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Letter to the Editor

Radio detection of ammonia in comet Hale-Bopp

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Abstract. Radio emission from ammonia, a suspected parent molecule in comets, was detected from comet Hale-Bopp near its perihelion passage with the 100-m Effelsberg Radio Telescope. Signals from the five lowest metastable inversion transitions of NH_3 were obtained to derive a rotational temperature of 104±30 K, assumed to be representative of the kinetic temperature in the comet's inner coma ($R < 5000$ km). The ammonia production rate at perihelion is calculated from these observations to be $6.6{\pm}1.3 \times 10^{28}$ s^{-1} (almost two tons of ammonia per second). Compared with independently determined water production rates near perihelion, the implied ammonia abundance ratio to water is in the range 1.0–1.8%.

Key words: radio line emission - comets - comet Hale-Bopp

1. Introduction

Observations of radio emission from ammonia in the gas coma of comet Hale-Bopp (C/1995 O1) were performed at the 100-m Radio Telescope of the Max-Planck-Institut für Radioastronomie in Effelsberg, Germany. Detections of all inversion transitions in the metastable states (J=K) of NH_3 up to (J,K) = (5,5) were made near the comet's perihelion in March/April 1997.

Ammonia is usually fairly prominent on the list of trace constituents in cometary nuclei. This hypothesis is supported by the presence of optical NH_2 spectra in many comets, assumed to be a dissociation product of NH_3 (Wyckoff et al. 1991). Further evidence was obtained from mass spectrometer measurements on the Giotto spacecraft during its encounter with comet Halley in 1986 (Allen et al. 1987; Meier et al. 1994).

Ammonia has been detected previously in two comets that approached very close to the Earth. The first successful detection (Altenhoff et al. 1983) was achieved for the presumably strongest line (3,3) with comet IRAS-Araki-Alcock (1983d = 1983 VII). Both the (1,1) and (3,3) lines were detected in comet Hyakutake (C/1996 B2) at the NRAO 43-m telescope at Green Bank, WV/USA (Palmer et al. 1996). Previous unsuccessful searches for ammonia at Effelsberg were undertaken during the apparitions of comet Kohoutek (Churchwell et al. 1976) and comets Giacobini-Zinner and Halley (Bird et al. 1987).

The 6_{16}–5_{23} transition line of water at λ = 1.35 cm was marginally detected during the same observation epoch. An analysis of these data will be reported in a future communication. The present note describes only the NH_3 observations of comet Hale-Bopp and their interpretation.

2. Observations

The ephemeris for comet Hale-Bopp was computed from the orbit solution #48 published 27 January 1997 by D.K. Yeomans and made available to the public via the World Wide Web (http://encke.jpl.nasa.gov/eph.html). The absolute positional residuals in the plane of the sky were estimated to be $< 3''$ for the epoch of observation, much smaller than the telescope's half-power beamwidth ($HPBW$) of $40'' \times 43''$ (azimuth × elevation).

The prime focus receiver system used for these observations is a K-band maser, tunable over the range 18-26 GHz. The spectra were recorded with a 1024 channel (2-bit) autocorrelator in a 12.5 MHz bandwidth centered on the predicted topocentric radial velocity of the comet. The spectral resolution in this configuration is 12.2 kHz (or $\sim$0.15 km s^{-1}) per channel over a total spectral range $\pm$78 km s^{-1}. Position switching was used for the observations, the off-source position located 1° east of the comet.

Pointing calibrations were carried out regularly using the nearby standard sources NGC 7027, DR 21, and 3C84. Comet

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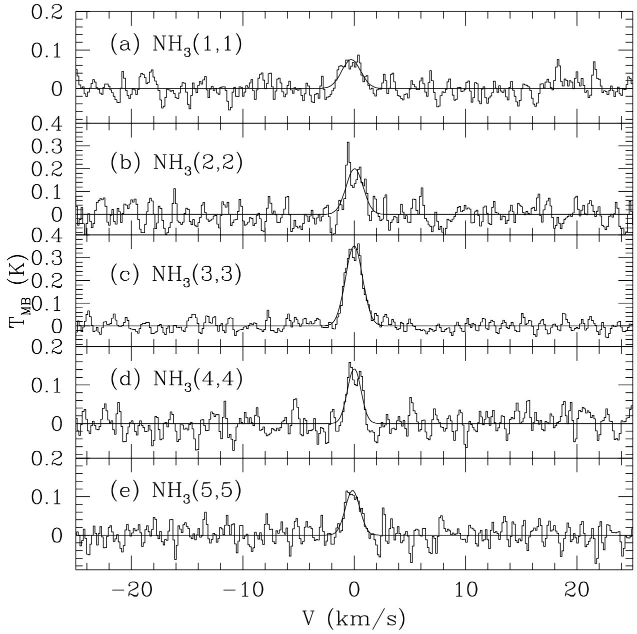

Fig. 1. Integrated ammonia spectra from comet Hale-Bopp. The NH_3 transitions $(J, K,\ J = K)$ are shown from top to bottom in order of increasing frequency from (J, K) = (1,1) to (5,5). The spectra are averages of T_{MB} over all data recorded during four observation days. The velocity scale is centered on the topocentric radial velocity of the comet. Parameters derived from Gaussian fits to the lines are given in Table 1.

line flux densities were calibrated relative to the epoch-corrected intensity of NGC 7027, which was taken to be 5.2 Jy ($T_{MB} \simeq 7.1$ K) at 23.78 GHz (Ott et al. 1994). Small corrections to the brightness temperature were applied for changes in antenna gain over the range of elevations from 30–80°. The system noise temperature (T_{MB} scale) varied from $T_{sys} \simeq 150$ K to 240 K, depending on daily meteorological conditions.

The ammonia molecule has a series of inversion transitions at $\nu \sim 24$ GHz that arise from the oscillation of the nitrogen atom through the plane formed by the three hydrogens (see e.g., Ho & Townes 1983). For the densities and temperatures expected in cometary comae, the NH_3 population is most probably confined to the so-called metastable (J, K), $J = K$ states, which have considerably longer lifetimes than the corresponding states with $J > K$ (Rohlfs & Wilson 1996). Under this assumption, the relative strengths of several simultaneously observed inversion lines can be used to derive the "rotational temperature" T_R, generally taken to be a measure of the kinetic temperature of the neutral coma gas.

The ammonia observations at Effelsberg were performed on four days near the comet's perihelion. Table 1 is a compilation of the observational parameters for the lowest five metastable inversion lines of NH_3. Observation session numbers 1 to 4 in Table 1 were conducted on 13 March, 25 March, 1 April and 3 April 1997, respectively. Averaged spectra over all observation days for each radio transition line are shown in Fig. 1.

Table 1 gives the rest frequency of the observed inversion transitions in GHz, as well as the energy of the metastable state above ground level, expressed as a temperature (K). The integration time t_{int} refers to the total time on the comet's position (on-source). The baseline noise temperature T_{rms} and peak line intensity T_{peak} for each spectrum are given on a T_{MB} scale. Gaussian fits were performed to determine T_{peak}, center velocity v_0, and full width at half maximum ($FWHM$) of the line, denoted δv in the following. The errors for these parameters in Table 1 reflect the formal uncertainties in this fitting procedure. The integrated intensity of the line centered at v_0 was computed from $\int T_{MB}\, dv \simeq 1.064 \cdot T_{peak} \cdot \delta v$. The final column of Table 1 is the beam-averaged column density in both upper and lower level of the specific NH_3 state (Wilson et al. 1979), given by

$$\langle N(J,J)\rangle = 6.8 \times 10^{12}\ \frac{J+1}{J} \int T_{MB}(v)\, dv \quad [\mathrm{cm}^{-2}] \qquad (1)$$

for T_{MB} in K and dv in km s^{-1}. The integral in Eq. (1) should be taken over all hyperfine components. We integrated only over the main spectral line, but then applied a hyperfine correction (Ho & Townes 1983) that increases the value of $\langle N(J,J)\rangle$. The upward correction is a factor of 2 for the (1,1) line, ∼25% for the (2,2) line, and correspondingly smaller for higher-order states. It is further assumed that the emission is optically thin and that the main and satellite groups of hyperfine components have the same excitation temperature.

The values of $\langle N_i\rangle$ in Table 1 are referenced to a common date, taken as 1 April 1997 (third day of observation: perihelion). This normalization procedure was necessary because the observations for each transition were carried out on different days. In addition to the correction for different geometric conditions, an adjustment was applied for the calculated relative change in the intrinsic production rate of the comet (see Table 2). The final errors associated with the value of $\langle N_i\rangle$ were estimated by accounting for systematic effects (calibration, etc.) of roughly 20%, combined (root sum of squares) with the formal errors from the Gaussian fit procedure.

3. Estimate of the comet's production rate

The comet's ammonia production rate can be calculated if the source region is sufficiently constrained by credible values for the outflow velocity and lifetime of the NH_3 molecule. The source of the ammonia emission was centered on the velocity of the nucleus to within the measurement error. The linewidth of the optically thin emission δv can thus be interpreted as being related to $\pm u$, yielding values of the outflow velocity $u = \delta v/2 \simeq$ 0.7–1.0 km s^{-1}, consistent with the outflows observed during the Giotto flyby at comet Halley (Balsiger et al. 1986).

The photodissociation lifetime of ammonia at 1 AU has been given variously as $\tau \simeq 5600$ s (Huebner & Giguerre 1980), 6700 s (Allen et al. 1987), or 7700 s, (Palmer et al. 1996). One reason for variations is that τ is dependent on the actual solar UV flux ($\lambda \lesssim 230$ nm), which can vary significantly over the solar cycle and whether or not the comet is exposed to solar

Table 1. Ammonia line observations in comet Hale-Bopp

session no.	trans. line	frequency [GHz]	energy [K]	t_{int} [min]	T_{rms} [mK]	T_{peak} [mK]	v_0 [km s^{-1}]	$FWHM = \delta v$ [km s^{-1}]	$\int T_{MB}\,dv$ [K·km s^{-1}]	$\langle N_i \rangle$ [10^{12} cm^{-2}]
12 4	(1,1)	23.69450	23.2	144	23	75±9	-0.27±0.12	2.00±0.28	0.160	4.3±1.4
12	(2,2)	23.72263	64.1	99	43	201±18	0.04±0.08	1.80±0.19	0.385	5.9±1.3
1234	(3,3)	23.87013	122.9	132	23	351±10	-0.01±0.02	1.81±0.06	0.675	8.1±1.4
4	(4,4)	24.13942	199.3	66	26	143±12	0.01±0.06	1.43±0.14	0.217	1.8±0.5
34	(5,5)	24.53299	293.6	108	26	116±11	-0.15±0.07	1.53±0.17	0.189	1.5±0.4

active regions. A recently published compendium of rate coefficients for 80 atomic and molecular species irradiated by the solar spectrum (Huebner et al. 1992) lists τ as 5.88 $\times$ 10^3 s (quiet sun) and 5.35 $\times$ 10^3 s (active sun). At any rate, the lifetime of an ammonia molecule is short enough that the source region of emission will definitely be much smaller than the Effelsberg beam throughout the observation interval. A moderate value of τ = 5600 s will be used in the following.

In the case of an unresolved source, it can be shown (Snyder 1982) that the beam-averaged column density $\langle N(NH_3)\rangle$ is related to the production rate $Q(NH_3)$ by

$$\langle N(NH_3)\rangle = \frac{4Q(NH_3)}{\pi\delta v\ d}\left[\frac{d}{\Delta\theta}\right]^2 = \frac{4Q(NH_3)\tau r^2}{\pi\Delta^2\theta^2} \qquad (2)$$

where $d = \delta v \cdot \tau \cdot r^2 << \Delta\theta$ is the diameter of the (spherical) source region with r in AU, Δ is the distance from Earth, and θ is the $HPBW$ of the antenna. Mean values of these parameters during the observations were $d \simeq$ 9.9 $\times$ 10^3 km and $\Delta\theta \simeq$ 40 $\times$ 10^3 km.

Based on the spectra from the strong (3,3) transition recorded at each observation session, it is noticed that slight variations in the ammonia production rate may have occurred. If real, the apparent maximum coincides with the period between closest approach to Earth (22 March) and perihelion (1 April). The comet's geometric parameters (r = heliocentric distance; Δ = geocentric distance; $\angle SCE$ = sun-comet-earth angle), derived line parameters (refer to Table 1), the column density from Eq. (1), and the total ammonia production rates from Eq. (2) are presented in Table 2.

4. Estimate of rotational temperature

Fig. 2 shows the quantity $\langle N(J,J)\rangle/[g_{op}(K)(2J+1)]$, where $\langle N(J,J)\rangle$ is the beam-averaged column density in state $J = K$ for the normalized date at perihelion, as a function of the energy level of the metastable state above ground $W(J)/k$ in kelvin (k is Boltzmann's constant). The function $g_{op}(K)$ is 2 for K = 0,3,6,...(ortho-NH_3) and unity for all other values of K (para-NH_3). A linear least-squares fit to the data points (dashed line) is consistent with a rotational temperature of $T_R \simeq$ 104±30 K. This value is representative of the kinetic temperature if the various metastable states of NH_3 states are thermally populated (Rohlfs & Wilson 1996, chap. 14), and is quite comparable to the rotational temperature 119±9 K, derived from CH_3OH observations on 3 April at 256 GHz (Mehringer et al. 1997). Because

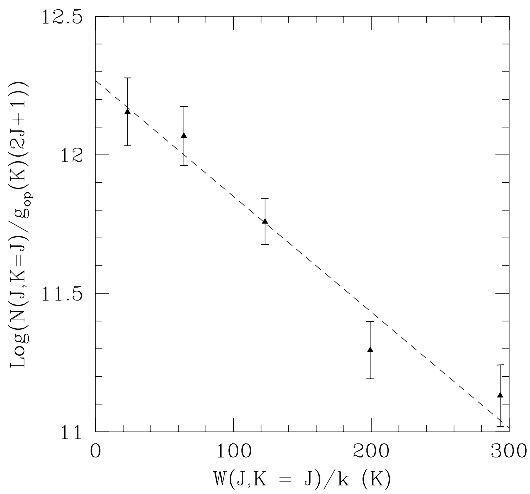

Fig. 2. Boltzmann plot of ammonia line strengths in comet Hale-Bopp. The quantity $\langle N(J,K=J)\rangle/[g_{op}(K)(2J+1)]$ is plotted versus the energy of the state above ground $W(J,K=J)/k$. The linear regression curve (dashed line) yields a rotational temperature T_R = 104±30 K.

ammonia molecules do not survive beyond about $R \simeq$ 5000 km after their sublimation from the nucleus, it is expected that the temperature T_R is applicable to only the comet's inner coma.

Knowing T_R (and thus the partition function), the beam-averaged NH_3 column density in all metastable levels (J=K) can be estimated. For example, it can be shown that $\langle N(NH_3)\rangle$ = 3.03 $\langle N(3,3)\rangle \simeq$ 2.4±0.4 $\times$ 10^{13} cm^{-2}. At this temperature 95% of the ammonia molecules are in states detected in their radio emission lines ($K < 6$). The ratio $\langle N(3,3)\rangle/\langle N(NH_3)\rangle$ is not very sensitive to the actual value of the rotational temperature, varying by only 3% over the range T_R = 104±30 K. The ratio decreases by only 27% if T_R is as low as 60 K (Palmer et al. 1996).

5. Discussion and Summary

The beam-averaged NH_3 column density for comet Hale-Bopp of 2.4 $\times$ 10^{13} cm^{-2} is about equal to that reported for comet IRAS-Araki-Alcock (Altenhoff et al. 1983), which was more than thirty times closer to Earth at the time of the observations, and about twice that of comet Hyakutake (Palmer et al. 1996), observed at a distance twelve times closer. Using this value in Eq. (2), we obtain a mean production rate of

Table 2. Ammonia (3,3) spectral line data for each observation date

date	r [AU]	Δ [AU]	$\angle SCE$ [$\circ$]	t_{int} [min]	T_{peak} [mK]	v_0 [km s^{-1}]	$FWHM = \delta v$ [km s^{-1}]	$\langle N(3,3)\rangle$ [10^{12} cm^{-2}]	Q(NH_3) [10^{28} s^{-1}]
13.26 Mar	0.974	1.349	47.3	63	287±16	0.06±0.04	1.47±0.10	4.4±1.0	3.3±0.8
25.31 Mar	0.922	1.318	49.0	39	375±17	0.07±0.05	2.15±0.11	8.5±1.9	6.7±1.5
01.34 Apr	0.914	1.354	47.6	15	426±22	-0.12±0.04	1.54±0.09	6.9±1.6	5.9±1.4
03.31 Apr	0.915	1.370	46.9	15	361±20	-0.04±0.05	1.96±0.13	7.4±1.7	6.5±1.5

$Q(NH_3)$ = 6.6±1.3 × 10^{28} s^{-1}, corresponding to ∼1.9 tons of ammonia per second. Comet Hale-Bopp's ammonia production rate is thus determined to be about 70 (100) times greater than that quoted by previous authors for comet Hyakutake (comet IRAS-Araki-Alcock).

For the observations of comet Hyakutake, Palmer et al. (1996) derived an excitation temperature $T_R \simeq 60$ K from the implied column density ratios of the (1,1) and (3,3) lines. An ammonia abundance of 0.3% was derived when compared with the comet's water production rate taken from IUE observations on the same date. This was a factor of 20 less than the abundance estimate for comet IRAS-Alraki-Alcock of 6% (Altenhoff et al. 1983), and considerably closer to the estimates of 0.1–0.2% from optical flourescence of NH_2 (Wyckoff et al. 1991) or to the range 0.44–0.94% from UV spectra (Feldman et al. 1993).

There is mounting evidence that the apparent ammonia abundance is not necessarily the same for all comets, and may even vary in the same comet during the course of a given apparition. Observations of comet Hale-Bopp by Biver et al. (1997) convincingly documented the distinct transition from a CO-driven gas coma to one driven by H_2O at approximately r = 2.8 AU. Biver et al. (1997) also showed that the pre-perihelion production rate increases of the many other observed volatile species did not follow a common dependence on heliocentric distance.

The Effelsberg radio observations of NH_3 in comet Hale-Bopp near its perihelion have been used to derive a production rate of $Q(NH_3) \simeq 6.6 \times 10^{28}$ s^{-1} and a probable kinetic temperature of the inner coma ($R < 5000$ km) of $T_R \simeq 104$ K. Water production rates of 4.3 × 10^{30} and 5 × 10^{30} have been derived from independent observations during the same epoch by Schleicher et al. (1997) and Dello Russo et al. (1997), respectively. The ammonia to water abundance ratio near perihelion is thus implied to lie in the range 1.4±0.4%.

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