complicated by the presence of emission from the hot core. In any case, as mentioned above, observations of the 1_1, 2_2, and 3_3 inversion lines are consistent with only small departures (less than a factor of 2) from equilibrium populations of ortho-ammonia and para-ammonia in OMC-1.

Let τ_{11} be the peak optical depth of the *main* hyperfine component of the 1_1 inversion transition and τ_{10} be the peak optical depth of the $J_K = 1_0 \rightarrow 0_0$ transition (all hyperfine components blended). If both lines are assumed to arise from regions with the same Gaussian velocity dispersion, therefore possessing line shapes with the same intrinsic line width, Δv_i, then the ratio τ_{10}/τ_{11} is given by

$$\frac{\tau_{10}}{\tau_{11}} = \frac{2g_{00}}{g_{11^s}} \frac{|\mu_{01}|^2}{|\mu_{11}|^2} \exp\left(E_{11^s}/kT_{rot}\right) \times \frac{1-\exp\left(-h\nu_{10}/kT_{rot}\right)}{1-\exp\left(-h\nu_{11}/kT_{ex}\right)}, \quad (1)$$

where g_{00} = statistical weight of the $J_K = 0_0$ level; g_{11^s} = statistical weight of the lower (symmetric) inversion state of the 1_1 level; μ_{01} = dipole matrix element of the $J_K = 0_0 \rightarrow 1_0$ transition; μ_{11} = dipole matrix element of the 1_1 inversion transition; E_{11^s} = energy of the lower inversion state of the 1_1 level above the 0_0 level; ν_{10} = frequency of the $J_K = 1_0 \rightarrow 0_0$ transition; and ν_{11} = frequency of the 1_1 inversion transition. The values of the dipole matrix elements and the statistical weights are taken from Townes and Schawlow (1955), while the energy E_{11^s} is derived from constants given by Urban *et al.* (1981). For $32 < T_{rot} \lesssim 70$ K, equation (1) gives $75 \lesssim \tau_{10}/\tau_{11} < 175$. Since the optical depth in the 1_1 line is 1–2 (Barrett, Ho, and Myers 1977; Ho *et al.* 1979, Wilson, Downes, and Bieging 1979; Ziurys *et al.* 1981), the optical depth in the $1_0 \rightarrow 0_0$ line is very large, $75 < \tau_{10} < 350$.[1]

The expected expansion in the apparent source size from the 1_1 to the $J_K = 1_0 \rightarrow 0_0$ transition may be calculated very approximately. We assume that the ammonia exists in a single clump with a Gaussian column density and that emission from the source is seen out to the radius where the optical depth falls to 1. For the 1_1 inversion transition, we assume the central optical depth, $\tau_{11}(0)$, is 2, and we set $\tau_{11}(r) = 1$ at $r = 8''.5$. Then, given the relation

$$\tau_{11}(r) = \tau_{11}(0) \exp - \left(r^2/r_0^2\right), \quad (2)$$

we have $r_0 = 10''.2$. Since $75 \lesssim \tau_{10}/\tau_{11} < 175$, the relation for τ_{10} is

$$\tau_{10}(r) \approx (150 \rightarrow 350) \exp - \left(r^2/r_0^2\right). \quad (3)$$

Solving for $r(\tau_{10} = 1)$, we find $r \approx 2.3\, r_0$ or $r \approx 23''$. This value is consistent with the value of $\gtrsim 18''$ which we derive from the $J_K = 1_0 \rightarrow 0_0$ filling factor of $\gtrsim 0.09$. The derived value of r depends strongly on the poorly known value of the parameter $\tau_{11}(0)$; therefore, this argument merely indicates that the observed source size may be consistent with the line optical depth.

The large optical depths of the low-lying rotation-inversion transitions in ammonia imply that radiative

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[1] From high spatial resolution observations of ammonia clumps 3′.5 north of our peak position, Harris *et al.* (1983) have shown that the optical depth of clumps may be greater than had been deduced from earlier low resolution observations. Therefore the peak optical depth in the $J_K = 1_0 \rightarrow 0_0$ line may be even greater.

excitation effects are important. For example, Sweitzer (1978) found that excitation of the 2_1 level occurs via trapping of 252 μm far-infrared line radiation and that excitation of the 3_2 and 4_3 levels is by continuum radiation from dust. The significant population of higher J_K levels in Orion requires that a large-scale calculation involving all accessible states be performed to determine accurately the nature of trapping effects in the $J_K = 1_0 \rightarrow 0_0$ line. This is not attempted here. We can, however, estimate some general effects of the far-infrared radiation field. Trapping of 524 μm line photons is essential to maintain the large apparent source size derived above. The H_2 density required for purely collisional excitation of the 1_0 level to $T_{\rm rot} > 32$ K is $n_{\rm coll} > 3 \times 10^7$ cm^{-3}. Complete thermalization requires about 10 times that density. Collisional excitation throughout the entire source is therefore unlikely. The density required to excite the 1_0 level, including trapping effects, can be estimated from $n_{\rm trap} \approx n_{\rm coll}/\tau_{10}$ (see, e.g., White 1977). Since $\tau_{10} < 350$, $n_{\rm trap}$ is $> 10^5$ cm^{-3}. However, if $T_{\rm rot} \approx 70$ K, $n_{\rm trap}$ is over a factor of 10 larger. The inferred density and source size are in agreement with observations of molecules such as CS (Goldsmith *et al.* 1980) which require high densities for excitation. The effect of far-infrared continuum radiation on the 1_0 level population is probably small.

The line width, $\Delta v \approx 7$ km s^{-1}, is larger than that observed for the spike component of the inversion transitions (Ziurys *et al.* 1981). This increase in line width is probably also due to the large optical depth in the line. Phillips *et al.* (1979) have shown for very optically thick lines with Gaussian line shapes that

$$\Delta v \rightarrow \Delta v_i \left(\frac{\ln \tau_p}{\ln 2}\right)^{1/2}, \qquad (4)$$

where τ_p is the peak optical depth in the line and Δv_i is the intrinsic velocity width of the line (FWHM). In this source, $\Delta v_i \approx 2.6$ km s^{-1} (Ziurys *et al.* 1981) and $75 \lesssim \tau_p < 350$. This implies that $2.5 \lesssim \Delta v/\Delta v_i < 2.9$ or $6.5 \lesssim \Delta v < 7.6$ km s^{-1}, as observed.

It is interesting to ask how much the hot core component of OMC-1 can contribute to the observed intensity in our beam. Genzel *et al.* (1982) have deconvolved the spectrum of the 3_3 inversion transition observed by Wilson, Downes, and Bieging (1979) into its hot core and spike components. They find that the hot core component is very optically thick and has an antenna temperature of 1.7 K in a 40″ beam. Correcting for the aperture efficiency of 0.29 (Wilson, Downes, and Bieging), the main beam brightness temperature, $T_{\rm MB}$, is ~ 5.9 K. Since the brightness temperature of the hot core as measured at the VLA is ~ 200 K, $\gg h\nu_{10}/k$, the contribution into our 2′ beam can be estimated by multiplying $T_{\rm MB}$ in a 40″ beam by the beam dilution factor; no Planck correction is necessary. We assume that the hot core material is spatially confined and that the size cannot be further extended by the larger opacity of the $J_K = 1_0 \rightarrow 0_0$ line. The resultant estimate of the contribution from the hot core is $T_A^* \approx 0.7$ K. There is possibly a broad emission component at about that level at the peak of OMC-1 (Fig. 1a) but more observations are necessary to confirm its presence.

To summarize, strong emission from the lowest rotation-inversion transition of ammonia, $J_K = 1_0 \rightarrow 0_0$, has been observed in OMC-1 at 572.5 GHz. The line velocity of 9 km s^{-1} indicates that it arises in the molecular cloud material, commonly called the spike component. A large increase in effective source area relative to the emitting area of the metastable 1_1 inversion transition is found from the filling factor derived by assuming a rotational temperature of $\lesssim 70$ K. This increase in source size and the large line width (~ 7 km s^{-1}) are consistent with the large peak optical depth estimated for this line in OMC-1 (75–350).

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